NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Introduction: Letter from the Director

An Open letter from the Deputy (previously Acting) Director
Rosalind Grymes

The year just concluded, the Institute's fifth, has been a year of milestones and accomplishments. The achievements, as in the past, are focused on both individual and collective efforts from our member researchers; their work, their publications, their contributions to the landscape of science.

And, once again, in their participation with initiatives either conceived by them and supported by NAI Central, or vice versa. The partnership between our distributed Teams and the centralized administrative directorate persists, and continues to generate productive results in a variety of endeavors that define and nurture the astrobiology community. I will mention some of these here, and rely on the body of this Annual Report to detail the substantial scientific accomplishments and other results of Institute activities. Personally, however, this fifth year−during which I stewarded the Institute as Acting Director−is memorable for the incessant rush of institutional milestones. One by one, or in groups, these appeared on the horizon and then sped by breathtakingly fast.

These milestones represent maturation stages in the development of the NAI rather than individual annual achievements. They are close to my perspective not only because many proceeded from NAI Central, but because they intrinsically tested, and demonstrated, the continuum of the NAI as an entity that is 'more than the sum of its parts.' We have experienced a second change in leadership, the validation and formalization of the Institute's Executive Council, and a re−orientation of the NAI's research suite. Were there comparable shifts in the preceding four years, since the NAI's inception? In 1999, we saw the hand−over from the NAI's first director and interim manager, G. Scott Hubbard, to the stewardship of the second director, Dr. Baruch Blumberg. In 2001, the Institute felt an expansion in its membership with the selection of four additional Teams. These events were substantial milestones in the Institute's lifetime, certainly. However, the timing of these previous experiences, at two year intervals, highlights the unique circumstance of the simultaneous occurrence of three comparable defining alterations in one year.

As alluded to above, Dr. Blumberg retired from his NAI role late in 2002 (although remaining active with aspects of the NAI and with other scientific organizations at NASA), after having announced his intention to do so in December of 2001. We, as a group, experienced an unexpectedly long lag

between his leave−taking and the appointment of the third Director, Dr. Bruce Runnegar. Weathering a change in leadership is a classic challenge to any organization, and this one was more protracted than most. It was, even, two changes at once, as I stepped in to become Acting Director in October of 2002. I am deeply grateful to my colleagues in all fifteen of the NAI Teams for their cooperative and supportive input last year. Two different considerations permeated my time as NAI caretaker. One, that the business of the Institute and the maturation of science initiatives continue, seamlessly and with clear purpose. Two, that issues relating to strategic future directions and policy or precedent be handled gently, so as to provide ample room for the perspective of the new Director, and for the perspective of the Institute's Executive Council. To the extent that these competing views mingled successfully, I credit the professionalism and commitment of the NAI Central team and the good−will of the NAI members.

The Executive Council, this year, also experienced dramatic change. Crystallizing informal procedures, the Council was provided with a Charter (drafted in Year 5 and signed in November, 2003) defining its operational scope as the primary advisory body of the NAI. Among the specified functions of the Council is a new responsibility related to the use of the Institute Strategic Fund (ISF). The Council prioritizes the use of this fund and the NAI overall benefits from the relevant and knowledgeable advice of leading astrobiology experts−the PIs. In addition, through the ISF, the Institute maintains operational flexibility and responsiveness that are critical to research and technology innovation. Simultaneous with this change, however, the Executive Council itself was re−arranged. The change in Council membership did not occur until November 1, 2003, but the stage was set by the announcement, in June, of the selection results from the third Cooperative Agreement Notice. Like the challenge associated with the directorship, this substantial change to the operation and membership of the Executive Council relied on the underlying continuity of the Institute infrastructure.

The third Cooperative Agreement Notice (CAN) proposal cycle had far−reaching effects beyond its impact on the membership of the Executive Council, of course. The first Team selections, in CAN−1, established the founding Teams of the NAI. The second round, CAN−2, provided additional research elements, through the selection of four new Teams that joined the initial eleven. For the first time, in CAN−3, the NAI experienced a revision of its content, rather than an additive expansion. The process of CAN−3 and its outcome, and the perception of both these elements by the Institute's membership, the NAI's funding sponsors, and the astrobiology community at−large, were critical features of the Institute's maturation. Thoughtful, deliberate planning went into every aspect of CAN−3, for exactly these reasons. The experience of concluding the founding Team awards, at the five+ year mark (each CAN−1 Team was provided a four−month fully funded extension to the original five year period of performance, for transition purposes) was painful, but essential. Institute membership has become a sought−after, high profile recognition of excellence across the disciplines of astrobiology. This circumstance is due, quite directly, to the achievements of the scientists involved in the NAI during its first five years. At the same time, the NAI remains, not only nationally but internationally, a unique opportunity

for large−scale support of astrobiology research, a dynamic interdisciplinary endeavor. Both these features of the NAI, prestige and singularity, contribute to an intensely competitive selection environment.

The last five years of NAI activities, and the result of the CAN−3 selections in this year, highlight another challenging aspect to the Institute's collaborative community. The proposal evaluation process pointed out the dichotomy between the inter−Team competition that is intrinsic to peer−review processes and the inter−Team cooperation that is intrinsic to Institute membership. The solution, if there is one, to these apparently opposing interests lies in the advantages, project by project and researcher by researcher, that collaboration provides. We continue to observe dynamic interactions between NAI members, whose individual and Team activities benefit from collegial exchanges. One specific outcome of the competition/collaboration dipole is the Astrobiology Drilling Program (ADP). This initiative for the acquisition of Early Earth geological samples officially began in the summer of 2002. It is ongoing, and provides an umbrella organization to individual, even potentially competitive, projects. The ADP articulates, and manages through its Steering Committee, policies on research conduct, field investigation protocols, international cooperation, and sample curation/distribution. The program arose through initial dialogues with groups representing potentially competitive inter−Team interests. Facilitation of outside−the−box solutions to collaborative science is a key feature, and key success, of the NAI.

It is difficult to say whether these organizational developments occurred against the continuing backdrop of other events and annual accomplishments, or vice versa. Whichever attitude you prefer, the accustomed suite of repeat successes and innovations went forward in Year 5, as it always does. The NAI held its third Institute−wide meeting, maintained its visibility with international partners, interacted with several review, oversight, and advisory committees, and moved forward with ambitious Education and Public Outreach offerings while maturing as a 'virtual,' electronically−enabled, Institute.

The Third General Members' Meeting, held at Lead Team Arizona State University hosted by PI Dr. Jack Farmer and his associates, was notable for many reasons. The ASU administration offered us an extraordinary welcome, and many members of Jack's Team contributed long hours to planning and implementing this meeting. The NAI demonstrates its true nature as a working collaborative when research sites support Institute−wide activities of this scale, lending a warm and collegial atmosphere to a broad and inclusive undertaking. The meeting was filled with up−to−the−minute presentations of new information balanced with interdisciplinary reviews of current astrobiology science issues. A Town Hall Meeting broadcast to distant sites and a PDA−based alternative to either CD or hard−copy program books contributed a forward−looking use of technology to the meeting. The single highlight, though, must be the morning we spent interacting in open−ended, unstructured discussion groups as we waited for ASU security and local law enforcement officials to determine that the conference site was suitable for our use following a bomb−scare. This meeting, like most, had overtime sessions and speakers overly optimistic about their effective content delivery rates. However, our unexpectedly disrupted day concluded with only a deliberate 30

minute adjustment, and no loss of content. The cooperation of the re−scheduled plenary speakers, Drs. Steven Benner and David Deamer, and of the entire day's roster of presenters, enabled that outcome. The sangfroid of the combined ASU and NAI Central logistics teams, on this occasion, matched our previous high (with our hosts at the NAI Team Carnegie Institution of Washington) during the kitchen fire at the NAI Second General Members' Meeting in Washington, D.C. (you didn't know...?)

In a marginally less explosive development, the National Research Council's Committee on the Origin and Evolution of Life (COEL) last year produced a report on astrobiology, nationally and internationally, which included special comment on the NASA Astrobiology Institute. The COEL included positive and complimentary material on the accomplishments of the NAI. The committee also thoughtfully articulated its advice relative to ongoing challenges of balance among the NASA Astrobiology Program elements (individual grants for both research and technology efforts, the NASA Specialized Centers of Research and Training focused in the Origin of Life, and the NAI) and the inclusion of additional astrophysics and astronomy research in the astrobiology repertoire. The group also recommended, presciently, several initiatives that were already underway at NAI by the time the report was published and distributed, notably the formation of an Astronomy Focus Group. In their analysis of the international astrobiology science scene, COEL accurately pinpointed the positive effect of the Institute's program of Associate and Affiliate partnerships. This area, too, saw important developments this year, with the formation of the International Astrobiology Circle (IAC). The IAC's founding members include the NAI and each of the Institute's Associates (Centro de Astrobiología and Australian Centre for Astrobiology−which became an Associate following Affiliate status this past year) and Affiliates (Astrobiology Society of Britain, Groupe de Recherche en Exobiologie, and European Exo/Astrobiology Network Associate−a twelve member European conglomerate). These six groups were soon joined by the Swedish Astrobiology Network. Together, the IAC's members will focus on providing opportunities for young scientists, across the globe, and ensuring that workshops, conferences, and symposia include both student participants and appropriately diverse international contributors.

Two accomplishments come to mind for special acknowledgement in the arena of education, outreach, and training. One is a specific initiative aimed at the professional science community, the other a general recognition of the continued importance of using many and varied approaches targeted to multiple different audiences. In the first, a suggestion from Drs. Bruce Jakosky and Carl Pilcher led to the inception of the NAI Insight Courses. The concept behind the Insight Courses is simple; each is a full−featured 5−day introduction, presented by experts, to a domain of scientific inquiry. Each course includes some laboratory or field investigation elements, as appropriate, and each is designed specifically to accommodate participants with an advanced background in science, but one obtained in a different discipline than that addressed by the course. For example, this year, we presented Planetary Science for non−Planetary Scientists (led by Dr. Bruce Jakosky with a field component in the area surrounding Flagstaff, AZ) and Microbiology for non−Microbiologists (led by Dr. Ken Nealson with a field and

laboratory component at the Wrigley Marine Science Center, Catalina Island, CA). Registration in these courses is open to the entire community. A more general approach to the scientific, academic, and general public communities was articulated in one of the evaluative elements specified by CAN−3. The most recent selection opportunity for NAI Teams required each submission to detail the various ways in which the Team planned to 'strengthen the astrobiology community'−one of the encompassing goals of the NAI. Possible areas of emphasis included the pre−college education audience, the science−interested public, traditionally underrepresented communities, and the professional research community. NAI recognizes that informing and engaging each of these sectors is important, and that the most successful projects will leverage talented, creative partners experienced in a variety of media with scientists engaged directly in astrobiology research programs.

The virtual Institute has matured, year by year, over the preceding five. Throughout, we have endeavored to explore both synchronous and asynchronous technologies that enable effective, distributed interactions between the Teams and NAI Central, between the Teams themselves, and between the members individually. In addition to piloting the use of hardware and software tools, we have learned that the inclusion of 'users' in the process that identifies needs and solutions is critical, as is remaining in the loop following deployment and training to observe and measure how the tools are used. Following an extensive survey of NAI members regarding the needs and priorities they perceived for electronic resources, we discontinued our support for the *Postdoc* knowledge management software and performed a market survey of other tools. The primary videoconference solution originally acquired has stood the test of time, and has been upgraded constantly. It has been joined, now, by a desktop videoconferencing system that expands the ability of members across the NAI to participate in video−seminars and journal clubs as well as special interest meetings. Other asynchronous facilities have been piloted and distributed, and this approach will continue. The NAI is unique in the institutional breadth of its 'virtual' undertaking, in the complexity of its connectivity issues (multiple supported platforms, for example, and mixed user motivations), and in the highly technical nature of many of its supported collaborative dialogues. We demonstrate a broad natural laboratory of user interface issues.

Another of the critical interfaces in astrobiology arises from the diversity of disciplines represented within the astrobiology community. We continue together to face the ceaseless challenge of facilitating informed exchanges at the edges of our disciplines. In addition to this communication issue, we must continually address the dynamic balance between competition and collaboration. NAI members are diverse; they compete; they collaborate. Diversity, competition, exchange. This strategy has served well throughout the evolutionary history of life on Earth. It seems robust and dynamic enough to succeed. In fact, the NAI is counting on it.

Rosalind Grymes, Ph.D.
Deputy Director
NASA Astrobiology Institute

December 4, 2003

Introduction: Map of Team Locations

Geographic locations of the 15 NAI Lead Team institutions are indicated on a U.S. map. International Partners are listed below the map, with either Associate (formal agreement between NASA and the foreign government) or Affiliate (no formal government agreements) partnership arrangements.

Spain
Centro de Astrobiologia

United Kingdom
United Kingdom Astrobiology Forum

Australia
Australian Centre for Astrobiology

Groupement de Recherche en Exobiologie

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Lead Team Reports: Introduction

NAI is a partnership between NASA and 15 NAI Lead Teams located at 11 academic and research sites and 4 NASA centers. These teams work to promote, conduct, and lead integrated multidisciplinary science research and education in astrobiology. There are over 800 scientists and educators involved in these NAI endeavors.

Lead Team Reports (for each of the 15 NAI Lead Teams) include these sections:

- Executive Summary- written by the Lead Team Principal Investigator
- Project Reports- describing specific research projects in the Lead Team group
- NAI-NRC Postdoctoral Fellows- listed if working with particular NAI Team
- Education & Public Outreach (EPO) activities- list with descriptions
- Publications- displayed as a full alphabetic list or in research project groups
- Team Members- list with each member?s name, email, and institution

Ames Research Center
Executive Summary
Principal Investigator: David Des Marais

Ames Research Center NAI team has maintained a coordinated research program that links the formation, evolution, and climates of habitable planets; the roles of interstellar chemistry in supplying potential biological precursors to these worlds; the origins and nature of metabolism in the first cells; the impact of established biospheres on planetary climate and crustal and atmospheric chemistry, emphasizing the formation of detectable biosignatures; the response of vegetation to regional climate change; and, finally, the potential for life to transcend planetary boundaries through transfer between habitable worlds. Our program for education and public outreach captures these themes to develop an engaging and informative package that is being disseminated to national− and international−scale audiences. This is being achieved through partnerships with the California Academy of Sciences (CAS), Yellowstone National Park (YNP), New York Hall of Science, and several K−14 educational organizations. Strong conceptual and functional links to multiple NASA missions provide context, motivation, and funding leverage for our research component, along with resource− and audience−sharing opportunities for our education and public outreach component.

Our investigations of the formation, evolution, and climatology of habitable planets have focused on terrestrial (rocky) planets where liquid water is stable at the surface. We chose this focus because extrasolar planets that host surface biospheres are the most likely to be detected by remote spectroscopic searches. Simulations of planetary accretion have shown that the amount of mass accreted by Earth from the asteroid region depends sensitively on the formation time and the early orbital evolution of the giant planets. In particular, the mass of volatile materials delivered to Earth depends critically on the orbital eccentricities of giant planets, because these control the width and strength of the unstable resonances in the asteroid region. Our team has shown that methane could have provided a maximum of 30 degrees C of surface warming on early Mars. Higher methane concentrations would have resulted in an anti−greenhouse effect that would have caused surface cooling. We proposed a novel explanation for the Martian rivers, namely that they originated as the result of impacts. This view greatly restricts the environments where life might have originated and suggests that the only likely place might be in the subsurface. For the first time, we created particles that may form in methane−rich atmospheres that also contain carbon dioxide. Such atmospheres might resemble those of early Earth.

We have studied the formation of complex and potentially protobiological organics under simulated interstellar conditions. We also have helped to trace, spectroscopically and chemically, the cosmic evolution of organic molecules from the interstellar medium to protoplanetary disks, planetesimals, and finally onto habitable bodies. We have made progress in tracing the link between ice processes and the organic molecules in meteorites.

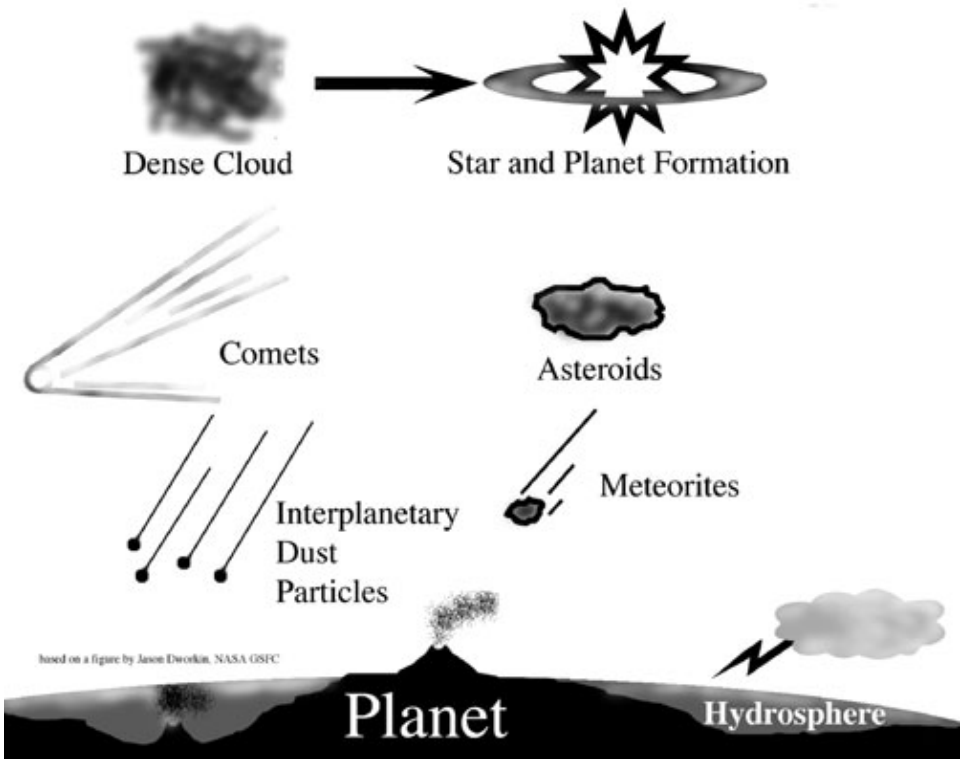


Figure 1. *Results from this past year's effort support the hypothesis that molecules that are important for the origins of life, might originate in the interstellar medium.*

First, we have demonstrated that the ultraviolet (UV) photolysis of presolar ices can produce the amino acids alanine, serine, and glycine, as well as hydroxy acids, and glycerol, all of which have been extracted from the Murchison meteorite. Thus, some of the meteoritic amino acids glycine, alanine and serine, as well as structurally related hydroxy acids, may have been synthesized in ice before our solar system formed. Also, the amino (NH_2), carboxylic acid (COOH), cyano (CN), ether ($O-CH_3$), hydroxy (OH), keto (>C=O), and methyl (CH_3) groups that decorate the aromatic compounds in meteorites and interplanetary dust particles (IDPs) can be formed by energetic processing of low temperature ices. This pathway is consistent with observed deuterium enrichments and is the first proposed mechanism that makes predictions on a molecular level.

We also address the origin of metabolism in the earliest ancestors of cells by testing the hypothesis that proteins might have arisen and initially evolved in the absence of a genome. We selected four new adenosine triphosphate (ATP)−binding proteins from a population of $>10^{12}$ random polypeptides.

Proteins from one family have been characterized. They are highly selective and do not bind either guanosine triphosphate (GTP) or deoxyadenosine triphosphate (dATP). They do not contain any known ATP−binding motifs, but they do require zinc ions and contain conserved cysteine residues, suggesting a possible structural similarity to zinc finger proteins. In order to test this possibility, and more generally to determine if these *de novo* evolved proteins resemble biological protein, we have evolved mutants that are suitable for biophysical studies by continued selection for ATP binding in the presence of guanidine. As expected, more of the newly selected proteins stay soluble in the presence of ATP, presumably because ATP binding stabilizes the folded state of the protein. We have established that some proteins remain stable as monomers. To simulate self−organization of protobiological proteins into metabolic networks capable of evolution towards increasing complexity we developed a computational approach for describing systems having many species and reaction channels. This method is not limited to chemical reactions, and it allows for incorporation of other cellular processes such as channel−mediated transport and cell growth and division.

We investigated living photosynthetic microbial mat ecosystems because they allow us to examine those microbiota and ecological processes that participated in early evolution, modified the early environment, and created biosignatures. Photosynthetically active cyanobacterial mats were studied in a hypersaline pond near Guerrero Negro, Mexico. We quantified the substantial quantities of volatile fatty acids (VFA) produced by these mats. We measured fluxes of dimethylsulfide (DMS) and methanethiol (MT) under a range of conditions. These two gases are probably formed by reactions that occur between low molecular weight organic carbon compounds and biogenic hydrogen sulfide. In an early anoxic global environment, DMS and MT can escape to the atmosphere and serve as biosignatures of these microbial communities. Our microscopic, genetic, biomarker and biogeochemical observations indicated that hypersaline mats can be maintained in a greenhouse at Ames for more than a year without sustaining major changes. This greenhouse will allow astrobiologists to explore the microbiological effects of environmental conditions that were widespread on early Earth but that are rare today. We documented a high diversity of uncultivated green nonsulfur bacteria (GNS) in photosynthetic microbial mats in the hot, alkaline Mushroom Spring, Yellowstone National Park. Some GNS were observed in close association with cyanobacteria, and diverse members of the GNS group assimilated acetate.

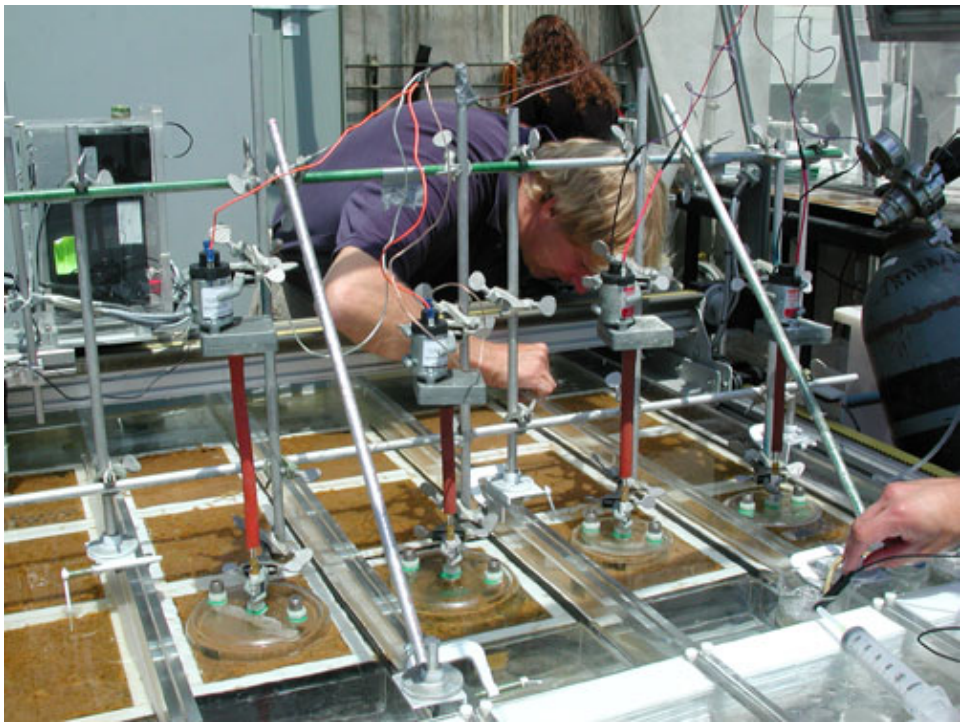


Figure 2. *Recent experiments indicate that the Ames greenhouse facility enables us to study microbial mats under environmental conditions that were important on early Earth but are either rare or absent today.*

We are extending the ecosystem−level studies of photosynthetic microbial mats to a planetary scale by creating quantitative models that simulate energy relationships, biogeochemical cycling, trace gas exchange, and biodiversity. We developed a simulation model called MBGC (Microbial BioGeoChemistry) to infer effects of major environmental controllers on microbial community structure and function. Already the model reproduces major diel fluctuations in trace gases in hypersaline subtidal mat layers and into the overlying water column. We are testing various approaches to simulating the net hourly emissions of O_2, CO_2, and H_2S gases to the atmosphere above the mat ecosystem, over the course of several days during which actual measurements of these same fluxes have been made.

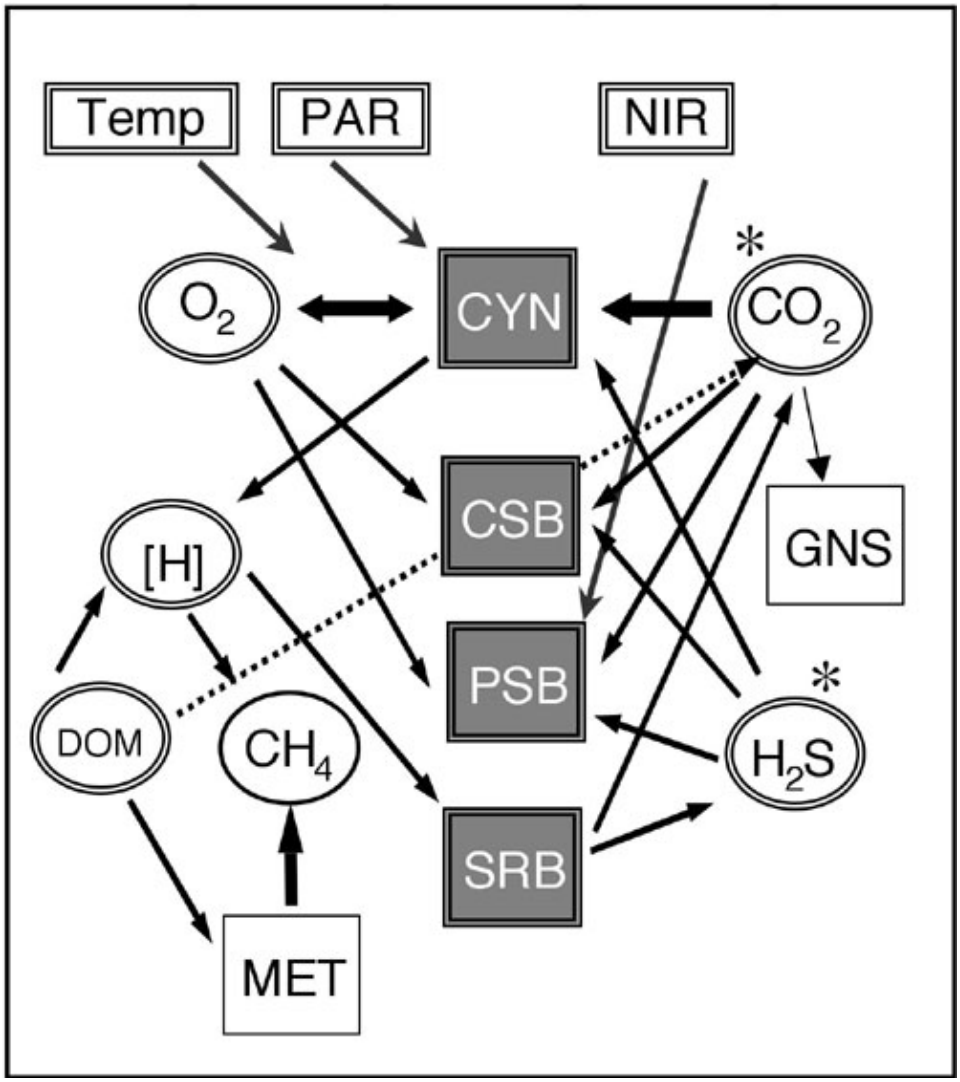
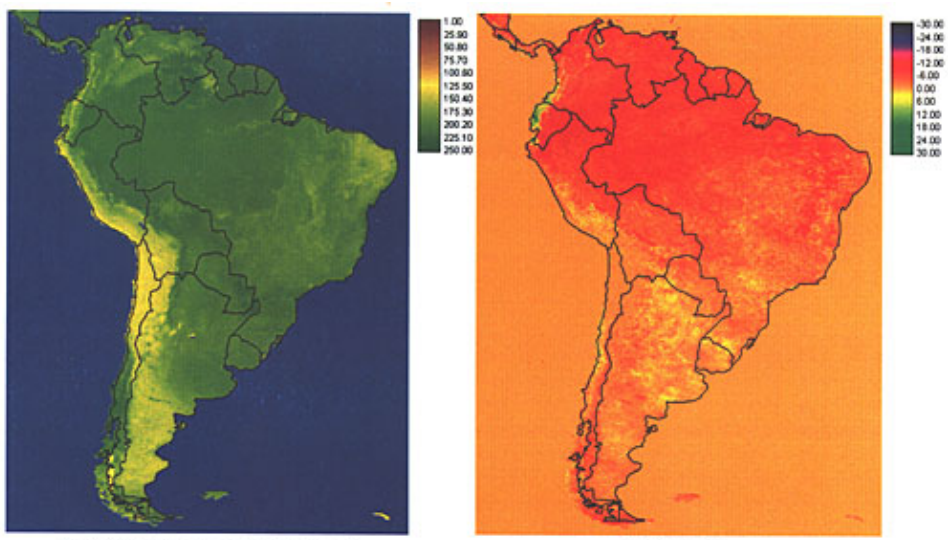


Figure 3. *Schematic representation of the MBGC model (Decker and Potter, 2002), including bacterial pools (squares), light (PAR, NIR) and temperature input as model drivers, and gas concentration pools (circles).*

We have developed, for community use, a new Global Atmospheric Integrator for Astrobiology (GAIA). It is unique in that it can consistently leap from simulations of a "typical" day of varying atmospheric chemistry to periods of geologic time. GAIA incorporates fully modern descriptions of atmospheric photolysis and UV shielding, photochemical reactions, thermal reactions, a simple water cycle, and lower and upper driving fluxes, i.e., biogeochemical interchange and hydrogen escape. GAIA performs stably as fluxes of O_2 and reduced (CH_4, H_2) gases are increased, thus allowing a full study of composition accompanying the rise of aerobic life.

We are examining the effects of climate variability on a vegetation−rich biosphere over intermediate time scales, using South American ecosystems as a model. Previously, we demonstrated that a strong correlation exists between vegetation changes at 32 South American sites and variations in sea−surface temperature (SST) over a 12−year period, related to the El Niño

Southern Oscillation (ENSO). This past year, our map of remote−sensing−based estimates of vegetation indices (advanced very−high−resolution radiometer − normalized difference vegetation index (AVHRR−NDVI)) for the subtropical growing season of South America (October through January) on monthly data from 1981 through 2000 validates earlier ground−level studies by other investigators. Our graphic model also has modified current knowledge regarding the areas affected by "El Niño" Southern Oscillation in South America. We identified areas that are affected differently by El Niño, and La Niña, as well as the "normal" conditions. We should eventually be able to link SST to tree−ring widths. Finally, our reconstructed "paleo"−SST simulation correlates well with volcanic phenomena, the Little Ice Age, and other events. The simulation also complements, often with greater detail, reconstructions made with other proxy records, such as paleomicroplankton.



Average NDVI for 1981-2000 (Oct-Jan)

El Nino Years

"Normal" Years

La Nina Years

Figure 4. *Summary description of South America's AVHRR−NDVI−deviations from normal (1981−2000) under "El Niño", and "La Niña" conditions.*

We are assessing the potential for life to move beyond its planet of origin, as a potentially important component in the evolution of life in our own solar system. We address natural transport where survivors must withstand radiation, desiccation, and time in transit. Observations both in the laboratory and in nature indicate that low levels of radiation and oxidative damage on cells can result in a mitogenic effect, meaning that responses to radiation are non−linear and cannot be predicted from simple models. Experiments conducted in the space simulation facility at the Deutsche Forschungsanstalt für Luft− und Raumfahrt (DLR) in Cologne, Germany reveal that the cyanobacterium *Lyngbya* can survive exposure to both UV radiation and desiccation. The number of organisms that might be able to survive exposure to the space environment might be far greater than originally recognized.

The strong mission relevance of our research, combined with the direct participation of several team members in the planning and execution of NASA missions, places the Ames team in a position to influence strongly the astrobiology content of ongoing and future missions. Studies of planet formation and habitability currently benefit the Space Infrared Telescope Facility (SIRTF), Kepler, Eddington and Terrestrial Planet Finder (TPF) missions. Giant planets orbiting nearby stars can be detected using current technology, and the masses and orbits of these objects can be calculated. By combining these observations with simulations by our group, it will be possible to determine promising candidate stars for future missions and observing programs designed to detect Earth analogues, such as Kepler and TPF. We address the effects of methane on the Martian climate evolution. Our work concerning CO2 clouds and the effects of impacts is relevant for interpreting data from Mars Odyssey and future Mars missions, such as the 2009 Mars Science Laboratory rover. Our team's studies of cosmic ices and organics are synergistic with the Stratospheric Observatory for Infrared Astronomy (SOFIA), SIRTF and Stardust missions. The work with microbial ecosystems strengthens the systematics for interpreting the microbial fossil record and thereby enhances astrobiological studies of Martian samples. A team member serves as interdisciplinary scientist for astrobiology on the 2003 Mars Exploration Rover (MER) Mission. Models of biogenic gas emissions will enhance models of atmospheres that might be detected on inhabited extrasolar planets. One of us is first author on a major white paper that addresses the feasibility of searching for biosignatures during the proposed TPF mission. This white paper was just published in the peer−reviewed literature.

We have served the needs and interests of the nation's educators, students and public through a high−impact education and public outreach program. Specifically, we partner with the California Academy of Sciences (CAS), Yellowstone National Park (YNP), and the New York Hall of Science to develop new astrobiology workshops, activities, exhibits, and other products for the public. CAS has chosen to utilize astrobiology to link its natural history museum, planetarium, and aquarium under the theme, "Earth and its Place in the Universe." Ames personnel serve directly on the CAS design and exhibit

development teams. Ames and CAS also facilitate interactions between researchers and educators in order to develop inquiry−based programs and activities for K−14 students. Our partnership with YNP combines a large annual visitation with a highly effective venue for conveying astrobiology−related content. With material input from the Ames team, YNP is introducing astrobiology content into trailside interpretive signs, brochures, and the Yellowstone Resources and Issues Guide. Ultimately, astrobiology will be integrated into permanent exhibits for the major visitor centers.

Figure 5. *The Trailside Sign Project represents the E/PO collaboration between the NAI Ames Team and Yellowstone staff, to allow park visitors to learn about Astrobiology by experiencing Yellowstone?s natural features.*

We have extended this impact to the professional level by engaging graduate students and postdoctoral associates in the proposed research activities, through the teaching of undergraduate courses in astrobiology at Stanford University and at local community colleges.

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Project Report: Biogeochemistry of Earth's Greenhouse Leading to the Rise of Oxygen

Lead Team:	***Ames Research Center***
Project Title:	***Biogeochemistry of Earth's Greenhouse Leading to the Rise of Oxygen***
Project Investigator:	***Robert Chatfield***

Project Progress

The second complete year of this module work has accomplished the technical objective: production of a respectable modern atmospheric chemistry model, which has been incarnated as GAIA, Global Atmospheric Integrator for Astrobiology. GAIA is capable of extending full diel variability of emissions and photochemical concentrations to estimate the composition of a planetary atmosphere on a geologic timescale. GAIA incorporates fully modern descriptions of atmospheric photolysis and ultraviolet (UV) shielding, photochemical reactions, thermal reactions, a simple water cycle, and lower and upper driving fluxes, i.e., biogeochemical interchange and hydrogen escape. It is driven by data tables where possible, making it easy to accomplish parameter studies and to share with other research groups. GAIA performs stably as fluxes of O_2 and reduced (CH_4, H_2) gases are increased, thus allowing a full study of composition accompanying the rise of aerobic life. Interactions with the radiative consequences of composition must be iterated offline, at this point. Previously, there was a "forbidden zone" of parameters using prior models where convergence was not possible, and separate "low−productivity" and "nearly modern" regimes were required. The difficulties of the "forbidden zone" are of course promising that there might be purely chemical instabilities in Earth's oxic transition. We have found none, yet. Simulations of atmospheric concentrations of greenhouse gases can be achieved for a larger spectrum of plausible O_2 and reduced−gas emissions fluxes. The significance of this technology is that we may simulate conditions for the full rise of O_2 in the Earth's atmosphere, including periods associated with "Snowball Earth" and other interesting episodes. The model has been adopted by University of Washington for use by Dr. David Catling's group. Mr. Mark Claire, a member of Dr. Catling's group, has received a Graduate Student Research Program grant that will enable him to apply the simulation technique.

Highlights

- GAIA, a new Global Atmospheric Integrator for Astrobiology, has been

produced for community use. It is unique in that it can consistently leap from simulations of a "typical" day of varying atmospheric chemistry to periods of geologic time.

- GAIA incorporates fully modern descriptions of atmospheric photolysis and UV shielding, photochemical reactions, thermal reactions, a simple water cycle, and lower and upper driving fluxes, i.e., biogeochemical interchange and hydrogen escape. It is driven by data tables where possible, making it easy to accomplish parameter studies and to share with other groups.

- GAIA performs stably as fluxes of dioxygen and reduced (CH_4, H_2) gases are increased, thus allowing a full study of composition accompanying the rise of life. Interactions with the radiative consequences of composition must be iterated offline, at this point.

- University of Washington investigators have been awarded a Graduate Student Research fellowship to employ GAIA to study compositional change accompanying significant biogeochemical changes such as the oxic transition and the possibility of climatic cycling.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

This project has interacted principally with David Catling, University of Washington. A graduate student in Dr. Catling's group has received a NASA Graduate Student Research Fellowship to work with the GAIA model.

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Project Report: Chemical Building Blocks

Lead Team:	***Ames Research Center***
Project Title:	***Chemical Building Blocks***
Project Investigator:	***Louis Allamandola***

Project Progress

We have made progress in tracing the link between ice processes and the organic molecules in meteorites. First, we have demonstrated that the ultraviolet (UV) photolysis of presolar ices can produce the amino acids alanine, serine, and glycine, as well as hydroxy acids and glycerol, all of which have been extracted from the Murchison meteorite (*Nature* (2002) 416, 401−403). Thus, some of the probiologically interesting organic compounds found in meteorites may have formed in presolar ice and have not solely been a product of parent body liquid water chemistry. Second, we have shown that energetic processing of polycyclic aromatic hydrocarbons (PAHs) with ices containing simple insterstellar molecules like NH_3, HCN, CH_4, CH_3OH, and CO_2 results in the addition of amino, cyano, methyl, methoxy, and carboxylic acid groups: *Astrophys. J.* (2002) 576, 1115−1120, and *Astrophys. J.*, (2003) 582, L25−L29. This is a plausible explanation for the functional groups on aromatics in meteorites and is consistent with patterns of deuterium enrichment, suggesting low temperature chemistry. Third, we have continued to explore the connection between ice photochemistry and meteoritic amphiphiles, and the role that they may have played in the origin of life: *Astrobiology* (2003) 2, 371−381. In a related project we have examined the Luminescence of these same product mixtures that contain the amphiphiles: *Astrophys. J.*, (2003) 583, 514−523.

Highlights

- Some of the meteoritic amino acids, glycine, alanine and serine, as well as structurally related hydroxy acids, may have been synthesized in ice before Solar System formation.

- The amino (NH_2), carboxylic acid (COOH), cyano (CN), ether ($O-CH_3$), hydroxy (OH), keto (>C=O), and methyl (CH_3) groups that decorate the aromatics in meteorites and IDPs can be formed by energetic processing of low temperature ices. This pathway is consistent with observed deuterium enrichments and is the first proposed mechanism that makes predictions on a molecular level.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	SOFIA	Planning support, data analysis, background research, instrument/payload development, research
1	SIRTF	Planning support, data analysis, background research, instrument/payload development, research
1	Stardust	Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research
2	ABE	PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research
2	CSSR −Comet Surface Sample Return	Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission

Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These are all NASA Missions.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Early Metabolic Pathways

Lead Team:	***Ames Research Center***
Project Title:	***Early Metabolic Pathways***
Project Investigator:	***Andrew Pohorille***

Project Progress

As previously reported, we have used messenger ribonucleic acid (mRNA)−display to select four new adenosine triphosphate (ATP)−binding proteins from a population of $>10^{12}$ random polypeptides. Proteins from one family have been characterized − they are highly selective, and do not bind either guanosine triphosphate (GTP) or deoxyadenosine triphosphate (dATP). They do not contain any known ATP−binding motifs, but require zinc ions and contain conserved cysteine residues, suggesting a possible structural similarity to zinc finger proteins. In order to test this possibility, and more generally to determine if these *de novo* evolved proteins resemble biological protein, we have evolved mutants that are suitable for biophysical studies by continued selection for ATP binding in the presence of guanidine. Guanidine is a denaturant of protein structure and its presence in solution favors selection of proteins with stable folded states. As expected, more of the newly selected proteins stay soluble in the presence of ATP, presumably because ATP binding stabilizes the folded state of the protein. We have established that some proteins remain stable as monomers. We have optimized a rapid, efficient purification scheme that allows for generating a sufficient amount of proteins for biophysical characterization.

We also initiated efforts to use in vitro selection to evolve novel enzymes. Our initial efforts have concentrated on enzymes that catalyze Diels−Alder reactions. The initial library of random−sequence proteins has been created and selection is in progress.

To simulate self−organization of protobiological proteins into metabolic networks capable of evolution towards increasing complexity, we develop a computational approach for describing systems with many species and reaction channels. This approach is based on Next Reaction Method, an exact and efficient approach to simulating coupled chemical reactions. The method is not limited to chemical reactions and allows for incorporation of other cellular processes such as channel−mediated transport and cell growth and division.

Highlights

- We have used directed evolution to obtain mutants of a novel ATP−binding protein that have improved solubility in water and stability of the folded state, and are suitable for biophysical studies.

- We developed a new computational approach to model evolution of metabolic networks of protobiological proteins. The method allows for describing many species, reaction channels and other cellular processes, such as cell growth and division.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Early Microbial Ecosystems

Lead Team:	***Ames Research Center***
Project Title:	***Early Microbial Ecosystems***
Project Investigator:	***David Des Marais***

Project Progress

We investigate photosynthetic microbial mat ecosystems and their fossils. These mats allow us to examine microbiota and ecological processes that participated in early evolution, modified the early environment, and created biosignatures. Photosynthetically active cyanobacterial mats were studied in a hypersaline pond near Guerrero Negro, Mexico. These mats produced substantial quantities of volatile fatty acids (VFA), most of which derived specifically from fermentative processes. We investigated the mechanisms and conditions that favor the production of dimethylsulfide (DMS) and methanethiol (MT). DMS and MT are probably formed principally by reactions between low molecular weight organic carbon compounds and biogenic hydrogen sulfide in mat porewaters. DMS and MT can escape to the atmosphere and become biosignatures for these microbial communities. We compared H_2 concentrations in anoxic open marine shelf sediments with those in hypersaline phototrophic cyanobacterial mats. In contrast with the anoxic shelf sediments, the phototrophic mats sustain high H_2 levels that facilitate methanogenesis even in the presence of elevated sulfate concentrations. We demonstrated that hypersaline mats can be maintained in a greenhouse for more than a year without sustaining major changes, as indicated by microscopic, genetic, biomarker and biogeochemical process observations. Because sulfate levels were low in ancient seas, we recently conducted a greenhouse experiment for more than one year to document the effects of submillimolar sulfate levels upon hypersaline cyanobacterial mats. We investigated the diversity, distribution and phenotypes of uncultivated green nonsulfur bacteria (GNS) in photosynthetic microbial mats in the hot, alkaline Mushroom Spring, Yellowstone National Park. We found a large diversity of GNS. Some GNS occurred in close association with cyanobacteria. Diverse GNS assimilated acetate. We determined carbon isotope discrimination during both heterotrophic and lithotrophic growth of pure cultures of sulfate reducing bacteria (SRB). SRB grown lithoautotrophically exhibited substantially larger discrimination, relative to their carbon sources, than SRB grown heterotrophically.

Highlights

- We documented a high diversity of uncultivated green nonsulfur bacteria (GNS) in photosynthetic microbial mats in the hot, alkaline Mushroom Spring, Yellowstone National Park. Some GNS were observed in close association with cyanobacteria, and diverse members of the GNS group assimilated acetate.

- Mechanisms for the production of dimethylsulfide (DMS) and methanethiol (MT) were determined in moderately hypersaline mats, Guerrero Negro, Mexico, and are probably formed by reactions between low molecular weight organic carbon compounds and biogenic hydrogen sulfide. DMS and MT can escape to the atmosphere and, in an early anoxic global environment, can serve as biosignatures of these microbial communities.

- We demonstrated that hypersaline mats can be maintained in a greenhouse for more than a year without sustaining major changes, as indicated by microscopic, genetic, biomarker and biogeochemical process observations. This greenhouse capability will allow us to explore the microbiological consequences of environmental conditions that were widespread on early Earth but are no longer prevalent today.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	MER 2003	P. I. Des Marais serves on the Science Operations Working Group as a chair of the Long Term Planning Science Theme Group
1	MRO 2005 CRISM spectrometer	P. I. Des Marais serves as Interdisciplinary Scientist for Astrobiology on the CRISM team.
2	MSL 2009	P. I. Des Marais was an active member of the Mars Science Laboratory Payload Science Integration Group 1 and 2 (PSIG1

		PSIG2)
3	Astrobiology and Solar System Exploration	P. I. Des Marais is a member of the writing team for a HQ−mandated white paper on this topic

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These studies will strengthen the systematics for interpreting the microbial fossil record and thereby enhance astrobiological studies of Martian samples. Models of biogenic gas emissions will enhance models of atmospheres that might be detected on inhabited extrasolar planets. This work addresses the question: How can other biospheres be recognized? The Co−PI, Des Marais, has been extensively involved in mission planning and preparation. Accordingly, he establishes linkages between this research and NASA programs and missions. He is a member of Mars Exploration Payload Advisory Group. He represents astrobiology as a member of the Payload Science Integration Team for the 2009 Mars Science Laboratory mission. Des Marais is an interdisciplinary scientist for astrobiology on the Mars Exploration Rover (MER) Mission, launched in 2003. As a member of the Science Operations Working Group, Des Marais will participate in the strategic planning and operation of the twin MER rovers.

Field Expeditions

Field Trip Name: Early microbial ecosystems field trip to Baja California, Mexico	
Start Date: Sept. 5, 2002	***End Date:*** Sept. 18, 2002
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude: 27 degrees 40 minutes	***Longitude:*** 113 degrees 55 minutes
Name of site(cave, mine, e.g.): Exportadora de Sal, S. A. salt	***Keywords:*** microbial ecology, microbial mats, biosignature gases,

works	ecogenomics, cyanobacteria
Description of Work: Microbial ecological studies of the populations, processes and products of marine hypersaline microbial mats.	
Members Involved: Brad Bebout	

Field Trip Name: Early microbial ecosystems field trip to Baja California, Mexico	
Start Date: May 25, 2003	***End Date:*** May 30, 2003
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude: 27 degrees 40 minutes	***Longitude:*** 113 degrees 55 minutes
Name of site(cave, mine, e.g.): Exportadora de Sal, S. A. salt works	***Keywords:*** microbial ecology, microbial mats, biosignature gases, ecogenomics, cyanobacteria
Description of Work: Microbial ecological studies of the populations, processes and products of marine hypersaline microbial mats.	
Members Involved: Brad Bebout	

Cross Team Collaborations

- Arizona State University team: Field trip to Guerrero Negro, Baja California Sur, Mexico, October 2002 and May 2003. This study carries implications for our understanding of early evolution of microorganisms and animals, and for the interpretation of the factors that control the diversity of cyanobacteria.
- MBL team: The Ecogenomics focus group addresses the structure and function of microbial communities from the three perspectives of biogeochemistry, gene expression and population dynamics at the ecosystem level.
- University of Colorado team: Novel methods have been developed by the Pace Group for investigating sequences of deoxyribonucleic acid (DNA) molecules that are extracted from natural microbial populations. These new data are creating a broad, new perspective of the diversity of microbial life. Samples of photosynthetic subtidal microbial mats are collected to determine the richness of microbial species present. Numerous previously unidentified microorganisms have already been revealed.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Ecosystem to Biosphere Modeling

Lead Team:	***Ames Research Center***
Project Title:	***Ecosystem to Biosphere Modeling***
Project Investigator:	***Christopher Potter***

Project Progress

We have developed a simulation model called MBGC (Microbial BioGeoChemistry) to infer effects of major environmental controllers on microbial community structure and function (Decker and Potter, 2002). Microbial growth, metabolic reaction rates, and mass flows are represented within and between vertical sediment layers of a microbial mat in the hypersaline environment (Figure 1). In addition, diel cycles are simulated to capture natural variation in environmental boundary conditions, such as light and temperature. The fundamental structure of our MBGC simulation model follows that of a previous model (de Wit et al., 1995) of population dynamics and biogeochemistry within benthic mats containing cyanobacteria (CYN), purple sulfur bacteria (PSB) and colorless sulfur bacteria (CSB). Specific additions were incorporated recently into our MBGC model in order to (1) represent CYN photosynthesis metabolism operating as a light−driven quantum efficiency function, (2) complete the microbial sulfur cycle, and (3) enable a comparison of the model predictions to hourly field−measured biogeochemical fluxes. More specifically, we have added sulfate−reducing bacteria (SRB) to MBGC, which can consume organic carbon and produce the H_2S oxidized by PSB and CSB. In addition, molecular hydrogen (H_2), decomposition of dead organic matter (DOM), CO_2 fluxes, and realistic (time−varying) temperature and light controls on major metabolic pathways are included in MBGC as extensions of the original de Wit model structure.

Decker K.L.M. and C. Potter, 2002. Mathematical model of a marine microbial mat ecosystem. Abstracts of the Second Annual Astrobiology Conference. Moffett Field, CA.

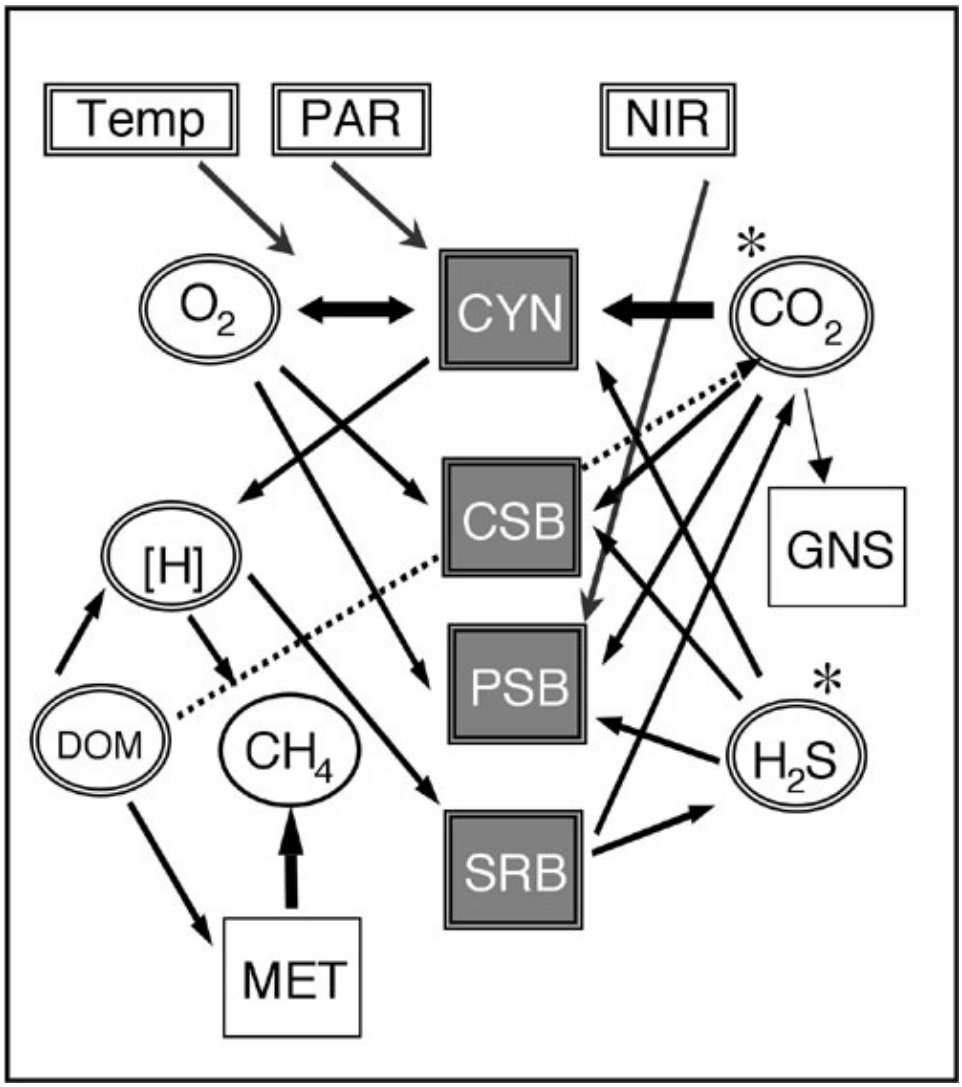


Figure 1. *Schematic representation of the MBGC model (Decker and Potter, 2002), including bacterial pools (squares), light (PAR, NIR) and temperature input as model drivers, and gas concentration pools (circles).*

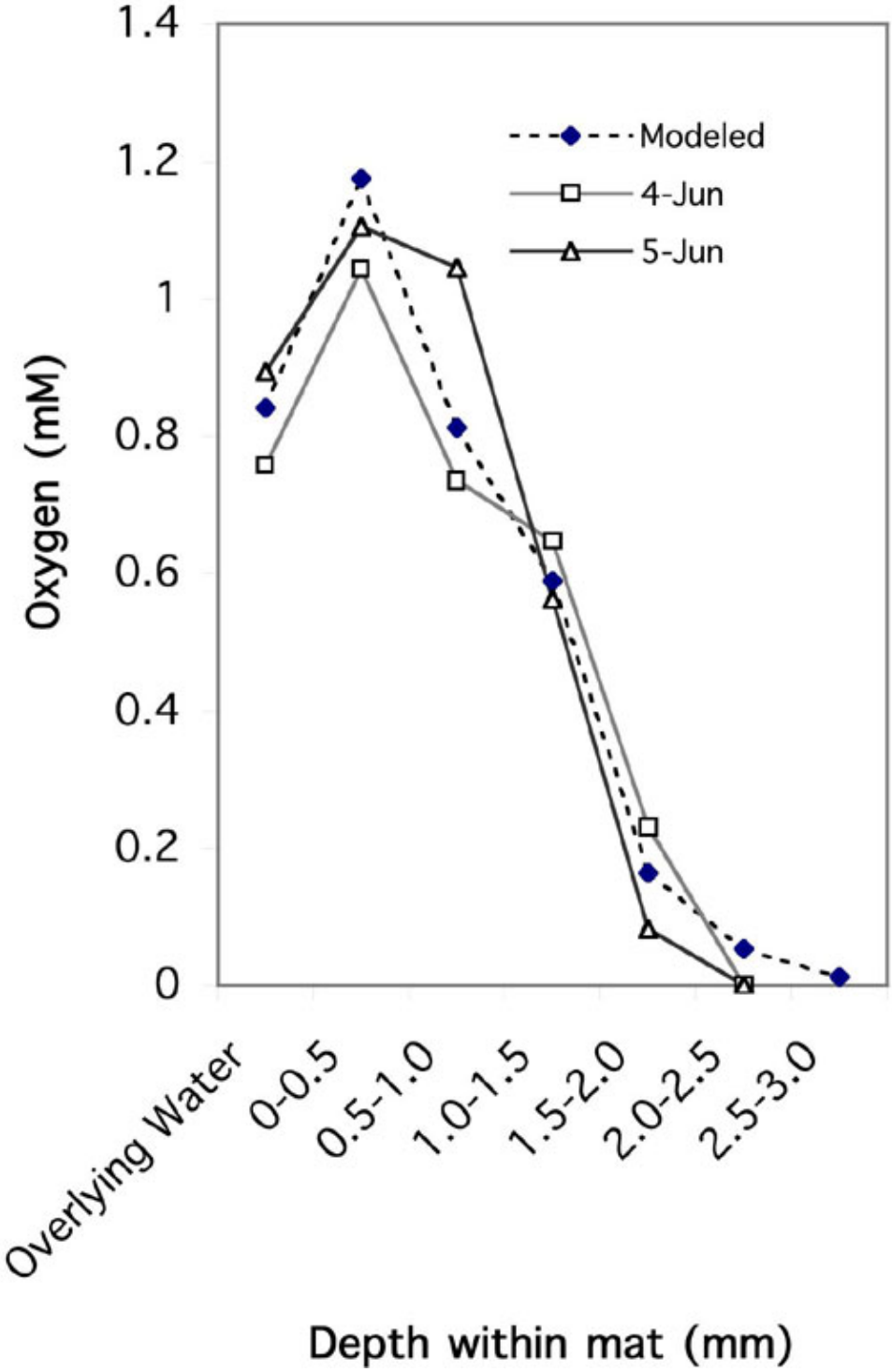


Figure 2. *Oxygen concentration within the top layers of a cyanobacterial mat at mid−day for two dates in June 2001 in salt ponds near Guerrero Negro, Baja (Source: S. R. Miller), compared to results of a MBGC simulation using light and temperature values measured during the same period of the field measurements.*

Highlights

- Early results from MBGC simulations show that the model reproduces major diel fluctuations in trace gases in hypersaline subtidal mat layers and into the overlying water column (Figure 2).

- To extend our knowledge further of the principal controls over the light/energy relations and biochemical pathways by which these mat ecosystems consume and emit trace gas biosignatures, we are testing various approaches to simulating the net hourly emissions of O_2, CO_2, and H_2S gases to the atmosphere above the mat ecosystem over the course of several days during which actual measurements of these same fluxes have been made.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Guerrero Negro, Baja	
Start Date: September 10, 2002	***End Date:*** September 17, 2002
Continent: North America	***Country:*** Mexico
State/Province: Baja California	***Nearest City/Town:***
Latitude: 27° 40'	***Longitude:*** 113° 55'
Name of site(cave, mine, e.g.): Guerrero Negro Salt Ponds	***Keywords:*** microbial mat, cyanobacteria, spectra
Description of Work: We collected near−simultaneous in situ spectral data and satellite images of radiation absorption and reflectance of subtidal microbial mat communities. After correction for the absorption of incident solar radiation by the overlying water column and the atmosphere, we can attempt to isolate the absorption spectrum of the mat community to infer spatial variability of PAR and NIR attenuation by the various bacteria groups. Spectral results from absorption and reflectance studies of subtidal microbial mat communities. The water column was found to absorb 60−75% of incident PAR energy and more than 95% of incident NIR energy entering at the pond surface. The subtidal mat absorbs 85−95% of the residual PAR and NIR energy that is transmitted through the water column from the pond surface.	
Members Involved: Steven Klooster	

Project Report: Habitable Planets

Lead Team:	***Ames Research Center***
Project Title:	***Habitable Planets***
Project Investigator:	***Richard Young***

Project Progress

Recent simulations of planetary accretion by J. Chambers and collaborators have shown that the amount of mass accreted by Earth from the asteroid region depends sensitively on the formation time and the early orbital evolution of the giant planets. In particular, the mass of volatile materials delivered to Earth depends sensitively on the giant planets' orbital eccentricities, since these control the width and strength of the unstable resonances in the asteroid region. Most of the planets recently discovered in orbit around other Sun−like stars have orbits that are substantially more eccentric than those of Jupiter and Saturn. Therefore, even if these stars developed protoplanetary disks with similar masses and thermal histories to the Sun's nebula, and even if terrestrial planets formed in these disks, the volatile inventories of these planets will differ widely depending on the characteristics of the giant planets in these systems.

J. Kasting and graduate student H. Justh have completed a study of the effects of methane on early Mars' climate. It is found that methane mixing ratios of 10^{-3} (0.1% by volume) could have raised the surface temperature of early, 3.5−Ga Mars by 30 K (from 220 K to ~250 K). This is not by itself enough to explain the existence of fluvial features on Mars' surface, but it could have been a contributing factor. Greenhouse warming by CO_2 ice clouds could have provided the additional warming needed to bring global surface temperatures up to near the freezing point of water. Surprisingly, CH_4 mixing ratios higher than 10^{-3} would have cooled the surface, rather than warming it. This is because CH_4 absorbs visible and near−infrared (IR) radiation from the sun; thus, high CH_4 concentrations lead to stratospheric warming and an anti−greenhouse effect. A CH_4 mixing ratio of 10^{-3} could probably not have been sustained abiotically. Thus, life must have been present on the Martian surface if this explanation for surface warming is correct.

During the previous year the group led by Brian Toon and Margaret Tolbert at the University of Colorado has made progress in a number of areas. Through a combination of laboratory studies and numerical modeling, they were able to show that carbon dioxide clouds are unlikely to have provided a significant greenhouse warming in the early history of Mars. Therefore, the greenhouse

model to explain the ancient river valleys on mars is seriously flawed. They were also able to use the lab data and a model to explain observed clouds on current day Mars. Building on this work they also suggested that the Martian rivers were not formed under a more equitable climate, but rather are the results of impacts early in Mars' history. This finding means that there may never have been an extended period with warm temperatures and flowing water on Mars. Instead there may have been high temperature bursts followed by decades or centuries of rainfall interspersed with millions of years of cold temperatures such as those currently found on Mars. This is a far different environment than envisioned previously for early Mars and one that is not conducive to the origin of life at the surface.

Further work in progress has shown what types of particles may have formed in the early terrestrial atmosphere {Trainer, MG et al., Astrobiology yearly meeting 2003, and 2002 A. G. U. meeting.}. The group at UC is presently writing a paper on the detailed chemistry of these particles, which is quite interesting from the point of view of sustaining atmospheres with large amounts of methane in them.

Highlights

- Simulations of planetary accretion by John Chambers and colleagues have shown that the amount of mass accreted by Earth from the asteroid region depends sensitively on the formation time and the early orbital evolution of the giant planets. In particular, the mass of volatile materials delivered to Earth depends sensitively on the giant planets' orbital eccentricities, since these control the width and strength of the unstable resonances in the asteroid region.

- It has been shown (Kasting and Justh) that methane could have provided a maximum of 30 degrees of surface warming to early Mars. Higher methane concentrations would have resulted in an anti−greenhouse effect that would have caused surface cooling.

- The group led by Toon and Tolbert has produced a novel explanation for the Martian rivers, which they originated as the result of impacts. This view greatly modifies the environment that life may have originated in on Mars, and suggests the only likely place is in the subsurface.

- The same group has for the first time created particles that may form in methane rich atmospheres also containing carbon dioxide, which may resemble that of early Earth.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
1	Kepler	Kepler Co−I (J. Lissauer)
1	Mars Odyssey	Background research
2	Mars Lander 2009	Background research
2	Terrestrial Planet Finder	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Giant planets orbiting nearby stars can be detected using current technology, and the masses and orbits of these objects can be calculated. By combining these observations with simulations like the ones our group (Chambers and Lissauer) are doing, it will be possible to determine promising candidate stars for future missions and observing programmes designed to detect Earth analogues, such as Kepler and the Terrestrial Planet Finder (TPF).

The Mars climate work addressing the climate effects of methane on the Martian climate evolution, the work concerning carbon dioxide clouds, and the effects of impacts, described previously, is relevant for interpreting data from Mars Odyssey and future Mars missions, such as the 2009 Lander.

Cross Team Collaborations

We collaborated with J. Kasting, Pennsylvania State University, on studies of methane in the Martian atmosphere.

We collaborated with B. Toon and M. Tolbert, Univ. of Colorado, and with A. Colaprete, Ames, on studies of carbon dioxide ice clouds on Mars.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Life Beyond the Planet of Origin

Lead Team:	***Ames Research Center***
Project Title:	***Life Beyond the Planet of Origin***
Project Investigator:	***Lynn Rothschild***

Project Progress

During this funding period work was continued primarily by Rothschild, Mancinelli and Horneck.

Rothschild developed techniques for measuring deoxyribonucleic acid (DNA) damage both in nature and in the lab. Protocols for measuring the ratio of 8−hydroxyguanosine to guanosine were established; the protocol involved isolation of DNA, digestion and analysis with EC−HPLC, with the high−performance liquid chormotography (HPLC) work conducted in the EPA−certified chemistry lab at NASA Ames. Her group also worked on studying the effect of low levels of radiation and oxidative damage on cells and showed both in the lab and in nature that this can result in a mitogenic effect, meaning that responses to radiation are non−linear and cannot be predicted from simple models. This work will help in the understanding of the ability of organisms to survive in the space environment.

Mancinelli pepared a sample of Lyngbya, as well as more strains of halophiles in the lab at Ames in preparation of simulatin tests at the Deutsche Forschungsanstalt für Luft− und Raumsfahrt (DLR) in Cologne, Germany. Using the space simulation facility at the DLR in Cologne, in Germany, he along with Rettberg and Horneck have completed a series of ground simulation experiments using Lyngbya aestuarii as well as a number of Archaeael halophiles. Using these facilities, they have exposed this organism to vacuum desiccation and ultraviolet (UV) radiation. These experiments reveal that the Lyngbya can survive exposure to both UV radiation and desiccation. We are currently developing methods to quantify their survival. In addition, we have run several organisms through the experiment verification test (EVT) for the Expose facility on the Space Station in prepartion for the ROSE series of experiments.

Highlights

- The number of organisms that may be able to survive exposure to the space environment may be more than we originally thought.

Roadmap Objectives

- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	EXPOSE (ESA ISS mission)	Co−I (Mancinelli) Co−I (Horneck)

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The research outlined in the proposal has been selected by the European Space Agency (ESA) based on my proposal in response to the ESA Announcement of Opportunity for Externally Mounted Payloads during the Early Space Utilization Period. (SP−1201). The hypotheses will be tested using ESA?s external platform space exposure facility (EXPOSE). The cost of all flight related activities, the design and fabrication of flight hardware, as well as equipment and supplies to conduct ground simulation studies conducted in Europe are paid by ESA, work conducted in the US, travel, and time (salary) spent on the project in the US and Europe are to be paid by NASA. That is, the funds are for ground based research in support of the ESA funded flight experiments.

EXPOSE is a multi−user external facility for exobiological experiments in the environment of space. It has been selected by ESA for the Early Utilization Period of the International Space Station (ISS) and will stay for 1.5 years in space.

Field Expeditions

Field Trip Name: Yellowstone National Park	
Start Date: June 2002	***End Date:*** September 2002

Continent: North America	***Country:*** United States
State/Province: WY/MT	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** algae, microbial mats, DNA
Description of Work: Measured oxidative damage in natural samples during several times of year	
Members Involved: Lynn Rothschild	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Rapid Rates of Change

Lead Team:	***Ames Research Center***
Project Title:	***Rapid Rates of Change***
Project Investigator:	***Hector D' Antoni***

Project Progress

1. A map of advanced very−high−resolution radiometer −− normalized difference vegetation index (AVHRR−NDVI) was produced for the subtropical and higher latitude growing season of South America (Oct−Jan, when El Niño Southern Oscillation (ENSO) effects are more intense) on monthly data from 1981 through 2000. This is the time when ENSO effects are strongest. Also, the map validates earlier ground−level studies by Hueck and Seibert (1982).

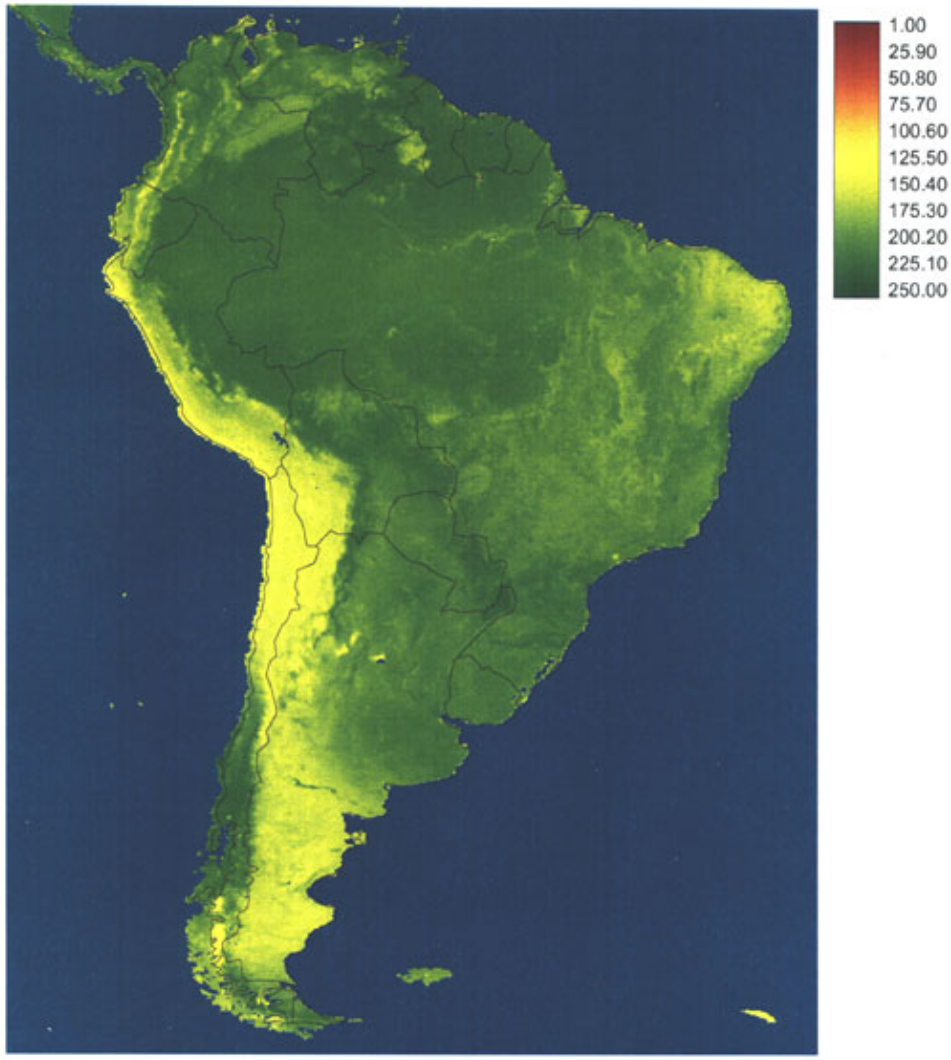


Figure 1. *AVHRR−NDVI map of South America. Monthly data (Oct−Jan, the austral growing season and the time when ENSO effects are stronger) were added for each year between 1981 and 2000, and averaged. This map validates ground−level studies by Hueck and Seibert (1982).*

2. Analysis of the South American AVHRR−NDVI database was completed and a summary description of the continent's NDVI−deviations from normal (i.e. 1981−2000) under "El Niño", "La Niña" and "Normal" conditions was produced.

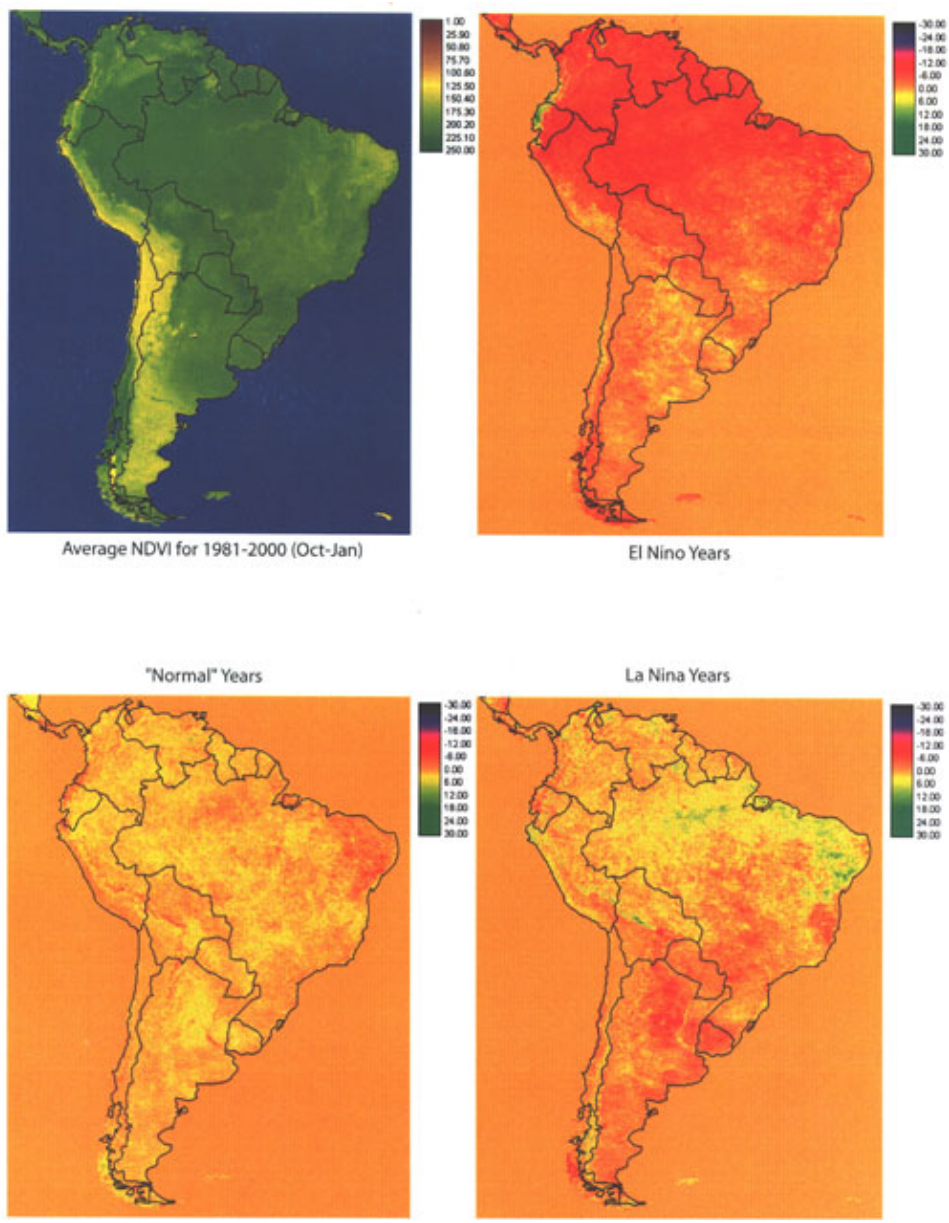


Figure 2. *Summary description of South America's AVHRR−NDVI−deviations from normal (1981−2000) under "El Niño", and "La Niña" conditions.*

3. In collaboration with the Drylands Institute in Tucson, we applied this method to the area including most of Texas, New Mexico, Arizona and Southern California, and the Mexican states of Tamaulipas, Nuevo Leon, Coahuila, Zacatcas, Chiuaua, Durango, Sonora, Sinaloa, Nayarit, Baja California Norte and Sur.

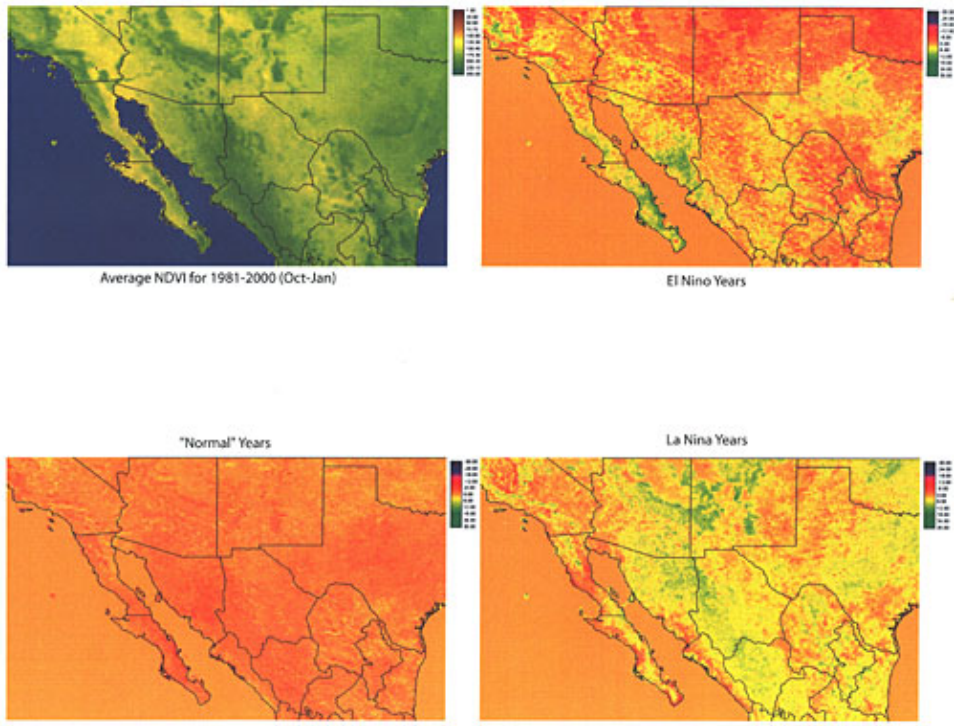


Figure 3. *Parts of Texas, New Mexico, Arizona and Southern California, and the Mexican states of Tamaulipas, Nuevo Leon, Coahuila, Zacatecas, Chiuaua, Durango, Sonora, Sinaloa, Nayarit, Baja California Norte and Sur, in "El Niño", "La Niña" and "Normal" conditions. Average map (1981−2000).*

4. Studying the forcing of South American climate we simulated the "Paleo" Sea Surface Temperature for the West Coast of the Americas ("Ship Track 1") and the Tropical Atlantic Ocean for the period 1246−1995 based on tree−ring widths.

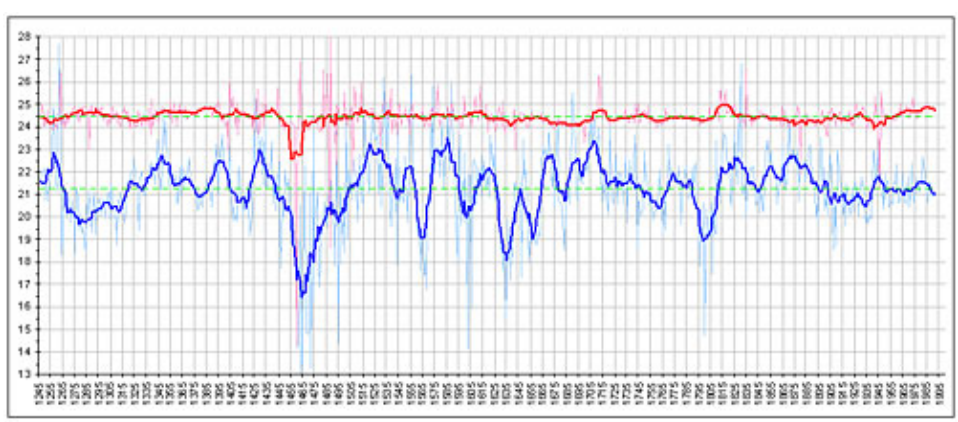


Figure 4. *Simulated "Paleo" Sea Surface Temperature for the West Coast of the Americas ("Ship Track 1") and the Tropical Atlantic Ocean for the period 1246−1995 based on tree−ring widths.*

5. In collaboration with the Ethnography Museum of Buenos Aires and the Anthropology Museum of Cordoba, we initiated research on the relationships of human society and the environment in the last 10,000 years using as testbed an area of highly diversified landscape and a consistent cultural feature of a prehistoric human society.
6. In collaboration with ESPOL (Guayaquil, Ecuador), several archeological "albarradas" were dated by radiocarbon, demonstrating that people in the Inca Empire understood and used ENSO events to improve agriculture.

A-number	Sample	Conventional Date, yrs BP	$\delta^{13}C$, ‰
11600	PACE-045-160401	1895 +100/-95	-26.9
11601	PACE-046-160401	2270 ± 120	-26.4
11602	PACE-053-180401	Not dated	
11603	PACE-63-200401	1670 ± 70	-27.2
11604	PACE-66-220401	Not dated	
11605	PACE-68-230401	Submitted to AMS Lab.	-22.0
11606	PACE-012-280309	Submitted to AMS Lab.	-25.2
11607	PACE-018-280301	Submitted to AMS Lab.	-25.7
11608	PACE-19-290301	Submitted to AMS Lab.	-27.9
11609	PACE-020-290301	< 275, Apparent age 95 (98.8 ± 1.1 pMC)	-25.4
11610	PACE-026-030401	960 ± 70	-26.0
11611	PACE-028-030401	965 ± 130	-25.1
11612	PACE-031-060401	Submitted to AMS Lab.	-13.3
11613	PACE-032-070401	1035 +100/-95	-26.0
11614	PACE-032-080401	1065 ± 105	-24.6
11615	PACE-033-070401	880 ± 100	-25.7
11616	PACE-033'-080401	870 ± 80	-25.7
11617	PACE-036-070401	Not dated	
11618	PACE-037'-090401	Submitted to AMS Lab.	-10.7
11619	PACE-037-080401	Not dated	
11620	PACE-038-090401	Not dated	
11621	PACE-039-100401	795 +135/-130	-25.4
11622	PACE-054-180401	2115 ± 150	-25.2
11623	PACE-062-200401	1965 +50/-45	-25.6

The dates are corrected for $\delta^{13}C$.

Figure 5. *Radiocarbon dates of materials from "albarradas" (crescent−shaped small dams used to avoid runoff and replenish the groundwater table in the coastal arid forest of Ecuador). Dates show that people in Ecuador used ENSO events to improve agriculture before the Christian era and continued to do so through the Inca*

Empire, the colonial time, and the time of independence.

Austin Long
Professor Emeritus
520-621-8888 (office)
520-621-2672 (fax)
along@geo.arizona.edu (e-mail)

THE UNIVERSITY OF
ARIZONA
TUCSON ARIZONA

Radiocarbon Laboratory
Department of Geosciences
Gould-Simpson Building
Tucson AZ 85721-0077
USA

November 5, 2001

Dr. Hector D'Antoni
NASA Ames Research Center, MS 239-20
Moffett Field CA 94035-1000

Dear Dr. ~~D'Antoni~~: Hector

Here are the results for the AMS samples you submitted in June.

A-number	Sample	AMS Date, yrs BP	$\delta^{13}C$, ‰
11605 AA43761	PACE-68-230401	17,550 ± 120	-22.0
11606 AA43762	PACE-012-280301	(104.8 ± 0.5 pMC)	-25.2
11607 AA43763	PACE-018-280301	(110.3 ± 0.6 pMC)	-25.7
11608 AA43764	PACE-19-290301	(106 ± 0.6 pMC)	-27.9
11612 AA43765	PACE-031-060401	2230 ± 220	-13.3
11618 AA43766	PACE-037'-090401	1060 ± 55	-10.7

The dates are corrected for $\delta^{13}C$. Best wishes with your research!

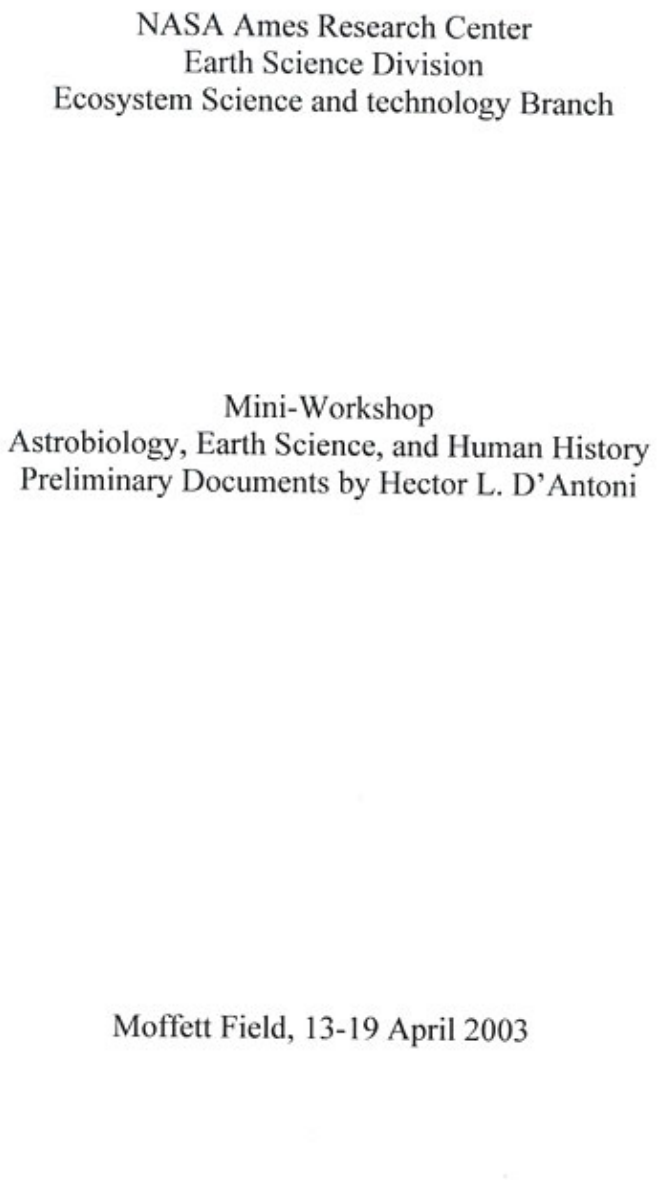
Austin

Austin Long
Professor

Page 1 of 1

Figure 6. *Radiocarbon dates of materials from "albarradas". One date is out of range, the rest is consistent with the dates obtained by standard ^{14}C technique.*

7. The Astrobiology, Earth Science, and History Workshop held in Morgan Hill and chaired by D'Antoni (April 13−19, 2003) set the basis for interdisciplinary, collaborative work in selected regions of South America.



NASA Ames Research Center
Earth Science Division
Ecosystem Science and technology Branch

Mini-Workshop
Astrobiology, Earth Science, and Human History
Preliminary Documents by Hector L. D'Antoni

Moffett Field, 13-19 April 2003

Figure 7. *Cover Page of the Preliminary Document for The Astrobiology, Earth Science, and History Workshop held in Morgan Hill (April 13−19, 2003).*

Highlights

- Our map of AVHRR−NDVI for the subtropical growing season of South America (Oct−Jan) on monthly data from 1981 through 2000 validates earlier ground−level studies by Hueck and Seibert (1982).

- Our graphic model modifies current knowledge on the areas affected by "El Niño" Southern Oscillation in South America. This study identified areas differently affected by El Niño, and La Niña, as well as

the "Normal" conditions and showed the feasibility of our study linking sea−surface temperature (SST) to tree−ring widths.

- Our "Paleo"−SST simulation correlates well with volcanic phenomena, the little Ice Age and other events. It complements (often with greater detail) reconstructions made with other proxy records, such as paleomicroplankton.

- The Workshop held in April 2003 discussed the application of Astrobiology's interdisciplinary approach to the study of human society and the environment over long−term periods and combining methods from space science, Earth science and archeology.

Roadmap Objectives

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MARTE	Spectroscopy analysis of samples with new, NASA sponsored technology.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

As a result of D'Antoni's involvement in the Small Business Innovative Research (SBIR) program, a new instrument named thermal infrared multispectral scanner (TIMS) was produced that offers reflectance, fluorescence and Raman spectroscopy; energy sources cover the range of 200 nm through 2 mm. Advanced interferometry increases spatial resolution over the traditional boundary of 1 µm. This instrument is being adapted to this mission (the MARTE Project) in order to use its leading−edge capabilities in the Mars analog in Spain (Rio Tinto).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems

Lead Team:	***Ames Research Center***
Project Title:	***Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems***
NAI−NRC Postdoctoral Fellow :	***Marc Kramer***

Project Progress

Gusev Crater is the landing site for the 2003 Spirit rover. Morphological evidence suggests that it is a favorable location to search for evidence of past water activity on Mars and better understand its origin and duration. The total size of the uplands area draining into, or possibly contributing groundwater recharge to Gusev Crater is 7M km^2 −− which is comparable to the largest terrestrial drainage basins on Earth− the Amazon or Nile Basins. Possible sources of water in the uplands include melt water from glacial/ice sheet, subsurface aquifers, hydrothermal activity and precipitation. Yet the duration for any surface water/ice activity remains unclear. We found evidence for surface water flow features throughout the uplands region of Gusev. Valley networks lack fine−scale features and bear close resemblance to streambeds found in the cold terrestrial region of Antarctica associated with intermittent melt from persistent subsurface ice. We also found evidence for numerous closed drainage basins in the uplands. These localized drainage basins would have limited overland flow directly into Gusev crater, although they may provide a source of subsurface recharge. The Mars Global Surveyor (MGS) and Mars Observer Camera (MOC) images also reveal that melt water (e.g., abundant gullies) and ice (e.g., pitted surfaces, cryokarst, solifluction (creep, massflows), and possibly polygons persist today in Ma'adim's watershed. Both the old and modern−day surface water features appear to be the result of movement of volatile−rich subsurface melting of surface ice and snow, which suggests that there might have been reactivation of the region during favorable obliquity cycles throughout Mars' history. This interpretation is consistent with the episodic fluvio−lacustrine activity found in the Ma'adim Vallis/Gusev Crater system.

Highlights

- We were able to reconstruct how surface water may have once flowed across several large drainage basins in the Noachis Terra and Sabaea Terra regions of the Highlands of Mars. We found that such a Martian

waterway would have comprised ancient lakes and discontinuous rivers.

- Larger shallow paleolake features in the main drainage system often contain multiple highly eroded craters, showing evidence of stream features in the extensive upland regions draining into them. They also become increasingly shallow downstream, suggesting increased sedimentation from water or ice that may have once flowed through them.

- The abundant shallow surface depressions and fragmented stream features of the Martian waterways examined strongly resemble the recently glaciated Great Lakes region in the United States, suggesting that they are relatively unevolved when compared with terrestrial surface water features.

- The Mars Exploration Rover (MER) site, Gusev Crater, is situated at the mouth of a vast 7M Km^2 upland region (−as big as the largest terrestrial drainage basins on Earth). The uplands region could have potentially delivered substantial quantities of water/ice and sediments through Gusev Crater, making it an ideal landing site.

- The presence of periglacial, (polygonal ground, collapse features, pingos) features in the deepest portions of large depressions in the uplands suggests surface ice in its past and present history, while the many incised stream features also implicate surface water flow activity. Currently, we are evaluating possible sources for, and duration of flow of, surface water, ice and groundwater activity.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Exploration Rover (MER) 2003	I am a MER science team member through participating MER PI scientist Nathalie Cabrol's group.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)

2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Helped to develop testable hypotheses for the 2003 MER mission, and provided background scientific study of the landing area.

Cross Team Collaborations

Jack Farmer −− Mars focus group. Farmer participated in Mars Explorer Rover (MER) 2003 (through Nathalie Cabrol) and other upcoming Mars related activity, he participated in tele−confereces on MER and upcoming publications, and he planned meeting abstracts.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Evolution of Desiccation Tolerance in Cyanobacteria

Lead Team:	***Ames Research Center***
Project Title:	***The Evolution of Desiccation Tolerance in Cyanobacteria***
NAI−NRC Postdoctoral Fellow :	***Tracy Norris***

Project Progress

The broad goal of this project is to investigate the ecological, physiological and genetic aspects of desiccation and freezing tolerance in cyanobacterial crusts and cryptoendolithic photosynthetic communities. Travertine terraces have been deposited by hot springs in Yellowstone from as early as 365,000 years ago to the present. Most of these $CaCO_3$ rocks (old or new) contain a 1−2 mm thick greenish band about 1−3 mm below the surface. These bands are composed of cyanobacteria and, sometimes, unicellular green algae. Although some moisture may be retained for a while, all undergo freezing in winter and desiccation in summer. The most amazing characteristic of these microbes is their ability to tolerate extreme desiccation in an environment where water is only rarely or occasionally available. The cyanobacteria that mainly comprise these communities are able to survive long periods of desiccation without specialized spores, and yet have water contents much lower than that of the endospores of Gram positive bacteria, which are able to endure desiccation for thousands or millions of years. Both molecular and culture based methods were used to investigate cryptoendolithic communities and microbiotic soil crusts in Yellowstone National Park. The results of DGGE (denaturing gradient gel electrophoresis) and environmental clone library analysis show that these communities are composed of a few (2−5) groups of nearly identical 16S ribosomal deoxyribonucleic acid (rDNA) phylotypes. Clonal cultures have also been established and sequenced. All those tested are able to survive extreme desiccation. Sequence analyses of cultures show that some strains are nearly identical to known cyanobacterial strains while others show little similarity. A few show 99−100% identity to cyanobacteria from very different habitats (e.g. Baltic Sea, Antarctic ponds). However, both Antarctic ponds and Yellowstone travertine are environments in which adaptations for desiccation and/or freezing tolerance are crucial. The lack of ecological similarity among nearly identical 16S rDNA phylotypes indicates that other genes must be used for differentiation.

Highlights

- Enrichment and dilution to extinction methods were used to obtain pure clonal cultures of cyanobacteria and microalgae. Low 16S rDNA similarity scores for BLAST searches of GenBank (94% or less) indicate that many of these culture isolates represent novel phylotypes or species of cyanobacteria, and thus significant additions to our knowledge of microorganisms from extreme environments.

- In a few cases, 16S rDNA sequences of Yellowstone cyanobacterial culture isolates were identical or nearly identical to sequences deposited in GenBank that originate from vastly different habitats. Therefore, genetic differences beyond the 16S level are likely to be important for the ability of these Yellowstone isolates to survive in the cryptoendolithic environment.

- Comparison of DGGE and clone library analysis with 16S rDNA sequence analysis of culture isolates indicates that predominant cyanobacteria inhabiting cryptoendolithic travertine communities were isolated. Future work will focus on physiological experiments with these pure cultures.

- Molecular analysis suggests that travertine cryptoendolithic communities consist of a few groups composed of nearly identical phylotypes.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Field Expeditions

Field Trip Name: Yellowstone Field Trip	
Start Date: 08/04/2002	***End Date:*** 08/15/2002
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:***
Latitude: 44 N	***Longitude:*** 111 W
Name of site(cave, mine, e.g.): Yellowstone National Park	***Keywords:*** desiccation, cyanobacteria, microbial ecology, cryptoendolithic communities
Description of Work: Collection of microbiotic crusts and travertine samples containing cryptoendolithic communities for both culture dependent and molecular analysis.	
Members Involved: Tracy Norris	

Field Trip Name: Baja Field Trip

Start Date: 09/04/2002	***End Date:*** 09/17/2002
Continent: North America	***Country:*** Mexico
State/Province: Baja California, Sur	***Nearest City/Town:***
Latitude: 27 N	***Longitude:*** 113 E
Name of site(cave, mine, e.g.): Exportadora de Sal, S. A. salt works	***Keywords:*** desiccation, cyanobacteria, microbial ecology, microbial mats
Description of Work: Collection and microscopic analysis of cyanobacterial mats for studying desccation tolerance; studying the resumption of photosynthetic activity of desiccated hypersaline cyanobacterial mats following rehydration.	
Members Involved: Tracy Norris	

Cross Team Collaborations

Collaborative Project: The Effects of Environmental Factors on the Resumption of Photosynthetic Activity of Cyanobacterial Mats Following Rehydration.

Individuals involved: Eric Flemming and Dr. Richard W. Castenholz (University of Oregon); Dr. Brad Bebout, Dr David Des Marais and ARC−NAI associates and collaborators.

Outcome of collaboration: A manuscript is in preparation with Eric Flemming as senior author.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: Ames Research Center

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Marc Kramer
Project Title: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems
Advisor: David Des Marais, Advisor
NAI Lead Team: Ames Research Center
Fellowship Began In: August 2001

Recipient: Tracy Norris
Project Title: The Evolution of Desiccation Tolerance in Cyanobacteria
Advisor: Richard Castenholz, Project Investigator
NAI Lead Team: Ames Research Center
Fellowship Began In: August 2002

EPO: Ames Research Center

These are the Education and Public Outreach activities for the Ames Research Center.

USC Wrigley Institute Geobiology Course

This is an intensive training course in a rapidly evolving field offered by the USC Wrigley Institute sponsored by the Agouron Institute held on Catalina Island, CA. The course offers intense interactions between the fields of biology and Earth history on an advanced level. Over a period of six weeks the participants are exposed to an in depth treatment of how biology interacts with environment and how these interactions have shaped the evolution of the Earth. The course focuses on five main themes that are most central to the discipline: Early Biomolecular Chemistry, Earth History, Earth Systems, Physiological Diversity of Microbes, Microbial Evolutionary Ecology. A core team of biologists, chemists, geologists, and astrobiologists will lecture on these topics with mini−symposiums featuring outside experts to discuss specific fields. Dr. Dave Des Marais, Dr. Lee Prufert−Bebout, and Dr. Brad Bebout will attend as lecturers and provide hands−on experiences on modern research methods while participating in on−site research groups solving current questions relevant to the field of astrobiology.

Astro−Venture Content Development and Review

The NASA Ames Astrobiology team is participating as Subject Matter Experts (scientists) to review the content of an Astrobiology−related website called Astro−Venture. This is an educational site designed for students in grades 5 − 8. The students role−play NASA occupations to learn about what characteristics make our planet habitable to humans. Our team offers Atmospheric Scientists, Geologists and Biologists to the project (Dr. Hector D'Antoni, Dr. Lou Alamadolla, Dr. Dave Des Marais, Dr. Mary Hogan, Dr. Brad Bebout). This is an ongoing activity for the Ames team.

Yellowstone National Park Offers the Public a Portal to Astrobiology

The Ames Astrobiology team is working with Yellowstone National Park (YNP) on a tiered, long term, public engagement program that includes exhibits, literature, field experiences, educator workshops, and "fireside chats" with astrobiologists that will reach the three million visitors of all ages who experience YNP each year. The NAI team is working with Yellowstone staff on several projects within the park including the development of ten exhibits that

will illustrate astrobiology throughout the trails in Yellowstone. The team is also developing chapters on astrobiology and microbiology for the Yellowstone Resources and Issues Guide, which is a training manual for the interpretive research staff used to develop hikes and talks for the public. The Guide will be published and available for purchase from the gift stores throughout the park. It will also be available for virtual visitors through research libraries in the national park system, the Yellowstone National Park Web site and the NAI site.

The team is also developing exhibit ideas to go into a planned new visitor center at Old Faithful geyser basin. This partnership with YNP is helping the general public to enhance their knowledge and skills and to access NASA research in astrobiology, including geology, microbiology, and space missions.

Understanding how life began on Earth is a natural starting point for astrobiology. Yellowstone is providing insights into the origin and evolution of life and the potential for life to exist beyond Earth. Biochemical clues hint that early life might have lived in high−temperature environments, including hot springs. The park's hot springs provide a glimpse into the nature of the early biosphere. Ancient spring alcoves on the flanks of Martian volcanoes invite comparisons with YNP, whose fossil−rich sinter spring deposits may, in turn, resemble deposits on Mars.

Microbial Mat Laborarory Tours

The Ames Astrobiology team has a unique laboratory tour available to visiting researchers, NASA officials, local education groups, and outside organizations. Dr. Dave Des Marais, Dr. Brad Bebout and Dr. Tori Hoehler are the lead researchers who prepare their presentations based on the type of group that is scheduled to tour the labs. The public is given a unique opportunity to view the samples and hear from the principal investigators on the project. The tours occur on a continuous basis throughout the year with requests coming from the NAI, Public Affairs, Education and Public Outreach, and other NASA centers.

"The Great Desert: Geology and Life on Mars in the Southwest

"The Great Desert" is a NASA−sponsored training workshop for science teachers focusing on the geology and biology of Mars through analogies on Earth and will be held from July 12−20, 2003. Sites for field studies will include the Grand Canyon, the Meteor Crater, Sunset Crater Volcano, the Jemez Caldera volcano and its hot springs, and faults of the Rio Grande Rift. At the University of New Mexico (Albuquerque), classroom learning will complement the field studies, and include up−to−the−minute results from spacecraft exploration of Mars. Tested classroom activities will help illustrate the field studies, and will be shared with students, school, and district. The field and classroom work will be augmented by extensive background materials, activity plans, and references. The workshop will be taught by geologists, planetary

scientists, and astrobiologists from the Lunar and Planetary Institute, the University of New Mexico, NASA Ames Research Center, and the New Mexico Museum of Natural History. The scientists will participate throughout the workshop, in the field, in the lab, and in the classroom.

Young Astronauts

The Young Astronauts program is created for 4th−6th graders using aerospace themes to develop student interest and proficiency in science technology and math. The curriculum is developed by the Young Astronaut Council, the world's largest space/technology education organization. Dr. Lynn Rothschild was featured in the "live" interaction portion of the program which introduced scientists to the students on television. The Astrobiology Educator Guide was provided for the teachers of the program for continued astrobiology exposure during the course.

2003 NASA Astrobiololgy Institute General Meeting

The NASA Astrobiology Institute 2003 General Meeting took place at Arizona State University February 11−13, 2003. Through serving as the Outreach Chairperson on the General Meeting Planning Committee, Catherine Tsairides helped to organize a program presenting astrobiology to the Arizona area educators. This was hosted by the Mars Space Flight Facility at ASU where we featured the Astro−Venture and Voyages Through Time projects. Sixty astrobiologists were invited to a science round table dinner with the educators prior to the public talk by Dr. Antonio Lascano.

Astrobiology Academy

The NASA Ames Astrobiology research team participates in the Astrobiology Academy by presenting lectures to the students, offering lab tours, and hosting student interns from the Academy. The students have a research mentor from Ames who works with them as they develop their projects and meets with them to oversee the research developments.

Public Outreach through Educational Film, Radio, Web, and Print Productions

The Ames Astrobiology Team is highly involved with public programming on television, radio, video, and publications. The distribution of astrobiology research, specific missions, and unique scientific events are shown nationally and internationally featuring any number of scientists on the Ames team. Team members have been involved in numerous diverse media events such as these: a guest speech for the 2002 Annual BASIC Dinner at Alien Technologies entitled "The Universe is only a Moderately Good Organic Chemist, but It Benefits from the Use of Big Beakers;" numerous live and taped TV spots discussing the Leonid meteor shower as part of a NASA "LiveShot" session; development meetings were held with Jonathan Renouf,

who broadcasts the BBC's Horizons Radio Program to prepare a special broadcast on the 50th anniversary of the Double Helix; a one−day field excursion on the microbiology of Yellowstone National Park as a part of a week−long Park Kids Program course; a press conference related to Mars exploration Rover launch; a one hour public radio talk show with phone−ins discussing the search for extraterrestrial life; a public event related to the Mars Exploration Rover launch.

Educational Workshops/Classroom/Lab Experiences

The Ames Astrobiology team has developed and organized educational sessions and workshops at national conventions or site locations across the country and internationally. Team members participated as keynote speakers, lecturers, and presenters of hands−on workshops targeted at students of all levels, university professors, and educators. The team also develops and presents science lessons for local and international classroom experiences at various schools. The presentations occur in places where team members are conducting research on site or involved in science conferences. The science team makes it a priority to present their research at the university, while providing a program for the K−12 school in the areas they are visiting. Because of return field experiences or invitations as speakers, the team does have more than a "one stop" experience with the local school districts. Students and educators are invited to various centers, universities, and field sites to participate with the science team. The experiences with the science team also include field expeditions, short courses, course series, and lesson development with the educators on site. The science team makes themselves available once they return to their sites to answer questions via e−mail from the students or educators that they've participated with. The themes usually addressed are the value of scientific training, participating in space exploration, as well as the exciting details of astrobiological research.

Public Presentations/Symposiums/Lecture series

The Ames Astrobiology Science Team has been invited as guest speakers and lecturers for professional and public symposia. NAI Ames team scientists have presented all over the world and have collectively given over 1200 hours to present astrobiology research to the community. A sample of these diverse events are: Argouron Institute, Catalina Island, CA, Breaman Germany, Michigan State University, Kennedy Space Center−Dr. David Des Marais, Astrobiology Seminar Series, activities, −Dr. Peter Visher, Leldon Observatory, Netherlands−Dr. Max Berstein Foothill DeAnza lecture series−Dr. Scott Sandford, University of Califonia, Berkeley−Dr. Lou Allamondola, Ethnography Museum Buenes Aires, Argentina−Dr. Hector D'Antoni Yellowstone Association Institute−Dr. David Ward, AAAS−Dr. Jack Szostak, Shlumberger Connecticut−Dr. Victoria Orphan, Yellowstone National Park series−Dr. Lynn Rothschild.

Stanford University Astrobiology Course

The Ames Astrobiology researchers participate in the development of the course presented at Stanford University to graduate students. Dr Mal Cohen is the director and the team collaborates each year on the design and content of the course. The researchers provide lectures, lessons, lab experiences, and projects for the duration of the semester long course. Each series of lecturers are responsible for preparing the mid term and final exams for their portion of the program.

Microbial Mat Sample Distribution

Microbial Mat samples are taken from around the world and maintained by the Ames Research team. The team is routinely asked to provide samples for classrooms, educator workshops, museum exhibits, and other displays. The microbial mat samples sent to various locations are used for the general public, professional development programs, and classroom activities providing a hands−on experience with this vital research tool. The mats are selected, packaged, and maintained by the Ames team for these venues.

Quest Profiles

NASA Quest is dedicated to bringing NASA people and science to classrooms through the Internet and is a resource for educators and the young public. The NASA Ames Astrobiology researchers have been featured on individual profiles of astrobiologists in the field in Baja, Mexico. Through interviews and web chats the public has the opportunity to learn about the astrobiology program and about the diverse and exciting careers from these enthusiastic NASA people.

California Academy of Sciences Partnership

New Exhibit Design and Development

The NASA Ames Astrobiology team has created a partnership with the California Academy of Sciences (CAS) to disseminate science to the public. We have entered into this formal and informal research education partnership with CAS in order to feature topics of astrobiology to bridge the three parts of the museum − natural history, planetarium, and aquarium − together. The Ames team has begun a series of meetings with the CAS science directors, educational specialists, researchers, architects, and exhibit design firms to serve on the design team. The Ames team is contributing to the new exhibit development and professional development programs at CAS involving scientific content meetings, professional development programs for the docents, area educators, and research partners.

Docent Trainings

The California Academy of Sciences, NASA Ames Research Center Education

Office and the Ames Astrobiology Team have developed a professional education partnership. Lively and informative expeditions through the California Academy of Sciences Exhibit Halls are led by museum docents who are education specialists. This partnership focuses on providing information about our scientific research to the docents who meet the public at CAS on a daily basis. The docents are invited to the astrobiology laboratories at Ames to receive tours of the greenhouse facility, which maintains live microbial mats, and the astrochemistry lab. Together with the Ames Education Office, hands−on educational materials, real laboratory experiences, and researcher involvement are available to the docents as they design museum tours focused on the exhibits we are developing with CAS.

K−14 Classroom Presentation

The Ames Astrobiology Team has developed a rapport with our local Bay Area school districts. Our scientists are asked to complement the existing science program for California by coming into the formal education classroom to provide specific lectures or hands−on demonstration activities. The researchers incorporate their science into the content that is part of the local and nationals standards for the district. The science team also invites the classrooms to NASA Ames for onsite demonstrations, tours, and access to the laboratories. The team is often called upon for career day programs, science fair judging, and special event programming for scientific events scheduled at the schools. This classroom involvement is initiated by the science team members themselves because of their interest in K−14 classroom partnerships; this involvement occurs throughout the NASA Ames Research Center Education Office.

New Exhibit Development with the New York Hall of Science

Planning meetings have begun for the exhibit development and curriculum project underway at the New York Hall of Science (NYHOS) in Queens, New York. This is a cooperative project between the Ames Astrobiology team, TERC, and the NYHOS for the "Search for Extraterrestrial Life" exhibit at NYHOS. Dr. Lynn Rothschild is on the advisory board for this project. The Ames team is providing content for the exhibit, and concept meetings have now taken place in conjunction with the California Academy of Sciences, and their architectural and design firms are participating. The Ames team is cooperating on the design of K−14 Discovery Center experiences and hands−on activity stations that the museum staff will use with formal education student groups that frequent the museum.

Participation on Education Review Panels

The Ames Astrobiology research team and outreach lead are continually invited to participate on review panels for research and outreach proposals. The team members have provided their expertise to these organizations and panels each year to provide valuable input to the mission and research grants

and opportunities in the scientific and educational community.

Minority University Collaborative

The Minority University Astrobiology Collaborative meeting was held at NASA Goddard Space Center September 18−21, 2002. This meeting brought together NAI lead outreach teams, minority universities, NASA headquarters officials, and interested parties. The Ames team was invited to participate in order to give insight into the type of outreach program we have and to speak directly to the Hampton University project started two years ago with Dr. Dave Des Marais as technical advisor. We collaborated with Dr. Brendalyn Faison as they began development on an Astrobiology course. The Ames team provided direction and content and a site visit for the postdoctoral student on the project. The project has continued under Dr. Arthur Bowman at Hampton University.

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Members: Ames Research Center

Team Members sorted by current team.

Name:	Daniel Albert
Email:	albert@marine.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Louis Allamandola
Email:	lallamandola@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Brad Bebout
Email:	bbebout@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Max Bernstein
Email:	mbernstein@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	John Bluck
Email:	John.G.Bluck@nasa.gov
Institution:	Ames Research Center
Name:	Lidia Burry
Email:	lburry@mdp.edu.ar
Institution:	National University of Mar del Plata
Name:	Nathalie Cabrol
Email:	ncabrol@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	Sherry Cady

Email:	cadys@ch1.ch.pdx.edu
Institution:	Portland State University
Name:	Steven Carpenter
Email:	scarpenter@mail.arc.nasa.gov
Institution:	Orbital Science Corporation
Name:	Michael Carr
Email:	carr@astmnl.wr.usgs.gov
Institution:	USGS Menlo Park
Name:	Richard Castenholz
Email:	rcasten@darkwing.uoregon.edu
Institution:	University of Oregon
Name:	David Catling
Email:	davidc@atmos.washington.edu
Institution:	University of Washington
Name:	J. Chambers
Email:	john@mycenae.arc.nasa.gov
Institution:	Ames Research Center
Name:	John Chaput
Email:	chaput@molbio.mgh.harvard.edu
Institution:	Harvard University
Name:	Robert Chatfield
Email:	chatfield@clio.arc.nasa.gov
Institution:	Ames Research Center
Name:	Mark Claire
Email:	mclaire@astro.washington.edu
Institution:	University of Washington
Name:	Tony Colaprete

Email:	tonyc@hellas.arc.nasa.gov
Institution:	Ames Research Center
Name:	Hector D' Antoni
Email:	hdantoni@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Brad Dalton
Email:	bdalton@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	Dave Deamer
Email:	deamer@chemistry.ucsc.edu
Institution:	University of California, Santa Cruz
Name:	Kelly Decker
Email:	kdecker@mail.arc.nasa.gov
Institution:	California State University, Monterey Bay
Name:	David Des Marais
Email:	ddesmarais@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Donald DeVincenzi
Email:	ddevincenzi@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Jesse Dillon
Email:	jdillon@u.Washington.edu
Institution:	University of Washington
Name:	Mykell Discipulo
Email:	mdiscipulo@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Moira Doty

Email:	mdoty@mail.arc.nasa.gov
Institution:	Orbital Science Corporation
Name:	Jason Dworkin
Email:	Jason.P.Dworkin@nasa.gov
Institution:	GSFC Raytheon
Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Name:	Richard Felger
Email:	rfelger@ag.arizona.edu
Institution:	Drylands Institute
Name:	Erich Fleming
Email:	efleming@darkwing.uoregon.edu
Institution:	University of Oregon
Name:	R. Freedman
Email:	freedman@darkstar.arc.nasa.gov
Institution:	Space Physics Research Institution
Name:	Ferran Garcia−Pichel
Email:	ferran@asu.edu
Institution:	Arizona State University
Name:	Edmund Grin
Email:	egrin@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	Robert Haberle
Email:	bhaberle@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Tori Hoehler

Email:	thoehler@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Mary Hogan
Email:	mhogan@mail.arc.nasa.gov
Institution:	University of California, Santa Cruz
Name:	Gerda Horneck
Email:	gerda.horneck@dlr.de
Institution:	DLReV Institute of Aerospace (Germany)
Name:	Colleen Howell
Email:	chowell@mail.arc.nasa.gov
Institution:	Orbital Science Corporation
Name:	Miguel−Angel Huerta−Diaz
Email:	mhuerta@faro.ens.uabc.mx
Institution:	University of Ensenada Baja CA
Name:	Linda Jahnke
Email:	ljahnke@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	James Kasting
Email:	kasting@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Steven Klooster
Email:	steve@gaia.arc.nasa.gov
Institution:	California State University, Monterey Bay
Name:	Marc Kramer
Email:	mkramer@gaia.arc.nasa.gov
Institution:	Ames Research Center
Name:	Andres Laguens

Email:	laguens@ffyh.unc.edu.ar
Institution:	University of Cordoba
Name:	Vanessa Lancaster
Email:	Vanessa.Lancaster@asu.edu
Institution:	Arizona State University
Name:	Carlos Lasta
Email:	clasta@inidep.edu.ar
Institution:	INIDEP (Argentina)
Name:	Jack Lissauer
Email:	jlissauer@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Kathleen Londry
Email:	londryk@cc.umanitoba.ca
Institution:	University of Manitoba
Name:	Rocco Mancinelli
Email:	rmancinelli@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	Jorge Marcos
Email:	jgmarcos_albarrada@espoltel.net
Institution:	Escuela Superior Politecnica del Litoral ESPOL
Name:	Christopher McKay
Email:	cmckay@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Betty Meggers
Email:	MNHan91@sivm.si.edu
Institution:	Smithsonian Institution
Name:	Scott Miller

Email:	srmiller@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Ante Mlinarevic
Email:	amlinare@hotmail.com
Institution:	California State University, San Jose
Name:	Tracy Norris
Email:	tnorris@darkwing.uoregon.edu
Institution:	University of Oregon
Name:	Ulrich Nuebel
Email:	unuebel@dsmz.de
Institution:	Deutsche Sammlung von Mikroorganismen und Zellkulturen
Name:	Enoma Omoregie
Email:	enomao@cats.ucsc.edu
Institution:	University of California, Santa Cruz
Name:	Victoria Orphan
Email:	vorphan@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Jose Perez Gollan
Email:	jagollan@mail.retina.ar
Institution:	University of Buenos Aires
Name:	David Peterson
Email:	dpeterson@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Peter Pilewskie
Email:	ppilewskie@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Andrew Pohorille

Email:	pohorill@raphael.arc.nasa.gov
Institution:	Ames Research Center
Name:	Christopher Potter
Email:	cpotter@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Lee Prufert−Bebout
Email:	lbebout@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Diane Purcell
Email:	dpurcell@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	M. Rabbette
Email:	mrabbette@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	R. Pamela Reid
Email:	preid@rsmas.miami.edu
Institution:	University of Miami
Name:	Petra Rettberg
Email:	Petra.Rettberg@dlr.de
Institution:	DLReV Institute of Aerospace (Germany)
Name:	Nina Rosenberg
Email:	rosenberg4@llnl.gov
Institution:	Lawrence Livermore National Laboratory
Name:	Michael Rothrock
Email:	rothrock@asu.edu
Institution:	Arizona State University
Name:	Lynn Rothschild

Email:	Lynn.J.Rothschild@NASA.gov
Institution:	Ames Research Center
Name:	Scott Sandford
Email:	ssandford@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Burckhard Seelig
Email:	seelig@molbio.mgh.harvard.edu
Institution:	Harvard University
Name:	Norman Sleep
Email:	norm@pangea.stanford.edu
Institution:	Stanford University
Name:	Ronald Sletten
Email:	sletten@u.washington.edu
Institution:	University of Washington
Name:	Roger Summons
Email:	roger.summons@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Brad Sutter
Email:	bsutter@mail.arc.nasa.gov
Institution:	SETI Institute
Name:	Jack Szostak
Email:	szostak@molbio.mgh.harvard.edu
Institution:	Harvard University
Name:	Cynthia Tao
Email:	ctao@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Margaret Tolbert

Email:	tolbert@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Owen Toon
Email:	btoon@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Matilde Trivi
Email:	mtrivi@mdp.edu.ar
Institution:	National University of Mar del Plata
Name:	Catherine Tsairides
Email:	ctsairides@mail.arc.nasa.gov
Institution:	Lockheed Martin
Name:	Kendra Turk
Email:	kturk@mail.arc.nasa.gov
Institution:	University of California, Santa Cruz
Name:	Pieter Visscher
Email:	visscher@uconnvm.uconn.edu
Institution:	University of Connecticut
Name:	David Ward
Email:	umbdw@gemini.oscs.montana.edu
Institution:	University of Washington
Name:	Kimberly Warren−Rhodes
Email:	kwarren−rhodes@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Nilda Weiler
Email:	weiler@cenpat.edu.ar
Institution:	National Patagonic Center
Name:	Michael Wilson

Email:	mwilson@mail.arc.nasa.gov
Institution:	University of California, San Francisco
Name:	Richard Young
Email:	reyoung@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Kevin Zahnle
Email:	kzahnle@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Richard Zare
Email:	zare@stanford.edu
Institution:	Stanford University

Arizona State University
Executive Summary
Principal Investigator: Jack Farmer

An Overview of Astrobiology at Arizona State

During our five years as an NAI charter member, Arizona State University sponsored a broadly based program of research and training in Astrobiology to address the origin, evolution and distribution of life in the Solar System. The following paragraphs provide an overview of the specific research areas pursued by the Arizona State University (ASU) Astrobiology team during Year 5. With such a large and diverse team, it is not possible in the space available to cover all details of the research progress made during the past year. For a more complete review, the reader is referred to the individual detailed reports for ASU that accompany this Executive Summary.

Section I: Origins of the Basic Builidng Blocks of Life

At ASU, the origins of living systems has focused primarily on understanding 1) the exogenous origins of carbon compounds through studies of the cosmochemistry of carbonaceous meteorites and 2) the endogenous abiotic synthesis of organics in deep sea hydrothermal vent environments.

A. Meteorite Cosmochemistry.

During Year 5, Co−I Laurie Leshin and her group continued studies of the chemistry of carbonaceous meteorites. By coupling accretion modeling of the early Solar System with D/H estimates obtained from meteorites, the group produced consistent water delivery scenarios for both the Earth and Mars (Lunine et al., 2003). In addition, Astrobiology Postdoctoral fellow Michele Minitti showed that the high D/H values of Martian rocks probably did not result from shock (Minitti et al. in preparation).

Research into nature of hydrous alteration environments on carbonaceous meteorite parent bodies was published by NAI Astrobiology Postdoc Gretchen Benedix in Geochemica et Cosmochemica Acta (Benedix et al. 2003). Using a combination of oxygen isotopic, electron microprobe and petrographic methods, this study established the nature and timing of aqueous alteration processes on the meteorite parent body. In addition, C isotope data provided new constraints on magmatic and surficial carbon reservoirs in the Martian carbon cycle (Goreva et al., 2003, Niles et al., in prep.)

B. Abiotic Synthesis of Organics in Hydrothermal Environments

Co−I's John Holloway and Peggy O'Day lead an effort to understand the endogenous (terrestrially based) synthesis of prebiotic organic compounds at high temperatures, specifically within seafloor black smoker hydrothermal systems. During Year 5, the group advanced a corollary to their previously published hypothesis that the degassing of seafloor basaltic magmas can provide hydrogen and carbon dioxide for abiotic organic syntheses (Holloway O'Day, 2000), showing that the same processes can operate in conjunction with silicic magmas (Holloway, submitted). The team also continued to explore the synthesis of organic compounds from hydrogen and carbon dioxide in the presence of mineral catalysts under seafloor hydrothermal conditions. In this work they showed that smectite clay minerals, common in seafloor hydrothermal deposits, provided reactive sites for synthesis of complex organic compounds such as hexamethylbenzene and long−chain methyl esters from aqueous methanol solutions (Williams, et al., 2002; Canfield, et al., 2003).

The Holloway−O'Day group also applied synchrotron computed microtomography to characterize hydrothermal microhabitats by imaging the physical structure of young hydrothermal chimneys from 9°N East Pacific Rise. This analysis showed that the internal structure of sulfide chimneys consisted of a loosely connected network of euhedral mineral grains (predominantly sulfide by bulk X−ray diffraction analysis) and is dominated by diffuse flow (i.e., unchannelized). Imaging established that the physical structure of sulfide chimneys can indeed serve as an effective molecular sieve for the adsorption of organic compounds and bacteria from vent fluids and seawater. This provided the basis for formulating a model to show how organic compounds can accumulate on catalytic mineral surfaces under pre−biotic conditions.

Section II: Early Biosphere Evolution

The early evolutionary history of living systems on Earth has been addressed in a variety of ways at ASU, including ecological and molecular studies aimed at understanding the origins of photosynthesis, studies of microbial fossilization in modern terrestrial environments, with applications in interpreting the biosignatures preserved in ancient terrestrial (and extraterrestrial) geological materials, by novel approaches for reconstructing the paleoenvironmental conditions on the Archean Earth and early Mars and by understanding the role played by of impacts in shaping the early biosphere.

The appearance of oxygenic photosynthesis is regarded as one of the pivotal evolutionary events in the development of Earth's biosphere in that the accumulation of photosynthetic oxygen at the Earth's surface and in the atmosphere ultimately paved the way for the origin of advanced multicellular life forms and human intelligence. Continuing controversy over the paleoenvironments and biogenicity of the oldest known terrestrial fossils, as well as the origin of putative fossil biosignatures in Martian meteorite ALH 84001, have emphasized the need for developing more robust chemical and morphological criteria for the recognition of ancient environments and fossil biosignatures in ancient rocks. At ASU, an interdisciplinary effort has been underway to address important aspects of the nature of Precambrian paleoenvironments and to define new approaches to fossil biosignature

capture, preservation and detection in ancient terrestrial and extraterrestrial materials.

A. Origins of Oxygenic Photosynthesis:
During Year 5, Co−I Robert Blankenship led a group to study the origin and evolution of photosynthetic systems. This effort involved a broadly based interdisciplinary collaboration between a half dozen partnering universities. Over the past year, the Blankenship team continued their search for novel phototrophs by exploring the non−solar environments around hydrothermal vents. Deep sea hydrothermal vents emit a small amount of fluorescent light from both thermal and non−thermal sources. This emitted light has been suggested as a potential energy source for photoautotrophic organisms. Organisms collected during a 2001 field expedition to hydrothermal vents of the Nine North vent system of the East Pacific Rise are now in laboratory culture and being evaluated for their phylogenetic affinities and metabolic capabilities. Additional light measurements taken at vents along the Mid−Atlantic Ridge gave results similar to vents in the Pacific (White et al. 2003). This work on alternative energy sources holds important implications for the exploration for habitable environments elsewhere in the Solar System (e.g. deep ocean floor environments of Europa).

Field and laboratory studies of photosynthetic organisms in iron−rich environments showed that some photosynthetic organisms utilize reduced iron as an electron donor. This has important implications for understanding the origin of banded iron formations in the Precambrian and for interpreting the rise of atmospheric oxygen. The Blankenship team isolated and analyzed mutant proteins that are potential candidates for Fe−oxidizing complexes.

B. Origins and Preservation of Fossil Microbial Biosignatures
1. Microbial Fossilization Processes in Alkaline Lakes and Hotsprings:
The interpretation of biosignatures in ancient terrestrial and extraterrestrial materials depends critically upon an understanding of the processes of microbial fossilization, inherent biases in biosignature capture and preservation and the effects of diagenesis (post−burial alteration) on biosignature retention. The most relevant systems for study are those extreme environments where active mineralization processes operate and where environmental conditions provide good analogs for the ancient Earth, or other planetary settings. During Year 5 of NAI membership, a group led by Co−I Jack Farmer completed a study of the fossilization processes associated with oncoids (spherical stromatolites) found in the Rio Mesquites, Cuatro Cienegas Basin, Central Mexico. Results were reported at the NAI general meeting and a manuscript is in preparation. This work was done in collaboration with James Elser's group, who have been studying the ecological aspects of the same system (see below). The work established that surface biofilms have a bi−layered community structure, with the upper zone being dominated by several groups of larger, mostly erect−growing filamentous cyanobacteria and many species of diatoms. Microelectrode studies showed that these surface species effectively control precipitation of calcium carbonate through photosynthesis. However, most mineralization is occurring at a depth of 1−2 mm below the biofilm surface in associaition with a subsurface community that is dominated by smaller filamentous species. Pervasive carbonate

precipitation at this depth entombs the deeper community, preserving numerous cellular remains. Interestingly, species of the surface community are rarely preserved, creating a strong taphonomic bias toward preservation of the subsurface community.

Farmer's group also began a study to charaterize bioflims and microbial fossil assemblages associated with low temperature carbonate−precipitating springs on the floor of Mono Lake, an alkaline−saline lake located in eastern California. (This comprises the topic of a PhD dissertation by Mike Thomas). The goal of the study is to trace the fate of biosignatures during carbonate precipitation, through early diagenesis. The results of the work in Mono Lake will be compared with ancient carbonate spring deposits elsewhere in the Mono Basin that were formed during the last glacial period when the lake was much deeper and colder. The work in the Mono Basin involves a collaboration with the Woods Hole team, who are focusing on the eukaryotic biodiversity of the lake biota.

2. Modes of Preservation in Precambrian Cherts:
Evaluating the nature of microbial biosignature preservation at the cellular scale is an important line of inquiry that may eventually lead to robust criteria for the recognition of biogenic signatures in ancient materials. During Year 5, Co−I Sharp (Dept. of Geological Sciences) continued to apply Analytical Transmission Electron Microscopy (ATEM) methods to characterize the nanometer scale microstructures and composition of kerogenous microbial biosignatures preserved in the 2.0 Ga Gunflint Iron Formation. Electron Energy−Loss spectroscopy (EELS) confirmed that microfossils consist of amorphous kerogen concentrated along grain boundaries of micro−quartz. Kerogen is amorphous, with little evidence for graphitization. In coccoidal microfossils, kerogen forms cell−wall like features around cores of granular microquartz, whereas in filamentous forms, the kerogen is disseminated along needle−shaped grain boundaries that separate submicron−sized fibers of chalcedonic quartz. Sharp's team are also applying similar methods to the study of putative biosignatures in the controversial 3.5 Ga Apex Chert from Western Australia. The goal is to characterize the composition, crystallinity and distribution of the kerogen to determine if this material is of biogenic or inorganic hydrothermal in origin. This work is ongoing and forms the basis for a PhD dissertation by Brad DeGregorio.

3. Origin of Magnetite in Martian Meteorite, ALH84001:
The hypothesis of a biogenic origin for magnetite grains preserved in carbonates of Martian meteorite ALH84001 is the most compelling line of evidence for the discovery of Martian life by McKay et al (1996). During Year 5, Co−I Peter Buseck and colleagues continued their work with electron tomography and holography to evaluate the biogenicity of putative magnetite biosignatures in Martian meteorite ALH845001 (Buseck et al. 2002). The ultimate goal of the research is to detemine whether the characteristics of crystal size distributions (CSDs) and shape factor distributions (SFDs) of magnetite obtained from magnetotactic bacteria can be used as mineral biosignatures. The group found that CSDs of magnetite obtained from 16 uncultured strains of bacteria showed both similarities and differences among crystals from bacteria from distinct localities and environments. Using a

numerical method, the group sorted magnetite crystal populations based on features of the SFD of all particles and found that the numerical methods are useful for identifying bacterial magnetite in rocks. Basic conclusions may be summarized as follows: 1) Using electron tomography, there is too much uncertainty in any TEM results to date to confirm a biogenic origin for the magnetite in meteorite ALH84001; 2) Magnetite crystals in bacterial strain MV−1, the standard for comparison for ALH84001 magnetite, show variations within a chain and rounding of faces, which are not as well developed, or as crisp as in published interpretations; and 3) Progress has been made in developing automated procedures for electron tomographic data acquisition, reconstruction, and visualization.

C. Inferring Paleoenvironmental Conditions on the Early Earth (and Mars):
The initial colonization of the land surface marked an important event in the evolution of the biosphere. This opened a whole new dimension for biological habitation and dramatically expanded microbial involvement in global biogeochemical cycles.

During Year 5, Co−I Paul Knauth (Dept. of Geological Sciences) submitted a manuscript that describes the geologic context of the world's oldest land−based microbial fossil assemblage, dated at 1.2 Ga (Apache Group paleokarst, north−central Arizona). A second manuscript is in preparation that describes cave deposits associated with the Apache Group paleokarst and the putative microfossils entombed within these deposits. In addition, a paleontological study of modern caliche developed by the surface weathering of basaltic lava flows is also nearing completion. This particular study also demonstrates the potential of caliche as a host medium for capturing and preserving microfossils on Mars. (Caliche is a predicted weathering product on Mars, provided the planet once had a warm, wet climate).

E. Role of Impacts in Early Biosphere Evolution:
Asteroid and cometary impacts have been identified as an important environmental and evolutionary agent throughout the history of Earth's biosphere.

During Year 5, Co−I David Kring's group determined the distribution of impact−generated wildfires for the Chicxulub (end Cretaceous) impact event (~65 Ma) and illustrated how impact parameters (e.g., trajectory) can influence the distribution of wildfires (Kring and Durda, 2002). An invited review paper outlined the environmental and biologic effects of large impact events, like Chicxulub, throughout Earth history (Kring, 2003). The Kring group also continued their analysis of lunar impact melts, to determine the flux of impact cratering events in the Earth−Moon system, particularly during the first billion years of Earth's history (Daubar et al. 2002; Cohen et al. submitted). In an invited review paper, the group also explored the impact delivery of Earth's water, a key ingredient for life's origin (Campins et al., 2003) and initiated new directions in the study of impact−generated hydrothermal systems, habitats that may have been a particularly widespread and important during the early evolution of life on Earth.

F. Microbially−based Ecosystems, Cuatro Cienegas Mexico: Windows for

Lower Cambrian Ecosystem Structure and Function.
The sudden appearance of complex, well−skeletonized invertebrates at the base of the Cambrian marks a singular event in the history of our biosphere. In an incredibly short interval of geologic time (

To better understand the ecological interactions that may have prevailed during the Cambrian transition, an interdisciplinary team of ASU and Mexican scientists, led by Co−I James Elser (Dept. of Biology) has been studying the ecology of simple, microbially based (fish−snail−microbial mat) ecosystems found in modern desert spring environments in the Cuatro Cienegas Basin, Central Mexico. Goals of the study include an improved understanding the energy flow within such simple ecosystems and an improved understanding of the ecological factors that contribute to explosive evolution within highly endemic clades, the nature of ecological interactions between grazers and stromatolite−producing microbial mat communities and mechanisms of microbial fossilization. Ultimately this highly interdisciplinary study aims to test specific hypotheses about the ecological mechanisms that contributed to the Proterozoic decline of stromatolite−producing microbial ecosystems, as well as the ecological and evolutionary factors (particularly stoichiometric constraints on evolution, arising from disparities in C:N:P) that could have contributed to the Cambrian explosion that followed.

During the last year the team tested the hypothesis that the metazoan grazers of stromatolitic microbes face a stoichiometric constraint that results from consuming microbial biomass with elevated C:P ratio. This would lead to microbes having a high biomass C:P ratio due to extreme limitation of their growth by PO4 in the well−illuminated, but oligotrophic spring fed environments that typify the study area. Sampling this past year confirmed that environmental levels of PO4 at CC are indeed extremely low (3000 (by atoms) to ~900. Snails (Mexithauma sp.) grazing on P−enriched mats had higher RNA:DNA ratios than those feeding on unenriched control stromatolites (generally RNA:DNA ratio is considered a good indicator of growth rate). The encouraging results from 2001 inspired a larger, longer−term (2−month) experiment performed during summer 2002 when we performed a factorial experiment in which both PO4 and the presence / absence of snails were manipulated. Data are preliminary but indicate that PO4 enrichment lowered microbial C:P from ~1000 to ~100. However, in contrast to the 2001 experiment, snails on P−enriched stromatolites had lower RNA:DNA ratios and experienced high rates of mortality and significantly lower rates of tissue and shell growth. Thus, P enrichment in 2002 appears to have "poisoned" the snails. This outcome was perplexing but is comprehensible in light of recent findings related to another herbivore known to be often P−limited, Daphnia, which grows slowly when food C:P ratios are reduced to unnaturally low levels. It was hypothesized that Mexithauma has evolved in the presence of consistently low P availability and experiences routine P−limitation in nature; however, when exposed to unnaturally P−rich food, it suffers a growth penalty. Thus, the simple food webs at CC may be poised on a stoichiometric "knife's edge" with regard to phosphorus. Could the same have held true for the simple microbially based ecosystems of the lower Cambrian?

The team also conducted a series of studies using microelectrode profiling and

bulk incubations to quantify calcification rates of stromatolites. This appears to be the first time this type of experiment has been accomplished on modern stromatolites. Measured areal rates of calcification were very high (~150 mg $CaCO_3$ cm^{-2} yr^{-1}), similar in magnitude to those measured in tropical coral reefs. However, rates of bioerosion by invertebrates in the same oncolites, measured by analyses of fecal pellet production, are only slightly lower (~106 mg $CaCO_3$ cm^{-2} yr^{-1}). This indicates that the system is in a precarious balance between net carbonate accumulation and destruction by consumers. This delicate balance could explain why stromatlites are so rare in grazer−dominated ecosystems, while also providing support for the grazer hypothesis as an explanation for the Proterozoic decline of stromatolites. The results of this work were submitted to Science and are presently in review (Garcia−Pichel et al. submitted).

Another goal of the Cuatro Cienegas study is to characterize the genetic and morphological diversity of its understudied biota (esp. microbes, cyanobacteria, and snails) in order to advance our understanding of the evolutionary forces that have affected species, especially the desert pupfish and snail species which exemplify extraordinarily rapid diversification under environmental extremes of temperature and salinity.

With regard to microbial diversity, Garcia−Pichel (et al, 2002) described associations of cyanobacteria that exhibit exceptionally novel adaptations for buoyancy involving calcite as ballast. In addition, a new form of extremely rare fresh−water red alga is in the process of formal description. Collaborator Valeria Souza (UNAM) isolated nearly 3500 separate strains of eubacteria and archaea from various habitats (benign to extreme) at Cuatro Cienegas and characterized the DNA for 350 strains using RFLP with sequencing of the 16S rDNA in selected cases. Sequenced strains from cultivable bacteria include Gram−positive taxa (Bacillus and Staphylococcus) and an ample suite of Gram−negative forms (Pseudomonas, Aeromonas, Aquaspirilum, Vibrio and Halomonas predominate, while clones of uncultivable DNA show marine Archaea and taxa previously isolated at hydrothermal vents). Preliminary analysis of TRFLP patterns of CC microbes shows a moderate alpha diversity with few species dominating the community (within a site) and a very large beta diversity (between sites) where each site has its own species.

The high levels of morphological diversity were also demonstrated for the hydrobiid snail Mexipyrgus by Co−Is Carol Tang and Peter Roopnarine. Morphometric analysis of samples of Mexipyrgus populations have revealed an extremely high level of morphological diversification and differentiation among even closely adjacent habitats. A goal of future work is to examine the ecogenomic basis of this diversification and to determine if the high degree of morphometric variation documented is controlled by dominantly environmental or genetic factors.

Section III. Exploring for Life in the Solar System.

The active involvement of ASU astrobiologists in NASA missions to Mars and Europa has provided ongoing opportunities for research and training in the exploration for life elsewhere in the Solar System. Data from the Mars Global

Surveyor (MGS) and Odyssey instruments have continued to provide the ASU team with basic mineralogical information needed to explore the past distribution of water on Mars and for identifying high priority landing sites for future Mars missions for Astrobiology. Orbital data from the Galileo spacecraft has allowed critical testing of the hypothesis of liquid water environments on Europa, Ganymede and Callisto and provided a basis for the selection of high priority landing sites for Astrobiology. Involvement of ASU astrobiologists in various Mars Program missions and mission planning efforts during Year 5 have continued to strengthen the NAI's contribution to NASA's missions.

Co−I Philip Christensen is Principal Investigator for three instruments on either current or planned missions to Mars, including the Thermal Emission Spectrometer (TES) instrument (onboard the Mars Global Surveyor (MGS) orbiter), the THEMIS instrument (onboard the Odyssey orbiter) and two mini−TES instruments (to be launched with the Mars Exploration Rover (MER) mission in 2003). Co−I Greeley is a former Chair of the Mars Exploration Payload Assessment Group (MEPAG), the primary community−based science strategy group for the Mars Program. Co−I Farmer was MEPAG Chair during 2002−03, was acting Chair of MEPAG's Astrobiology Science Steering Group during 2002−03 and is the current Chair of the NAI Mars Focus Group. Greeley and Farmer were members of the Mars Exploration Review Team (MERT) and MAST (Mars Ad Hoc Science Team) the past year, (each is an external oversight committee for the Mars Exploration Program). Greeley and Farmer are also participating scientists on the Mars Exploration Rover Mission and Phil Christensen is PI for the mini−TES instrument on MER. Co−I Laurie Leshin was PI for a Mars Scout mission proposal (SCIM).

A. Astrobiological Exploration of Mars.
Mars Global Surveyor Thermal Emission Spectrometer (TES) data continued to provide new information about the role of aqueous processes in shaping the history of Mars. Although no large−scale carbonate deposits have yet been detected on Mars, spectral evidence was obtained for the presence of H_2O−bearing minerals within Martian dust. Based upon spectral details of the dust, it appears that zeolites are a possible candidate for the aqueous mineral component.

TES data were also used to refine the candidate landing sites for the 2003 MER mission. Along with Gusev Crater, the specular hematite deposit at Meridiani Planum, discovered with TES data in 2001, was a designated as a primary landing site for one of two Mars Exploration Rovers launched in 2003. On Earth, coarse−grained (specular) hematite deposits only form in the presence of large amounts of water and most are hydrothermal in origin.

Newly acquired images from the Thermal Imaging System (THEMIS) on the Odyssey orbiter were used to characterize the candidate landing sites at Merdiaini Planum and Gusev Crater in much greater detail. Many new geologic features of these sites were revealed with stunning clarity using THEMIS data, helping to further refine the geologic context of the MER landing sites.

Masters student Alice Baldridge developed detailed mineralogical ground truth

for remotely sensed analog sites for Mars located in the Badwater Basin of Death Valley. MASTER (mid−infrared spectral) data were used to identify the locations of mineralogically pure, end−member pixels (carbonate, sulfate and silicates) within the basin. To establish ground truth, end member pixels were located on the ground and sampled for detailed laboratory analysis of mineralogy. Laboratory methods included X−ray Diffraction, electron microprobe, electron microscopy, thin section petrography and point counting, lab and ground−based spectral analysis (using TES analog spectrometers). To aid spectroscopic identifications, a mid−IR spectral library was developed for evaporate minerals and added to ASU's spectral data base for use by the TES and THEMIS project teams who are presently mapping Mars. These spectra will also be used by the MER project team. Results of this study were used to establish abundance thresholds (for natural mixtures in the Badwater Basin) necessary for the detection of discrete evaporite deposits (especially carbonates, sulfates and silicates, including zeolites). Results suggested that at the coarse spatial of the TES instrument (3 km/pixel), the detection of carbonates and sulfates is unlikely. However, at the enhanced spatial resolution of THEMIS (100 m/pixel), both carbonates and sulfates should be easily detected, provided they are present at abundances exceeding ~15%. This work was submitted to the Journal of Geophysical Research−Planets and is presently in review (Baldridge et al. in review). The next phase of this research will examine the spectral resolution thresholds for the same data sets.

A second Masters study was also completed during Year 5 that explored the margins of the North polar remnant ice cap of Mars to search for sites of possible magma−cryosphere (volcano−ice). This work comprised a Masters thesis by Meredith Payne who has now entered the PhD program at ASU. The study commenced with broad photogeological reconnaissance using Viking data to identify potential water−formed geomorphic features. This was followed by detailed studies at four sites, selected to cover a range of potential aqueous processes. Hypotheses posed for the origin of geomorphic features were tested using Mars Orbiter Laser Altimeter (MOLA) data and Geographic Information System (GIS) tools (e.g. Digital Elevation Models) and comparisons to terrestrial analogs. In the course of this work, it was discovered that MOLA data are sensitive to subglacal topography in areas that have been recently deglaciated, but are presently covered by snow. The ability to "see through the ice" broadens our access to polar geological history based on MOLA topography (Payne and Farmer, submitted, Icarus). In addition, the hypothesis of a pseudocrater origin for a small field of cinder cone−like features was tested using MOLA data. It was determined that they are more likely be of a subglacial origin, but still formed by a process involving liquid water (Payne and Farmer, submitted, JGR−Planets).

A highlight of Year 5 was the publication of a paper by Co−I Christensen in Science that provided an alternative hypothesis for the origin of the numerous seep sites identified previously by Malin and Edgett (2001) based on Mars Orbiter Camera (MOC) data (Christensen 2003). The Christensen paper was based on THEMIS visible imaging that suggests that the seeps could have formed beneath snow−pack that accumulated during a recent period of low obliquity, and not by outflows of subsurface water (e.g. hydrothermal brines) as previously suggested.

Reconnaissance studies of Astrobiology Martian landing sites for the Mars Exploration Rover mission (successfully launched in June), as well as detailed studies of the Gusev Crater landing site, provided another major focus for the project during Year 5. Gusev was selected as the site for the first MER landing, scheduled to occur in January 2004, while the hematite site was chosen for the second MER landing a few weeks later. Results of these landing site studies were presented at community workshops, to the Mars Exploration Payload Analysis Group (MEPAG) and to the MER project team.

In addition to planning for NASA missions, Ronald Greeley has also participated extensively in planning for the Mars Express mission, which was also successfully launched by the European Space Agency in 2003. Greeley is a Co−Investigator on the High Resolution Stereo Camera System (HRSC) imaging team and provided a list of high priority imaging targets for Astrobiology to the imaging team for use with that instrument. Similarly, Co−I Farmer provided a similar list of high priority Astrobiology targets to the CRISM instrument team (CRISM is a hyperspectral near−IR spectrometer that will be launched to Mars in 2005).

B. Astrobiological Studies of Europa.

Co−I Ron Greeley's group completed a study of the "mitten" feature on Europa, which represents the extrusion of ice onto the surface from a subsurface source (Figueredo et al. 2002). As such, the mitten structure comprises a high priority target for the future exploration of Europa to search for past or present life. Pole−to−pole geological mapping of Europa was also completed for strips representing the leading and the trailing hemispheres of Europa. This mapping was to explore for potential latitudinal or hemispheric asymmetries in ice fracture patterns. Studies of ice deformation in another region of Europa provided evidence for crustal fore−shortening, important for understanding deformation processes in Europa's crust. Each of the above activities helped to further characterize the nature and evolution of surface−near−surface environments on Europa needed to further assess the potential for habitable zones of subsurface liquid water. It was concluded from an analysis of domes and other features on Europa that they are geologically young and appear to have brought material to the surface from beneath the ice crust. Additional global geological mapping of Europa was also initiated during Year 5 as a first step toward identifying key sites for future surface exploration of Europa. Current data for Europa obtained by the Galileo project are also being analyzed to further understand the potential for europan environments conducive for life (Figueredo et al. in press).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Astrobiological Exploration of Mars

Lead Team:	***Arizona State University***
Project Title:	***Astrobiological Exploration of Mars***
Project Investigators:	***Jack Farmer , Philip Christensen , Ronald Greeley***

Project Progress

During Year 5 of NAI membership, we completed our remote sensing analog studies of the Badwater Basin in Death Valley designed to evaluate spatial resolution detectability thresholds for a variety of evaporite minerals under natural geological conditions (e.g. complex mixtures involving silicates) and at the spatial resolutions of the Thermal Emission Spectrometer (TES) and Thermal Emission Imaging System (THEMIS) instruments, both of which are presently mapping from Mars orbit. The work had two basic thrusts: Predictive mapping of surface mineralogy using high altitude remote sensing (MASTER) data and the Environment for Visualizing Images (ENVI) analysis tools, as well as ground truth, involving field spectroscopy and lab determinations of mineralogy. This work was submitted to the Journal of Geophysical Research−Planets and is presently in review. The basic findings follow: At TES resolution (3 km/pixel), carbonate abundances were at the detection limit in Death Valley, while sulfates were not detectable. However, at THEMIS spatial resolution (100 m/pixel), both carbonates and sulfates were detectable. The flat responses of halite in the mid−infrared (IR) rendered it essentially invisible at both resolutions. The next phase of this research will examine the spectral resolution thresholds for the same data sets. This work formed the basis for a Masters Thesis by Alice Baldridge, who defended last year and is presently in the PhD program at ASU.

A second study completed during Year 5 was a study of the margins of the Martian North polar remnant ice cap to search for sites of possible magma−cryosphere (volcano−ice) interactions. The study commenced with broad photogeological reconnaissance using Viking data to identify potential water−formed geomorphic features. This was followed by detailed studies at four sites, selected to cover a range of potential processes. Hypotheses posed for the origin of geomorphic features were tested using Mars Orbiter Laser Altimeter (MOLA) data and geographic−information−system (GIS) tools (e.g. Digital Elevation Models) and comparisons to terrestrial analogs. In the course of this work, we discovered that MOLA data are sensitive to subglacial topography in areas that have been recently deglaciated, but are now covered by snow. This ability to see through the ice has opened up our access to polar

geological history using MOLA topography. In addition, the hypothesis of a pseudocrater origin for a small field cinder cone−like features was tested using MOLA data. It was determined that they are more likely of a subglacial origin, but still formed by a process involving liquid water. At another site, we discovered that small coniform features hypothesized to be of volcanic origin are likely of a volcanic origin and that associated channels may have been formed by hydrothermal outflows. Finally, we investigated the margins of Chasma Boreal, a major re−entrant feature in the North polar cap margin and two associated chasmata. We documented additional evidence to support a formation by subglacial outfloods along the ice margin very recently in Martian history. The first three of the study sites have been written up and submitted to the Journal of Geophysical Research−Planets and Icarus. Our study of the Chasma Boreal site is still in progress and awaiting new data releases from THEMIS expected in the Fall. The above studies formed the basis for a Masters thesis by Meredith Payne, who successfully defended in December 2002 and is now enrolled in a PhD program at ASU.

A highlight of Year 5 was the publication in Science of a paper by Co−I Christensen that provided an alternative hypothesis for the origin of the numerous seep sites identified previously by Mailn and Edgett with Mars Orbiter Camera (MOC) data. Christensen's paper, based on THEMIS visible imaging, suggests that the seeps could have formed beneath snow−pack that accumulated during a recent period of low obliquity, and not by outflows of subsurface water (e.g. hydrothermal brines) as previously suggested.

Reconnaissance studies of Astrobiology landing sites on Mars for the Mars Exploration Rover mission (successfully launched in June), and detailed studies of the Gusev Crater site constituted another major focus of the project during Year 5. Gusev was selected as the site for the first MER landing, scheduled to occur in January 2004. Detailed studies of the second landing site for MER, the hematite site at Meridiani Planum, were also carried out incorporating new imaging data from the Odyssey Mission. Results of these Mars landing site studies were presented at a community landing site workshop, to the Mars Exploration Assessment Group (MEPAG), and to the MER project team.

In addition to planning for NASA missions, Ronald Greeley also participated extensively in planning for the Mars Express mission, which was successfully launched by the European Space Agency in 2003. Greeley is a Co−Investigator on the German High Resolution Stereo Camera, and he provided our list of high priority imaging targets for Astrobiology to the High Resolution Stereo Camera] (HRSC) imaging team.

Highlights

- Odyssey THEMIS imaging of seep sites on Mars suggest they originated by internal melting of snowpack that accumulated during a recent period of low obliquity (Christensen 2003).

- A study of the margins of the North Polar cap of Mars suggests that several alternative periglacial processes operated during the very

recent past to provide potentially habitable environments for life (Payne and Farmer, submitted).

- Landing sites selected for the Mars Exploration Rover mission hold high interest for Astrobiology.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor mission	Research and analysis methods
1	Mars Odyssey mission	Research and analysis methods
2	Mars Exploration Rover mission	Team members (Farmer, Christensen and Greeley), planning and support, background research.
3	Mars Reconnaissance Orbiter	Background research and analysis methods.
4?	Mars Science Laboratory (MSL) 2009	Background research and analysis methods; landing site selection; instrument and payload development.
1	Mars Express Mission	Team member (Greeley), planning and support, background research.
1	SCIM Mission (Scout mission; Phase A studies)	Leshin is PI; Greeley is a Co−I.
2	ARES mission (Scout concept, not yet selected)	Greeley and Farmer, Co−I's.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission

Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The strategy for Mars Exploration includes orbiters, landers, and eventual sample return. In support of planning for these missions, we are studying various potential sites for future landers and targeting sites for acquisition of data by orbiting spacecraft. This latter activity was undertaken as part of the science team on the Mars Express mission, and the Mars Exploration Rovers.The research carried out during Year 5 was important in the development of new methods of data analysis for Mars missions that in progress, as well as the Astrobiology landing site selection and payload development concepts that may be implemented during future Mars missions beginning in 2009.

Field Expeditions

Field Trip Name: Death Valley, Badwater Basin	
Start Date: 05/15/03	***End Date:*** 05/25/03
Continent: North America	***Country:*** United States
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** Evaporite playa
Description of Work: Field work carried out in Death Valley in connection with remote sensing analog study of playa evaporite environments.	
Members Involved: Jack Farmer	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Chasing water on Mars: A geochemical approach using martian meteorites

Lead Team:	***Arizona State University***
Project Title:	***Chasing water on Mars: A geochemical approach using martian meteorites***
NAI−NRC Postdoctoral Fellow :	***Michelle Minitti***

Project Progress

The Martian magmatic water reservoir represents an important portion of the Martian water cycle because it is linked to the atmospheric and hydrospheric reservoirs of water through degassing of the Martian interior. Understanding the Martian magmatic water reservoir places constraints on the atmospheric and hydrospheric reservoirs, both of which are important for the development and sustenance of life on Mars. Insight into the magmatic reservoir is available through the study of amphibole, a water−bearing mineral in Martian meteorites whose origin is tied to the presence and amount of magmatic water. Understanding the tie is complicated by the low water contents and enriched (D−rich) and variable H isotopic compositions of the amphiboles. The goal of the project is to investigate the effect of impact shock, a process known to drive off water and enrich H isotopic compositions in geologic materials, on water and H isotopes in amphibole. Constraining the degree to which impact shock influenced the water contents and H isotopic compositions of Martian meteorite amphiboles clarifies the tie between the amphiboles and the Martian magmatic water reservoir.

The first part of the project involved investigating the effect of impact shock in naturally shocked samples. We acquired shocked amphibole−bearing samples from Haughton Crater (Canada) and analyzed the H isotopic compositions of the most amphibole−rich samples with the Cameca IMS 6f ion microprobe at Arizona State University. Each analyzed sample experienced shock pressures equivalent to those experienced by the amphibole−bearing Martian meteorites (25−40 GPa). The most D−rich composition measured in the Haughton Crater shocked samples was ~0‰, and the maximum variation in H isotopic composition within a sample was ~50‰. Neither value is consistent with a significant shock−related effect on H isotopic composition; however, unshocked equivalents of the analyzed samples have been located and will be analyzed in order to confirm this finding.

The second part of the project involved investigating the effect of impact shock

in laboratory−shocked samples. We acquired a set of amphibole megacrysts and subjected them to shock of ~30 GPa in the 20 mm powder gun located in the Shock Wave Laboratory at Caltech. Pre− and post−shock water contents and H isotopic compositions were analyzed by ion microprobe. Impact shock consistently led to H isotopic enrichments of 50−90‰ but also led to increases in amphibole water content of 0.2−0.6 wt.% H_2O. Possible explanations for the combined result of water gain and H isotopic enrichment include shock−induced implantation of water or oxidation of the amphiboles. Alternative analysis techniques including XANES, water extraction and mass spectrometry are currently being utilized to explain the results. Preliminary modeling of the results suggests that while the laboratory impact shock influenced the amphibole water contents and H isotopic compositions, the size of the effect is not significant relative to the water contents and H isotopic compositions of Martian meteorite amphiboles.

Highlights

- The unique water contents and H isotopic compositions of Martian meteorite amphiboles were not significantly influenced by the impact shock that blasted the meteorites off of Mars. Thus, the conclusion (Leshin, 2000) that the Martian amphibole water contents and H isotopic compositions imply a Martian crustal water reservoir two times greater than previously suspected is valid.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	SCIM (Sample Collection for Investigation of Mars)	Planning support, background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The Sample Collection for Investigation of Mars (SCIM) mission is among the four finalists for the first NASA Scout Mission opportunity. SCIM will return atmospheric dust and gas from Mars, providing the first returned samples of Mars for study in terrestrial laboratories. Among the science goals of SCIM with astrobiological implications are understanding the weathering environment of the Martian surface and determining the precise isotopic composition of the Martian atmosphere.

Cross Team Collaborations

Tom Ahrens, JPL/California Institute of Technology: Dr. Ahrens acted as a Collaborator on the laboratory impact shock experiment project by overseeing the design and construction of impact experiment vessels and operation of powder gun for impact experiments. His involvement enabled the project that led to insights into the effects of impact shock on geologic materials that otherwise could not have been obtained.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Cosmochemistry of Carbonaceous Meteorites

Lead Team:	***Arizona State University***
Project Title:	***Cosmochemistry of Carbonaceous Meteorites***
Project Investigators:	***Laurie Leshin , Sandra Pizzarello***

Project Progress

Accretion modeling coupled with D/H data produced consistent water delivery scenarios for Earth and Mars (Lunine et al., 2003).

Preliminary results from terrestrial and experimentally shocked minerals showed low D−enrichment, supporting the hypothesis that high D/H rations in Martian rocks do not result from shock (Minitti et al, in prep.).

Carbonaceous chondrite analyses provided constraints on aqueous environments on asteroids (Airieau et al., 2003; Benedix et al., 2003).

C isotope data provided new constraints on magmatic and surficial carbon reservoirs in the Martian carbon cycle (Goreva et al., 2003, Niles et al., in prep.).

Highlights

- See accomplishments

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Sample Collection for	Leshin is PI of SCIM, in Phase

	Investigation of Mars (SCIM)	A concept study
2	Comet Surface Sample Return (CSSR)	Leshin is Co−I on New Frontiers proposal in formulation stage

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Early Environments

Lead Team:	***Arizona State University***
Project Title:	***Early Environments***
Project Investigator:	***Paul Knauth***

Project Progress

This year we published 3 papers. One dealt with isotopic variations in caliche developed on basalt and stressed implications for the search for past life on Mars as well as a new suggestion for the origin of carbonate in ALH 84001. We claim that isotopic variations in such caliche are actual isotope biosignatures independent of knowledge of past or present isotopic reservoirs. A second paper presented O isotope data for cherts in Archean cherts and argued that the Earth 3.5 billion years ago had climatic temperatures on the order of 50−70 degrees C. The 3rd paper dealt with the early hydrosphere of Mars and argued that remnant brines should still be present in the megaregolith if Mars indeed had a "warm, wet, early period". A test using remote geophysical prospecting was suggested.

A new manuscript that describes the geologic context of the 1.2 Ga palekarst that hosts the world's oldest onland microfossils was written and submitted. An additional manuscript is in preparation describing cave deposits associated with the paleokarst and presents evidence for microfossils entombed in these deposits.

A survey for entombed microfossils and organic materials in modern caliche in basalts is being concluded. This is to demonstrate the potential of caliche on basalt as a host medium for possible microfossils in caliche on Mars (which must be present if Mars indeed had a warm, wet early period).

Highlights

- Caliche developed on basalt on Earth contains a robust isotopic biosignature. If Mars had a warm wet early period, caliche would have developed and this can be easily searched for and sampled for possible presence of the isotopic biosignature.

- An exhaustive evaluation of O isotopes in Archean cherts indicates that Arcean climatic temperatures were on the order of 50−70 degrees C.

- Eutectic brines ("DEVIL BRINES") must be present in the Martian

megaregolith if 1) Mars outgassed a hydrosphere, 2) lost most of this hydrosphere early on to space and 3) subsequently froze down. Such brines could account for some of the apparent seeps and suggest that the early Martian hydrosphere was incredibly salty.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Martian hydrosphere, biomarkers	New ideas for testing hypotheses about martian hydrosphere and early life −− not part of current or planned missions.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These are new ideas for how to test hypotheses regarding early fluids and possible early life on Mars. Came out of Astrobiology research program but has not been carried to mission planners.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Evolution in microbe−based ecosystems: Desert springs as analogues for the early development and stabilization of ecological systems

Lead Team:	***Arizona State University***
Project Title:	***Evolution in microbe−based ecosystems: Desert springs as analogues for the early development and stabilization of ecological systems***
Project Investigators:	***James Elser , Jack Farmer***

Project Progress

During the past year we completed 4 expeditions and initated a 5th to our field site at Cuatro Cienegas, Mexico. The main focal point of the year's work was an 8−week field experiment during summer 2002 examining the effects of snail grazers and PO^4 enrichment on the biomass, productivity, C:P stoichiometry, and microbial community structure of oncoid stromatolites. In turn, we also examined the effects of PO^4 enrichment on snail growth rate, ribonucleic acid: deoxyribonucleic acid (RNA:DNA) ratio, and population change. The experiment revealed that snails had no discernible impact on the stromatolites but PO^4 had massive impacts on stromatolite productivity, communitry structure, and C:P stoichiometry. In turn, PO^4 enrichment had major impacts on the snails, resulting in greatly reduced growth rates and increased mortality. This outcome is in contrast to our experiment in 2001 in which stromatolite P enrichment led to increased snail performance. We have now developed a hypothesis that snails at Cuatro Cienegas live on a "stoichiometric knife's edge" in which stromatolite C:P ratios are excessively high in the field but where large P enrichments can poison them. Another important activity from the past year was the use of molecular microbial analyses to confirm that subterranean water being tapped by agricultural pumping outside of the basin is in communication with the springs at Cuatro Cienegas. This finding led to unprecedented conservation measures being imposed in the basin and surrounding region via strong actions from the highest level of the Mexican government. We also successfully completed field experiments documenting that endemic pupfishes in the basin are locally adapted to environmental conditions and thus shifting hybrid zones are driven by seasonal and longer−term environmental perturbations. Our work also continues to highlight extremely high levels of biological diversity in snail fauna and in microbes at Cuatro Cienegas.

Highlights

- "Life on a chemical knife edge". NAI researchers have used field experiments with living stromatolites representative of Earth's earliest life forms to show that these communities are extremely sensitive to the supply of the key limiting nutrient phosphorus (P). These results suggest that P availability on the early Earth may have played a major role in early ecology, including possible limitations on the emergence of higher animals prior to the Cambrian explosion.

- "Microbial fingerprints implicate environmental wrong−doing." Using techniques of DNA analysis that identify the species of microbes present in water samples, NAI researchers have demonstrated that illegal water extraction by large agricultural operations was tapping into water supplies supporting the desert springs at Cuatro Cienegas, one of Mexico's natural treasures. Based on these findings, officials at the highest level of the Mexican government shut down the pumping operations, punished those responsible, and implemented new regional measures to protect Cuatro Cienegas' ecosystems, which harbor innumerable forms of unique microbial, plant, and animal species.

- "There's no place like home for this desert fish." NAI researchers have used field experiments to show that an endemic species of desert pupfish that inhabits the relatively benign environment in the headspring pool of its desert drainage can't cope with local conditions at the other end of their thermal spring habitat where temperature and salinity can reach extreme levels. Nevertheless, a closely related species thrives there. The two species hybridize actively in intermediate habitats and thus these taxa present a classic example of local adaptation to the environment.

- "Each snail tells a story." New research by a team of NAI investigators is showing that the reconstruction of modern and subfossil thermal springs − including their spatial, environmental and ecological conditions − can be made with gastropod community compositions and morphologies. Statistically distinct shapes and community compositions can be correlated with specific hydrological and microgeographic variables.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Summer 2002	
Start Date: June 18 2002	***End Date:*** August 10 2002
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:***
Latitude: 26 50 00	***Longitude:*** 101 02 00
Name of site(cave, mine, e.g.):	***Keywords:*** limnology, genetics, food webs, diversity
Description of Work: Field sampling and experimentation associated with stromatolite, microbial, and metazoan studies in various habitats at Cuatro Cienegas field site.	
Members Involved: James Elser	

Field Trip Name: October 2002	
Start Date: October 5 2002	***End Date:*** October 17 2002
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:***
Latitude: 26 50 00	***Longitude:*** 101 02 00
Name of site(cave, mine, e.g.):	***Keywords:*** limnology, genetics, food webs, diversity
Description of Work: Field sampling associated with stromatolite, microbial, and metazoan studies in various habitats at Cuatro Cienegas field site. Filmed and interviewed at field site by Italian film crew for Naitonal Geographic International special on Cuatrocienegas Basin.	
Members Involved: John Schampel	

Field Trip Name: January 2003	
Start Date: January 2 2003	***End Date:*** January 17 2003
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:***
Latitude: 26 50 00	***Longitude:*** 101 02 00
Name of site(cave, mine, e.g.):	***Keywords:*** limnology, genetics, food webs, diversity
Description of Work: Field sampling and experimentation associated with stromatolite, microbial, and metazoan studies in various habitats at Cuatro	

Cienegas field site.	
Members Involved: John Schampel	

Field Trip Name: March 2003	
Start Date: March 12 2003	***End Date:*** March 23 2003
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:***
Latitude: 26 50 00	***Longitude:*** 101 02 00
Name of site(cave, mine, e.g.):	***Keywords:*** limnology, genetics, food webs, diversity
Description of Work: Field sampling and experimentation associated with stromatolite, microbial, and metazoan studies in various habitats at Cuatro Cienegas field site.	
Members Involved: John Schampel	

Field Trip Name: Summer 2003	
Start Date: June 12 2003	***End Date:*** August 10 2003
Continent: North America	***Country:*** Mexico
State/Province: Coahuila	***Nearest City/Town:***
Latitude: 26 50 00	***Longitude:*** 101 02 00
Name of site(cave, mine, e.g.):	***Keywords:*** limnology, genetics, food webs, diversity
Description of Work: Field sampling and experimentation associated with stromatolite, microbial, and metazoan studies in various habitats at Cuatro Cienegas field site.	
Members Involved: James Watts	

Cross Team Collaborations

Collaborative work involving Elser, Farmer, and Garcia−Pichel integrates activities across ASU NAI teams. C. Tang and V. Souza have been interacting with Dr. Monica Medina, who was an NAI student in Mitch Sogin's lab (MIT) and is currently employed at the Joint Genomics Institute in California. The group is collaborating on molecular analyses of snail populations from Cuatro Cienegas.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Exploring the Living Universe; Origin, Evolution and Distribution of Life in the Solar System (Europa)

Lead Team:	***Arizona State University***
Project Title:	***Exploring the Living Universe; Origin, Evolution and Distribution of Life in the Solar System (Europa)***
Project Investigator:	***Jack Farmer***

Project Progress

1. We analyzed domes and other features on Europa that are geologically young and that appear to have brought material to the surface from beneath the ice crust.
2. We initiated global geological mapping of Europa, as the first step in identifying key sites for future exploration.
3. We interacted with colleagues through the NAI Europa Focus group.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Galileo	Member of the science flight team
2	JIMO	Co−chairman, NASA Science Definition Team
3	Europa Lander	Science definition

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)

3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Current data for Europa obtained by the Galileo project are being analyzed to understand the potential environments conducive for organic evolution.

In addition, planning is underway by several groups for potential missions to Europa. We are making input to these studies to guide the astrobiological exploration.

Field Expeditions

Field Trip Name: Arctic Ice Field Conference	
Start Date: 22 April 2003	***End Date:*** 27 April 2003
Continent: North America	***Country:*** United States
State/Province: Alaska	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Examination of sea ice	
Members Involved: Ronald Greeley	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Impacts and the Origin, Distribution, and Evolution of Life

Lead Team:	***Arizona State University***
Project Title:	***Impacts and the Origin, Distribution, and Evolution of Life***
Project Investigators:	***David Kring , Jack Farmer***

Project Progress

We determined the distribution of impact−generated wildfires for the Chicxulub impact event and illustrated how impact parameters (e.g., trajectory) can influence the distribution of wildfires.

D.A. Kring and D.D. Durda, "Trajectories and distribution of material ejected from the Chicxulub impact crater: Implications for post−impact wildfires," *J. Geophys. Res.* 107(E8), pp. 6−1 through 6−22, 10.1029/2001JE001532, 2002.

In an invited review paper, we outlined the environmental and biologic effects of large impact events, like Chicxulub, throughout Earth history.

D.A. Kring, "Environmental consequences of impact cratering events as a function of ambient conditions on Earth," *Astrobiology* 3(1), 133−152, 2003.

We continued to analyze lunar impact melts, to determine the flux of impact cratering events in the Earth−Moon system, particularly in the first billion years of Earth's history.

I.J. Daubar, D.A. Kring, T.D. Swindle, and A.J.T. Jull, "Northwest Africa 482: A crystalline impact melt breccia from the lunar highlands," Meteoritics Planet. Sci. 37, 1797−1813, 2002.

B.A. Cohen, T.D. Swindle, and D.A. Kring, "Geochemistry and Ar_40_Ar_39 geochronology of impact melt clasts in lunar highlands meteorites: Implications for lunar bombardment history," *Meteoritics Planet. Sci.*, submitted 5/2002.

In an invited review paper, we also explored the delivery of Earth's water, a key ingredient for life, through impact events.

H. Campins, T.D. Swindle, and D.A. Kring, "Evaluating comets as a source of Earth's water," in *Origin, Evolution, and Biodiversity of Microbial Life in the Universe*, J. Seckbach (ed.), Kluwer Academic Publishers, in press, 5/2003.

We initiated our final year's study of impact−generated hydrothermal systems, which may have been a particularly important habitat for the early evolution of life on Earth.

O. Abramov and D.A. Kring, "Finite−difference modeling of impact−induced hydrothermal systems (extended abstract)," *Lunar and Planetary Science XXXIV*, Abstract #1846, Lunar and Planetary Institute, Houston (CD−ROM), 2003.

D.A. Kring, "Potential habitats in impact−generated hydrothermal systems," Goldschmidt Conference, invited for fall 2003 meeting in Japan, submitted 5/2003.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Microbial Fossilization Processes in Extreme Environments

Lead Team:	***Arizona State University***
Project Title:	***Microbial Fossilization Processes in Extreme Environments***
Project Investigator:	***Jack Farmer***

Project Progress

During Year 5 of NAI membership, we completed a study of the fossilization processes associated with oncoids (spherical stromatolites) of the Rio Mesquites in the Cuatro Cienegas Basin, Central Mexico. This was done in collaboration James Elser's group, who have been studying the ecological aspects of the same system. We determined that surface biofilms have a bilayered community structure, with the upper zone being dominated by several groups of larger, mostly erect−growing filamentous cyanobacteria and many species of diatoms. Microelectrode studies show that these surface species control precipitation of calcium carbonate through photosynthesis. However, at a depth of 1−2 mm below the biofilm surface, a second community is dominated by smaller filamentous species. This community is associated with pervasive carbonate precipitation that entombs the deeper community, preserving numerous cellular remains. At this depth in the bi−layered biofilm, the surface community is largely excluded, creating a strong taphonomic bias that favors preservation of the subsurface community. Larger filamentous forms of the surface community are rarely preserved in the oncoid interior and upon death, diatom remains (siliceous frustrules) appear to undergo rapid dissolution under the alkaline conditions that prevail in the surface biofilm environment. The basic results of this study were presented as a poster at the NAI General meeting and are presently being written up for publication.

A second study, started during Year 5, involves the characterization of biofilms and microbial fossil assemblages associated with low temperature carbonate−precipitating springs on the floor of Mono Lake, an alkaline−saline lake located in eastern California. The goal of the study is to trace the fate of biosignatures during carbonate precipitation and early diagenesis. The results of the work in Mono Lake will be compared with ancient carbonate spring deposits elsewhere in the Mono Basin that were formed during the last glacial period when the lake was much deeper and colder. The work in the Mono Basin involves collaboration with the Woods Hole team, who will be focusing on the eukaryotic biodiversity of the lake biota.

Highlights

- Studies in karst ponds and streams of the Cuatro Cienegas Basin link the origin of stromatolites (oncoids) and basic fossilization processes to microbial photosynthesis.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars Exploration Rover mission	Basic research and analysis methods
3	Mars Science Laboratory (MSL) '09 mission	Basic research and analysis methods

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Studies of microbial fossilization processes and the origin and preservation of fossil biosignatures in the aqueous sedimentary deposits of extreme environments provides an important context for planning future missions to Mars aimed at exploring for evidence of past life.

Field Expeditions

Field Trip Name: Cuatro Ciengas	
Start Date: 08/03/02	***End Date:*** 08/09/02
Continent: North America	***Country:*** Mexico

State/Province: Jalisco	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Rio Mesquites	***Keywords:*** Karst spring stromatolites
Description of Work: Field work was carried out in the Cuatro Cienegas basin, central Mexico, to study the preservation of biosignatures in oncoids of the Mesquites River. This work was closely interfaced with ecological work conducted by PI James Elser and his collabrators under another module of the ASU proposal.	
Members Involved: Jack Farmer	

Field Trip Name: Mono Lake	
Start Date: 05/20/03	***End Date:*** 05/28/03
Continent: North America	***Country:*** USA
State/Province: CA	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Mono Lake	***Keywords:***
Description of Work: Field work focused on the collection of tufa and biofilm samples for the purpose of laboratory characterization by SEM and light microscopy, culturing of organisms and molecular analysis to assess biofilm composition.	
Members Involved: Jack Farmer	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Nanoscale minerals as biomarkers

Lead Team:	***Arizona State University***
Project Title:	***Nanoscale minerals as biomarkers***
Project Investigator:	***Peter Buseck***

Project Progress

Using electron tomography, we showed that there is too much uncertainty in any transmission−electron−microscopy (TEM) results to date to confirm a biogenic origin for the magnetite in meteorite ALH84001. The magnetite crystals in bacterial strain MV−1, the standard for comparison for meteoritic magnetite, show variations within a chain and rounding of faces, which are neither as well developed nor as crisp as in published interpretations.

We implemented the acquisition and processing of digital three−dimensional (3−D) tomograms using several distinct methods of TEM imaging, which has involved the development of automated acquisition systems for two TEMs. One of these systems is fully implemented, and the other is in the process of testing and debugging. These modifications will allow computer control of the sample stage, electron beam, and focussing current so that the acquisition of a tilt−series of images (140 images) can be accomplished far more rapidly and with higher fidelity than if done "by hand." The several acquisition modes will allow us to extract complementary signals to fully characterize the crystallites.

We made modifications to accommodate differences in images arising from different acquisition modes. Visualization and extraction of quantitative data from the reconstructed 3−D data cube is an essential aspect of this research. Algorithms are being tested to define the boundaries of interior objects of different densities so that volume and bounding surface data can be obtained reliably.

We studied whether the characteristics of crystal size distributions (CSDs) and shape factor distributions (SFDs) of magnetite from magnetotactic bacteria can be used as biomarkers. CSDs of magnetite from 16 uncultured strains revealed both similarities and differences among crystals from bacteria from distinct localities and environments. Using a numerical method, we sorted magnetite crystal populations based on features of the SFD of all particles. We found that the numerical methods are useful for identifying bacterial magnetite in rocks.

Highlights

- Using electron tomography, we showed there is too much uncertainty in any TEM results to date to confirm a biogenic origin for the magnetite in meteorite ALH84001.

- Magnetite crystals in bacterial strain MV−1, the standard for comparison for ALH84001 magnetite, show variations within a chain and rounding of faces that are not as well developed or as crisp as in published interpretations.

- Progress has been made in developing automated procedures for electron tomographic data acquisition, reconstruction, and visualization.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Biomarkers	Co−I

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Organic Synthesis at High Temperature

Lead Team:	***Arizona State University***
Project Title:	***Organic Synthesis at High Temperature***
Project Investigators:	***John Holloway , Peggy O'Day***

Project Progress

We have advanced a corollary to our previously published hypothesis that degassing of seafloor basaltic magmas provides hydrogen and carbon dioxide for abiotic organic syntheses (Holloway O'Day, 2000) by demonstrating that the same processes can operate with more silicic magmas (Holloway, submitted).

We have demonstrated that smectite clay minerals, commonly found in seafloor hydrothermal systems, provide reactive sites for synthesis of complex organic compounds such as hexamethylbenzene and long−chain methyl esters from aqueous methanol solutions (Williams, et al., 2002; Canfield, et al., 2003). This research is ongoing. We are continuing to explore synthesis of organic compounds from hydrogen and carbon dioxide in the presence of mineral catalysts at seafloor hydrothermal conditions.

We are continuing to develop novel tools for studying hydrothermal microhabitats. We are using synchrotron computed microtomography to study the physical structure of young hydrothermal chimneys from 9°N East Pacific Rise. This analysis shows a loosely connected network of euhedral mineral grains (predominantly sulfide by bulk X−ray diffraction measurements) and no channelized flow, such that the physical structure is dominated by porosity (i.e., fluid) rather than minerals. This physical structure may serve as an effective molecular sieve for the adsorption of organic compounds and bacteria from vent fluid and seawater, and provides a model for how organic compounds may accumulate on surfaces under pre−biotic conditions.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Extreme 2002, Atlantis/Alvin cruise to 9°N East Pacific Rise	
Start Date: 10/20/02	***End Date:*** 11/12/02
Continent: Pacific Ocean	***Country:*** Pacific Ocean
State/Province:	***Nearest City/Town:***
Latitude: 9°N	***Longitude:*** 105°W
Name of site(cave, mine, e.g.): 9°N EPR	***Keywords:*** seafloor hydrothermal systems
Description of Work: We participated in the Extreme 2002 cruise to 9°50'N East Pacific Rise (EPR) with the DSV Alvin led by chief scientist S.C. Cary (Univ. of Delaware). We developed and tested new microcosms that can be deployed on diffuse−flow vents for periods of days to weeks in order to collect microorganisms and fragile young chimney samples intact. Our approach is to simulate the mixing environment of the chimney, to supply microbes with attractive mineral surfaces for colonization, and to grow natural chimneys on the microcosm that can be retrieved intact. We have instrumented one of the microcosms for continuous temperature monitoring and sampling of fluid from the chamber interior. These devices allow us to examine the habitats of extreme microorganisms in situ and enable retrieval of previously unknown microorganisms.	
Members Involved: Peggy O'Day	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Evolutionary Connection between Photosynthesis and Nitrogen Fixation

Lead Team:	***Arizona State University***
Project Title:	***The Evolutionary Connection between Photosynthesis and Nitrogen Fixation***
NAI−NRC Postdoctoral Fellow :	***Christopher Staples***

Project Progress

The title of my research plan is "The Evolutionary Connection between Photosynthesis and Nitrogen Fixation." In conducting my research here at Arizona State University, I have made collaborations with individuals performing phylogenetic analyses of whole genomes of 101 organisms in search of homologs of certain proteins involved in nitrogen fixation and bacteriochlorophyll synthesis. This has allowed us to find deeply branching possible relic proteins in many organisms, including in methanogens that are not known to perform nitrogen fixation, and are not photosynthetic. A radial plot showing the relationship between Bch, Nif, and the uncharacterized Nif−like proteins is shown in Figure1. I have collaborated with Biswarup Mukhadpadyay at Virginia Tech to examine the possible role for the Nif−like proteins (e.g. a non−specific reductase or a detoxyase, etc). I have cloned and expressed in *E. coli* five out of six proteins I will be using in this comparative study (four are Bch proteins and two are relic proteins related to both Bch and Nif proteins). Of these I have purified four and partially purified the fifth. I am working on a system for the overexpression of the Bch proteins in *R. capsulatus* (to which four out of six proteins I am working on are native), and have progressed in this endeavor. Initial characterization of some of the proteins has been conducted. Characterization of these proteins will reveal the specific changes in amino acid residues necessary to bring about changes in enzyme substrate specificity. Knowledge of this will allow us to determine the evolution of the enzyme from precursors. Furthermore, the different substrate specificities of Bch proteins and Nif−like proteins will allow us to infer substrates utilized by early Earth organisms and tell us something about the conditions in which life lived on the early Earth.

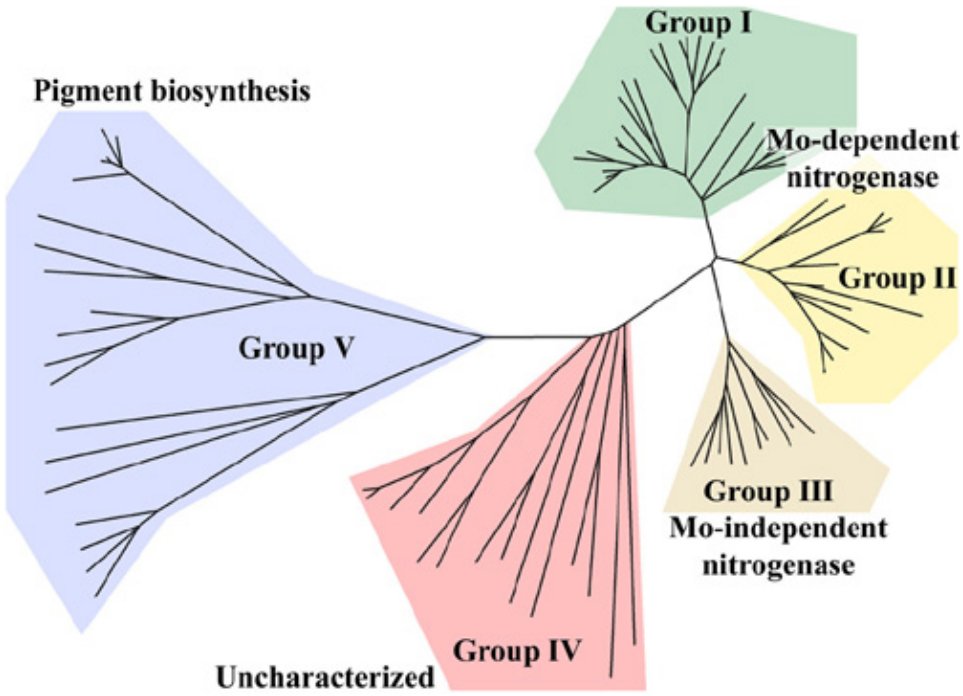

Figure 1 *Diagram showing the phylogenetic relationship of nitrogenase proteins (Groups I, II, III) to bacteriochlorophyll synthesis proteins (Group V). The atypical nif−like sequences (Group IV) lie basal to both groups.*

Highlights

- We have searched 101 reported whole genomes for NifH and NifD/K homologs and have found there lies a group of uncharacterized genes basal to both the Bch and Nif clades. These genes are scattered throughout the methanogens and some phototrophs and may represent a relic precursor protein to both Bch and Nif proteins.

- We have written a paper describing the natural history of nitrogenase and have submitted it to the Journal of Molecular Evolution.

- We have found that the NifH homologs BchL and BchX have very similar electron paramagnetic resonance spectroscopic signatures to NifH, suggesting they are quite similar in tertiary and quaternary structure. This is consistent with the high degree of sequence identity among these proteins.

- I was an invited speaker to the NASA Astrobiology Institute General Meeting, and was able to present my preliminary findings.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: Arizona State University

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Michelle Minitti
Project Title: Chasing water on Mars: A geochemical approach using martian meteorites
Advisor: Laurie Leshin, Advisor
NAI Lead Team: Arizona State University
Fellowship Began In: August 2001

Recipient: Christopher Staples
Project Title: The Evolutionary Connection between Photosynthesis and Nitrogen Fixation
Advisor: Robert Blankenship, Advisor
NAI Lead Team: Arizona State University
Fellowship Began In: July 2002

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

EPO: Arizona State University

These are the Education and Public Outreach activities for the Arizona State University.

Publications: Arizona State University

Arató, B. Pósfai, M. (2003). Crystal size distributions of magnetite from magnetotactic bacteria: Criteria for identifying biogenic particles in rocks [Abstract]. EGS−AGU−EUG Joint Assembly 2003, Nice, France. *Geophysical Research Abstracts, Vol. 5, Magnetism and Rock Physics Programme*. Abstract EAE03−A−10190.

Benedix G.K., Leshin L.A., Farquhar J., Jackson T.L. Thiemens M.H. (2003). Carbonates in CM2 chondrites: Constraints on alteration conditions from oxygen isotopic compositions and petrographic observations. *Geochimica et Cosmochimica Acta*, 67: 1577−1588.

Burt, D.R. Knauth, L.P. (2003). Electrically conducting, Ca−rich brines, rather than water, expected in the Martian subsurface. *Journal of Geophysical Research − Planets*, 108(E4): doi:10.1029/2002JE001862.

Buseck, P.R., Weyland, M., Midgley, P.A., Dunin−Borkowski, R.E. Frankel, R.B. (2003). Are current TEM techniques adequate to resolve the ALH84001 life−on−Mars controversy? [Abstract]. *Abstracts of Papers, Thirty−Fourth Lunar and Planetary Science Conference, Houston, TX*. Abstract #2044.

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NASA ASTROBIOLOGY INSTITUTE
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Members: Arizona State University

Team Members sorted by current team.

Name:	Oleg Abramov
Institution:	University of Arizona
Name:	Erika Aguirre
Institution:	UNAM (Mexico)
Name:	Thomas Ahrens
Email:	tja@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Sabine Airieau
Institution:	University of California, San Diego
Name:	Dawn Ashbridge
Email:	ashbridge@asu.edu
Institution:	Arizona State University
Name:	Alice Baldridge
Email:	alice.baldridge@asu.edu
Institution:	Arizona State University
Name:	Carl Bauer
Email:	Cbauer@bio.indiana.edu
Institution:	Indiana University
Name:	Dennis Bazylinski
Email:	dbazylin@iastate.edu
Institution:	Iowa State University
Name:	Robert Blankenship

Email:	RBlankenship@asu.edu
Institution:	Arizona State University
Name:	Donald Burt
Email:	burt@asu.edu
Institution:	Arizona State University
Name:	Peter Buseck
Email:	pbuseck@asu.edu
Institution:	Arizona State University
Name:	Andrea Campusano
Institution:	UNAM (Mexico)
Name:	Evan Carson
Email:	evan.carson@asu.edu
Institution:	Arizona State University
Name:	S. Cary
Email:	caryc@udel.edu
Institution:	University of Delaware
Name:	Pablo Castillo
Institution:	UNAM (Mexico)
Name:	Rene Cerritos
Institution:	UNAM (Mexico)
Name:	Philip Christensen
Email:	Phil.Christensen@asu.edu
Institution:	Arizona State University
Name:	Ricardo Colin
Institution:	UNAM (Mexico)
Name:	Max Coon
Email:	max@nwra.com

Institution:	Northwest Res. Assoc.
Name:	Dennis Dean
Email:	deandr@vt.edu
Institution:	Virginia Tech.
Name:	Kelli Donnelly
Email:	juliet4always@yahoo.com
Institution:	Arizona State University
Name:	Thomas Dowling
Email:	thomas.dowling@asu.edu
Institution:	Arizona State University
Name:	Rafal Dunin−Borkowski
Email:	rafal.db@msm.cam.ac.uk
Institution:	University of Cambridge, UK
Name:	Eileen Dunn
Email:	EEDunn@aol.com
Institution:	Arizona State University
Name:	Darby Dyar
Email:	mddyar@amherst.edu
Institution:	Mount Holyoke College
Name:	Luis Eguiarte
Email:	fruns@servidor.unam.mx
Institution:	UNAM (Mexico)
Name:	James Elser
Email:	j.elser@asu.edu
Institution:	Arizona State University
Name:	Ana Escalante
Institution:	UNAM (Mexico)

Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Name:	James Farquhar
Email:	jfarquhar@ucsd.edu
Institution:	University of Maryland
Name:	Patricio Figueredo
Email:	patan@asu.edu
Institution:	Arizona State University
Name:	Tom Foltz
Email:	Foltz@asu.edu
Institution:	Arizona State University
Name:	Richard Frankel
Email:	rfrankel@calpoly.edu
Institution:	Cal Poly State University
Name:	Heiner Friedrich
Email:	heiner.friedrich@asu.edu
Institution:	Arizona State University
Name:	John Gable
Institution:	Arizona State University
Name:	Ferran Garcia−Pichel
Email:	ferran@asu.edu
Institution:	Arizona State University
Name:	Julia Goreva
Email:	jgoreva@asu.edu
Institution:	Arizona State University
Name:	Doug Grant

Email:	Frederick.Grant@asu.edu
Institution:	Arizona State University
Name:	Ronald Greeley
Email:	greeley@asu.edu
Institution:	Arizona State University
Name:	Yunbin Guan
Email:	Yunbin.guan@asu.edu
Institution:	Arizona State University
Name:	Victoria Hamilton
Email:	hamilton@higp.hawaii.edu
Institution:	University of Hawaii, Manoa
Name:	Jen Harden
Institution:	Arizona State University
Name:	John Holloway
Email:	john.holloway@asu.edu
Institution:	Arizona State University
Name:	Anne Kelsen
Email:	Anne.Kelsen@asu.edu
Institution:	Arizona State University
Name:	Paul Knauth
Email:	knauth@asu.edu
Institution:	Arizona State University
Name:	David Kring
Email:	kring@LPL.Arizona.Edu
Institution:	University of Arizona
Name:	Ruslan Kuzmin
Email:	rok@geokhi.ru

Institution:	Verndansky Institute
Name:	Laurie Leshin
Email:	laurie.leshin@asu.edu
Institution:	Arizona State University
Name:	Karla Lopez
Institution:	UNAM (Mexico)
Name:	Donald Lowe
Email:	lowe@pangea.stanford.edu
Institution:	Stanford University
Name:	Jonathan Lunine
Email:	jlunine@lpl.arizona.edu
Institution:	University of Arizona
Name:	Zita Maliga
Institution:	San Francisco State University
Name:	Amy McAdam
Email:	Amy.Mcadam@asu.edu
Institution:	Arizona State University
Name:	Martha McCartney
Email:	molly.mccartney@asu.edu
Institution:	Arizona State University
Name:	Kat McFadden
Email:	pitpatkitkat@hotmail.com
Institution:	Arizona State University
Name:	Paul Midgley
Email:	pam33@cus.cam.ac.uk
Institution:	University of Cambridge, UK
Name:	Michelle Minitti

Email:	Michelle.Minitti@asu.edu
Institution:	Arizona State University
Name:	Jeffrey Moersch
Email:	jmoersch@utk.edu
Institution:	University of Tennessee
Name:	Biswarup Mukhopadhyay
Email:	bmukhopa@vt.edu
Institution:	Virginia Tech.
Name:	Lynn Neakrase
Email:	lynn.neakrase@asu.edu
Institution:	Arizona State University
Name:	David Nelson
Email:	nelson99@asu.edu
Institution:	Arizona State University
Name:	Paul Niles
Email:	Paul.niles@asu.edu
Institution:	Arizona State University
Name:	Peggy O'Day
Email:	oday@asu.edu
Institution:	Arizona State University
Name:	Meredith Payne
Email:	mcpayne@asu.edu
Institution:	Arizona State University
Name:	John Peters
Email:	john.peters@chemistry.montana.edu
Institution:	Montana State University
Name:	Sandra Pizzarello

Email:	Sandra.Pizzarello@asu.edu
Institution:	Arizona State University
Name:	Mihaly Posfai
Email:	posfaim@almos.vein.hu
Institution:	University of Veszprém, Hungary
Name:	Jason Raymond
Email:	jasonraymond@asu.edu
Institution:	Arizona State University
Name:	Juriko Rios
Institution:	UNAM (Mexico)
Name:	Peter Roopnarine
Email:	proopnarine@calacademy.org
Institution:	California Academy of Sciences
Name:	Michael Rothrock
Email:	rothrock@asu.edu
Institution:	Arizona State University
Name:	Valeria Routt
Email:	Valeria.Routt@asu.edu
Institution:	Arizona State University
Name:	Steve Ruff
Email:	ruff@tes.la.asu.edu
Institution:	Arizona State University
Name:	Evan Saint−Pierre
Institution:	University of California, Santa Cruz
Name:	John Schampel
Email:	John.Schampel@asu.edu
Institution:	Arizona State University

Name:	Steve Skotnicki
Email:	Skotnicki@aol.com
Institution:	Arizona State University
Name:	Valeria Souza
Email:	souza@servidor.unam.mx
Institution:	UNAM (Mexico)
Name:	Christopher Staples
Email:	Christopher.staples@asu.edu
Institution:	Arizona State University
Name:	Carol Tang
Email:	ctang@calacademy.org
Institution:	California Academy of Sciences
Name:	Mark Thiemens
Institution:	University of California, San Diego
Name:	Mike Thomas
Email:	mdthomas@asu.edu
Institution:	Arizona State University
Name:	Kenneth Voglesonger
Email:	kendoo@imap4.asu.edu
Institution:	Arizona State University
Name:	Brian Wade
Email:	brian.wade@asu.edu
Institution:	Arizona State University
Name:	James Watts
Email:	j.watts@asu.edu
Institution:	Arizona State University
Name:	Matthew Weyland

Email:	mw259@cus.cam.ac.uk
Institution:	University of Cambridge, UK
Name:	Nathan Wilkens
Email:	Nathan.Wilkens@asu.edu
Institution:	Arizona State University

Carnegie Institution of Washington
Executive Summary
Principal Investigator: Sean Solomon

The team led by the Carnegie Institution of Washington is studying the physical, chemical, and biological evolution of hydrothermal systems, including vent complexes associated with ocean ridges, deep aquifers, and other subsurface aqueous environments, both on Earth and on other Solar System and extrasolar bodies. Such diverse systems are important environments for life on Earth and possibly elsewhere in the cosmos.

The traditional view of life's origin on Earth has focused on processes near the photic zone at the ocean−atmosphere interface, where ionizing radiation provides energy for prebiotic organic synthesis. In the context of astrobiology, this origin paradigm restricts the initial "habitable zone" around stars to planets and moons with surface water. According to this view, subsequent adaptations on Earth, and possibly elsewhere, led to expansion of the biosphere into subsurface habitats.

An alternative hypothesis is that life−forming processes may also occur in subsurface hydrothermal environments at the water−mineral interface. This hypothesis, that life on Earth originated from oxidation−reduction reactions in deep hydrothermal zones, perhaps at or near ocean ridge systems (Figure 1), opens exciting possibilities for astrobiological research. If a subsurface, high−pressure origin of life is possible, then the initial habitable zone around stars is greatly expanded to aqueous environments where redox reactions can be driven along thermal and chemical gradients.

The black smoker sulfide chimney Finn (A) was recovered from the Mothra Vent Field on the Endeavour Segment of the Juan de Fuca Ridge in July 1998. Finn was venting 302°C fluid upon recovery (B, close−up of Finn) and contained complex mineralogical gradients within its walls. The structure was sampled by Co−I Baross for co−registered microbiological and petrological studies. Attached microbial communities, some of which formed 10 ¼m−thick biofilms (C), were observed, by use of fluorescent probes, throughout the structure, including high−temperature regions near the central vent conduit.

Several lines of evidence lend credibility to the hydrothermal origins hypothesis. Numerous recent discoveries of high−pressure life, especially lithotrophic prokaryotes, suggest that hydrothermal environments support abundant life. Models of the Earth's formation postulate large,

surface−sterilizing impacts as recently as 3.8 billion years ago, but deep hydrothermal zones may have insulated life from these traumas. Studies of molecular phylogeny reveal that thermophilic microbes are perhaps the closest living relatives of the last universal common ancestor. Finally, hydrothermal organic synthesis experiments reveal unexpectedly facile synthetic pathways. Whether or not life originated in a subsurface hydrothermal zone, these lines of evidence, coupled with the assumed widespread distribution of such environments in our Solar System and elsewhere, point to the need and opportunity for an intense study of the characteristics of hydrothermal systems.

Our consortium's research activities explore the physical, chemical, and biological evolution of hydrothermal systems from these complementary fronts:

- We model planetary formation, and we detect and characterize extrasolar planets, in an effort to understand the range of objects that develop hydrothermal systems as well as the distribution of volatiles, especially water, within those objects.
- We investigate the circumstances under which hydrothermal systems form on planets and other bodies and the expected physical and chemical characteristics of those systems as they evolve.
- We study geochemical processes in hydrothermal systems, especially those that lead to abiotic organic synthesis. A particular focus is the role of mineral catalysis in these systems.
- We consider the origin and evolution of biological entities in hydrothermal systems through studies of the biochemistry of contemporary hydrothermal organisms.

A complete understanding of hydrothermal systems and their role in life's origins requires substantial advances on all of these fronts, as well as an extensive and challenging integration of these topics. During the past year we achieved significant progress in each of these research areas, as well as increased attention to the interfaces among these theoretical, experimental, and field approaches.

Among the highlights from the past year's research in the area of **planetary formation and evolution** were the following:

- Ten new planets were discovered by high−precision radial velocity surveys, including the closest known analogue to our Solar System.
- A transit−planet search yielded three promising candidates for new extrasolar planets.
- Orbital stability of Earth−like, habitable planets in known extrasolar planetary systems has been constrained by theoretical modeling.
- Observations of suspected protoplanetary disks imply that planet formation must occur faster than previously thought.
- A new scenario for Solar System formation raises the estimated frequency of habitable planetary systems by a factor of five.
- A new hypothesis to account for the pattern of crustal magnetic anomalies on Mars suggests that these features may provide a basis for assessing early hydrothermal activity and hence possibilities for early life on Mars.

Highlights in the area of the **evolution of organic matter and water in meteorites** included the following:

- Chondrule formation may produce observable chemical signatures in a disk.
- CR chondrites contain the most primitive organic matter yet studied from meteorites. The range of compositions seen in chondrites result from aqueous alteration and/or thermal metamorphism under a variety of conditions on the different chondrite parent bodies.
- Pyrolysis of organic matter in interplanetary dust particles during atmospheric entry may have had an important influence on atmospheric chemistry early in Earth's history.
- Ion imaging has revealed for the first time clear evidence for a D−rich, but C−poor, component in interplanetary dust particles. This material most likely consists of hydrated minerals such as phyllosilicates and has a D/H ratio similar to that observed in cometary water.
- There is a hint that Martian meteorites preserve a record of the evolution of the Martian atmosphere, but the potential influences of shock and/or terrestrial contamination in the meteorites need to be better understood.
- Measurements have revealed isotopically heavy Fe (^{56}Fe ranging up to +0.5‰) in Fe−rich sediments associated with Fe−metabolizing bacterial colonies around hydrothermal vents on the Loihi seamount. This result holds out the promise that Fe isotopes will be a useful biomarker.

Highlights in the area of **experimental tests of proposed hydrothermal organic synthesis reactions** included the following:

- A robust abiotic chemical pathway from citrate to aspartate has been demonstrated. This pathway requires that citrate undergoes a retro−aldol reaction to form oxalacetate and that the oxalacetate has sufficient (albeit low) stability to remain long enough to be "trapped" as aspartate. Aspartate lies on the path toward pyrimidine synthesis and hence is a threshold into the ribonucleic acid (RNA) world.
- The facile conversion of nitrate and nitrite to ammonia at elevated pressures (to 0.2 GPa) and temperatures (to 250°C) has been documented in the presence of 20 different transition−metal oxide and sulfide minerals.
- A surprisingly facile, straightforward course to chirality and functional polypeptides has been proposed. The pathway stems from the creation and survival of polyamino acids in impacting cometary bodies, a statistical demonstration of large fractions of chiral segments in the racemic polymers, and hydrolysis kinetics analyses showing the sole survival of the chiral segments.
- A reversal reaction has been demonstrated in the system FeO + $CaCO_3$ + water by producing methane at 5 GPa pressure and temperatures greater than 1800 K. Such a result may have important implications for the generation of hydrocarbons in the hot, deep interiors of terrestrial planets.

In the area of supporting **theoretical studies of hydrothermal synthesis reactions**, a highlight was the following:

- Thermodynamic calculations support the possibility that sulfate reduction may be metabolically viable on Europa given the complex chemical processes thought to occur there.

Highlights in the area of **isotopic and molecular tracers of life** during the past year included the following:

- There is chemical evidence that the ancient (400−My−old), now extinct, vascular plant Asteroxylon Milleri had the biochemical capability for lignin synthesis whereas the slightly more primitive Aglaophyton did not. Identifying the point in the evolution of plants when lignin synthesis arose may provide insight into the vital evolutionary step that aided colonization of the continents by plants.
- The trophic interactions that characterized the ancient ecosystem preserved in the now−fossilized Enspel Formation in Germany have been reconstructed from the stable isotopic abundances of carbon and nitrogen.
- Preliminary data on five microbial species show mass−dependent fractionation of sulfur isotopes.
- Mass−independent sulfur isotope anomalies correlate with depositional environments of 2.5− to 2.7−Ga black shale and dolomite deposits from the Hamersley and Fortescue Groups, Western Australia.

Highlights in the area of **biological studies of hydrothermal systems** included the following:

- A characterization of microbes in subsurface fluids from Axial Volcano, Juan de Fuca Ridge, has demonstrated that there is a highly diverse community of bacteria and archaea that are unique to the subsurface of mid−ocean ridges.
- A community of potentially nitrogen−fixing archaea and bacteria that occupies the hot, anaerobic habitats of the mid−ocean ridge subseafloor is not dependent on electron acceptors and nitrogen compounds produced by photosynthetic organisms.
- Studies of microorganisms within sulfide chimneys at active hydrothermal vents suggest that biofilm formation on minerals may be associated with microbial growth or survival at extremely high temperatures.
- The first phylogenetic characterization of a microbial community associated with a peridotite−hosted hydrothermal vent field has been completed.
- Deoxyribonucleic acid (DNA) microarrays for *E. coli* have been optimized to screen for changes in gene expression at high pressures.
- Isotopic analysis indicates that lithotrophic Fe−oxidizing bacteria appear to be heterotrophic, i.e., they obtain their energy from an inorganic energy source (Fe^{2+}) and their C from organic matter.

In the area of **new molecular recognition instruments for astrobiological**

applications, highlights of the past year included the following:

- Antihopane antibodies have been developed for rapid screening of the presence of hopanes in extracts of soil samples.
- Optimization of organic and aqueous extraction protocols have been developed for the extraction of viable and fossil biomarkers for future use in robotic systems.
- Initial testing protocols have been designed to place these extraction techniques onto a lab−on−a−chip format.
- Microfluidic devices for the handling of sample extraction and inoculation of microarrays are in the design stage as part of a collaboration with Marshall Space Flight Center.

In summary, our team's recent research, including discoveries of new planetary systems, exploration of possible hydrothermal regimes on other worlds, elucidation of robust hydrothermal synthetic pathways, documentation of novel microbial metabolic strategies, and finding unexpected high−pressure environments for life, inform the central questions of astrobiology. Taken together, these discoveries are changing our views of life's origin and its distribution in the universe.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: A New Molecular Recognition Instrument for Astrobiological Applications

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***A New Molecular Recognition Instrument for Astrobiological Applications***
Project Investigators:	***Marilyn Fogel , Andrew Steele***

Project Progress

Task 1. Molecular Recognition Instruments for Astrobiological Applications (Fogel, Steele)

Fogel and Steele have been applying the Cyphergen Protein Chip reader to detect small lipid molecules in modern and fossil samples. Together with postdoctoral fellow Jake Maule, they have made an antibody to the bacterially derived lipids, hopanes, and have successfully tested this antibody using enzyme−linked immunosorbent assay (ELISA) techniques. The antibody was created in the usual manner by injecting the hopane molecule bound to a small peptide into a rabbit. The goal of the experiment was to test whether biomarkers can be concentrated from solutions with antibodies for subsequent biosignature identification as might ultimately be done on the surface of Mars. Specialized chip surfaces were used to bind IgG proteins, proteins that provide a "handle" for the antibodies. This was the first test of the protein chip reader with antibody−based chips. Using standard reagents, it was found that the instrument could selectively detect specific proteins that had been bound to antibodies. With the hopane antibody, no evidence for hopane binding could be found, but this technique is being evaluated further. In control experiments where hopane−bearing solutions were analyzed directly, the chip reader was able to detect signals from small quantities of material. In addition, lipid extracts obtained from the fossiliferous Enspel Formation in Germany were tested for the presence of bacterial lipids. For these samples hopanes and other lipid molecules were detected by the Chip reader, but their molecular weights (around 200 daltons) were nearly identical to energy−absorbing molecules needed for matrix assisted laser desorption, so that the detections may be artifacts.

Steele's group has also begun to fabricate high−spot−density protein chips, printed at CIW, using a deoxyribonucleic acid (DNA) protein printing system and hydrogel−coated slides. Optimization of the protocols for printing and evaluating the results using fluorescence are underway. The development of further antibodies to molecules potentially relevant for Martian exploration is

underway. These include oxidized polycyclic aromatic hydrocarbon (PAH) molecules, suggested as a possible organic constituent in Martian regolith. The group also initiated fabrication of a bench−top instrument to test soil extraction protocols and establish extraction efficiencies to aid in the development of remote handling systems for samples returned from future missions. The latter work is in collaboration with NASA, Johnson Space Center (JSC), Oceaneering Space Systems, Lockheed Martin Space Operations (LMSO), and Montana State University. Finally, Steele has also initiated a new collaboration with the lab−on−a−chip (LOAC) group at Marshall Space Flight Center for testing microfluidic chips. These chips will be used for the extraction, reaction, concentration, and buffering of an inoculum before being introduced to enzyme and microarray chips that are also being developed as part of the Modular Arrays for Solar System Exploration (MASSE) project.

Highlights

- Antihopane antibodies have been developed for rapid screening of the presence of hopanes in extracts of soil samples.
- Optimization of organic and aqueous extraction protocols have been developed for the extraction of viable and fossil biomarkers for future use in robotic systems.
- Initial testing protocols have been designed to place these extraction techniques onto a lab−on−a−chip format.
- Microfluidic devices for the handling of sample extraction and inoculation of microarrays are in the design stage as part of a collaboration with Marshall Space Flight Center.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MSL 09	Instrument/payload development
3	Mars 13	Instrument/payload development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Steele plans to submit a proposal to the March 2004 announcement of opportunity (AO) for Mars Smart Lander (MSL) for both a robotic sample−handling system and a flight instrument (MASSE). He is also working on refining and improving the MASSE design for flight as a life−detection instrument on a 2013 Mars lander.

Field Expeditions

Field Trip Name: ASTEP preliminary field trip	
Start Date: 26 April 2003	***End Date:*** 26 April 2003
Continent: North America	***Country:*** USA
State/Province: Maryland	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Jug Bay	***Keywords:***
Description of Work: To test a mobile molecular biology laboratory, sample extraction methods, and sample sterility monitoring in an environment close to services. This project is supported by the NASA Astrobiology Science and Technology for Exploring Planets (ASTEP) Program.	
Members Involved: Marilyn Fogel	

Cross Team Collaborations

Steele maintains collaborations on the development of biomarker−detection instruments for future flight opportunities with David McKay of the JSC NAI team and with several colleagues (Juan Perez Mercader, Victor Parro Garcia,

and Carlos Briones) at the Centro de AstrobiologÃ-a (CAB) in Spain.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Biological Studies of Hydrothermal Systems

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Biological Studies of Hydrothermal Systems***
Project Investigators:	***John Baross , David Emerson , Marilyn Fogel , James Scott , Andrew Steele***

Project Progress

Task 1. Field Studies and Laboratory Characterization of Hydrothermal Vent Microbes (Baross)

During the past year Baross and his group continued their efforts to understand the phylogenetic, metabolic, and physiological diversity of microorganisms indigenous to hot sulfide chimneys and subsurface habitats associated with submarine hydrothermal systems. On the basis of the characteristics of "particle−attached" and "free−living" bacteria in subsurface fluids from Axial Volcano, Juan de Fuca Ridge, work complementary to an earlier assessment of the diversity of archaea from the same samples, there is a highly diverse community of bacteria and archaea that are unique to the subsurface. Included in this group are thermophilic and hyperthermophilic organisms that fix CO_2 and oxidize H_2 using elemental sulfur or polysulfides as the electron acceptors. This is a new group of bacteria that evidently use the reductive citric acid cycle to fix carbon dioxide. Other unique microorganisms isolated from subsurface fluids include thermophilic iron−reducing bacteria and archaea. The epsilon−proteobacteria were found to be the dominant bacteria identified in subsurface habitats on and off axis. While there are only limited data on the epsilon−proteobacteria from vent environments, they are clearly indigenous to vent habitats and are likely to be involved in sulfur cycling.

The group completed preliminary analysis of the diversity of microorganisms in the subsurface that harbor the nifH gene, which is involved in nitrogen fixation. This study was initiated because N_2 is the only abundant form of nitrogen in the hot, anerobic subsurface at many mid−ocean ridge sites. Earlier results suggested the presence in this habitat of a diverse community of potentially nitrogen−fixing archaea and bacteria. The latest work supports the hypothesis that a unique subsurface microbial community is not dependent on electron acceptors and nitrogen compounds produced by photosynthetic organisms.

Baross and colleagues also completed a preliminary study on the incidence and diversity of microorganisms in active sulfide chimneys. Results of the study show that microorganisms exist throughout these structures, even in

zones that have experienced temperatures considerably greater than 100°C on the basis of mineral compositional constraints. Two observations from this study were particularly surprising. First, microbial communities, detected optically with deoxyribonucleic acid (DNA)−specific fluorescent stains and ribonucleic acid (RNA) probes, inhabit the hot interior zones of the sulfide chimney. All of these organisms belong to the Archaea, and most could be detected with RNA probes, indicating that they may well be viable and active. Second, and in all cases, the microbial communities exist by forming biofilms on mineral surfaces. These observations suggest that biofilm formation on minerals may be associated with microbial growth or survival at extremely high temperatures. The group completed preliminary phylogenetic characterization of the microbial community associated with the carbonate chimneys at Lost City Hydrothermal Field. Lost City is a novel off−axis hydrothermal system driven by serpentinization reactions between seawater and ultramafic oceanic crust. This reaction is exothermic and can produce high concentrations of hydrogen, methane, and low−molecular−weight organic compounds.

Task 2. Microbial Activity at Gigapascal Pressures (J. Scott, Fogel, Sharma, Steele)

In follow−on work to an initial demonstration that microbial activity can persist at pressures in excess of 1 GPa (Figure 1), Sharma, Scott, and colleagues have been working toward determining the pressure−expressed proteins and genetic elements of *Escherichia coli* and *Shewanella oneidensis*. The past year has been spent developing and optimizing techniques for recovering cells for manipulation in order ultimately to resolve the processes involved in prokaryotic stress response at the molecular level. Most living organisms survive under suboptimal conditions. It is therefore essential to understand how stress affects the formation of the molecular components of cells that make up the subpopulation of biomarkers and bio−indicators that potentially serve as evidence of biological activity.

One of the most important developments of the past year has been a move away from diamond anvil cells as the exclusive means for exposing microbial communities to excess pressure. The goal of these efforts is to optimize working volumes for performing basic microbiological, biochemical, and molecular−genetic manipulations on cells exposed to pressures approaching 1 GPa. To date the group has been able to expose *E. coli* cells to pressures in excess of 350 MPa in a hydrothermal pressure vessel and then recover cells aseptically in a volume of up to 2 milliliters for cultivation in a complex growth medium.

Together with Steele and Fogel, Scott has begun to identify key proteins and genetic components involved in the response of *E. coli* to pressure−induced stress. Steele's laboratory provides an ideal battery of molecular approaches (from genome array technology to gene−amplification) for resolution of pressure−induced operons or regulons that play a key role in the the response to stress. A time−of−flight mass spectrometer system in Fogel's laboratory is being optimized for identification of proteins found in a typical prokaryotic cell. Scott is also involved, with colleagues at The Institute for Genomic Research and the University of Southern California, in efforts to resolve the genome and

proteome for *S. oneidensis* strain MR1. This work will provide an important second bacterium to determine whether the response of *E. coli* is common or unique among prokaryotes. Further, *S. oneidensis* is an environmentally important bacterium that should provide a good model for understanding the full range of environmental implications of prokaryotic stress responses.

Task 3. Iron−Oxidizing Lithotrophs (Emerson, Fogel, Sutka)

A major emphasis of the research by Emerson's group during the past year was on C and N metabolism by lithotrophic Fe−oxidizing bacteria that grow at neutral pH. The guiding assumption, based on substantial circumstantial evidence, was that these organisms were autotrophic. Work led by postdoctoral fellow Robin Sutka, however, on isotopic analysis of ^{13}C−labled bicarbonate, does not support this assumption. Instead, these bacteria appear to be obligate lithoheterotrophs, i.e., they obtain their energy from an inorganic energy source (Fe^{2+}) and their C from organic matter. While this type of metabolism is unusual, what is particularly striking is that these organisms appear to use only certain amino acids as C−sources. Attempts to feed them on a number of more commonly used carbohydrates and organic acids were unsuccessful.

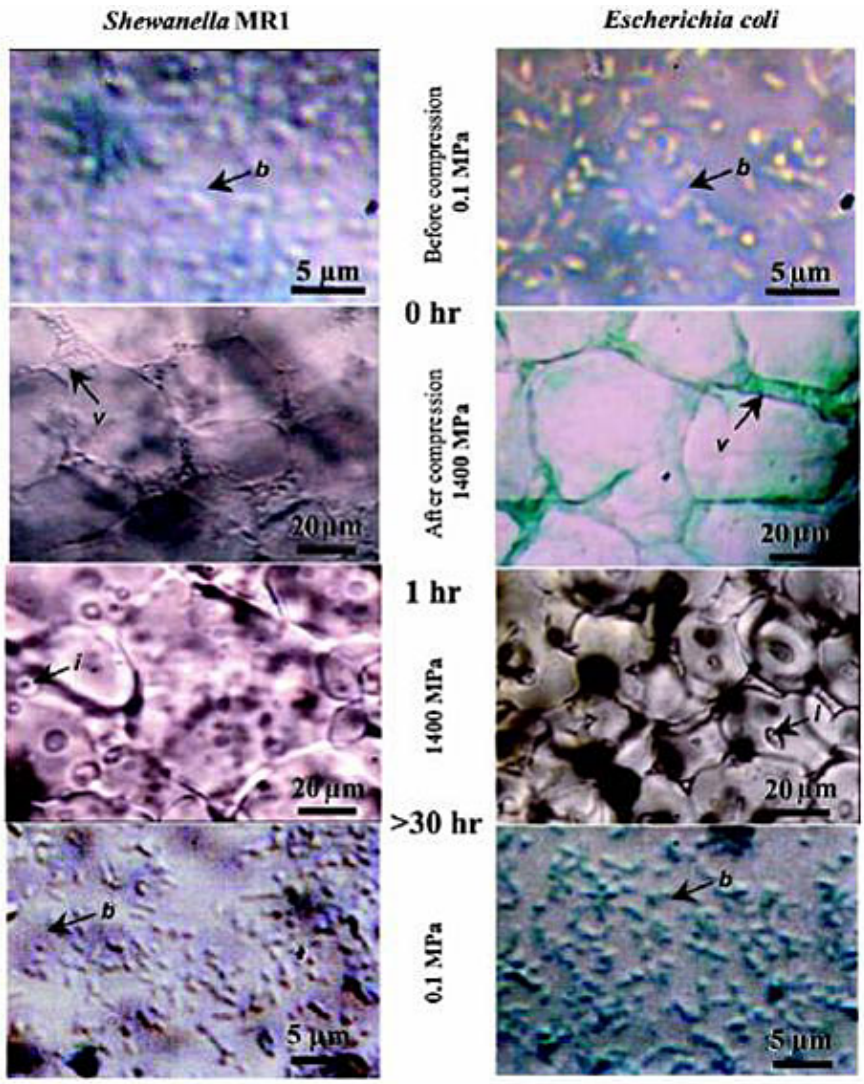

Figure 1. *Microbial activity and viability in ice−VI (1400 MPa) documented by Co−I J. Scott and colleagues. Upon ice nucleation (0 hr, 1400 MPa), organic fluid veins (v) filled with bacteria (*Shewanella *MR1 on the left,* E. coli *stained with methylene blue on the right) appear. After ~ 1 hr, textural changes occur in the ice, defined by the formation of organic−rich inclusions (i) containing motile bacteria. Viable and countable bacteria were observed upon subsequent lowering of pressure.*

Highlights

- A characterization of microbes in subsurface fluids from Axial Volcano, Juan de Fuca Ridge, has demonstrated that there is a highly diverse community of bacteria and archaea that are unique to the subsurface of mid−ocean ridges.

- A characterization of microbes in subsurface fluids from Axial Volcano, Juan de Fuca Ridge, has demonstrated that there is a highly diverse community of bacteria and archaea that are unique to the subsurface of mid−ocean ridges.

- Studies of microorganisms within sulfide chimneys at active hydrothermal vents suggest that biofilm formation on minerals may be associated with microbial growth or survival at extremely high temperatures.

- The first phylogenetic characterization of a microbial community associated with a peridotite−hosted hydrothermal vent field has been completed.

- DNA microarrays for *E. coli* have been optimized to screen for changes in gene expression at high pressures.

- Isotopic analysis indicates that lithotrophic Fe−oxidizing bacteria appear to be heterotrophic, i.e., they obtain their energy from an inorganic energy source (Fe^{2+}) and their C from organic matter.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Oceanographic cruise, Mid−Atlantic Ridge	
Start Date: April 2003	***End Date:*** May 2003
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Lost City Vent Field	***Keywords:***
Description of Work: This cruise was the first to study a peridotite−hosted hydrothermal system. Peridotite material characteristic of ultramafic seafloor environments consists of olivine that upon contact with seawater is readily altered, resulting in the consumption of oxygen and the production of heat and hydrogen. Further chemical reactions of hydrogen with metal−bearing catalysts can result in the production of methane and other hydrocarbons. Preliminary results from samples of carbonate edifices obtained in December 2001 showed the presence of a single phylotype of methane−metabolizing Archaea. During the cruise, work continued on identifying the bacterial and archaeal diversity of carbonate structures and	

hot fluids from a range of locations. In addition an effort will be made to determine if some key genes in the nitrogen cycle, such as nitrogen fixation and nitrate reduction, and methane metabolizing genes are expressed in situ, as well as the specific groups of microorganisms responsible for these activities.
Members Involved: Billy Brazelton

Field Trip Name: Baby Bare and Ocean Drilling Project (ODP) Hole 1026B	
Start Date: September 2002	***End Date:*** July 2003
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Juan de Fuca Ridge	***Keywords:***
Description of Work: The primary goal of this project, supported by NAI and the NSF LExEn program, is to determine if older oceanic crust on ridge flanks supports a microbial community. In September 2002, stainless steel probes were used successfully to penetrate into crust. High−temperature microbes were detected in crustal fluids using both molecular and culturing methods. However, the numbers of microbes in the crustal fluids were extremely low, and so data are limited. Baross and Huber will revisit these sites in July 2003 with the goal of obtaining larger quantities of crustal fluid so as to derive a more comprehensive picture of the microbial community indigenous to these crustal environments.	
Members Involved: John Baross	

Cross Team Collaborations

J. Scott maintains an active collaboration with the JPL/USC team (Kenneth Nealson) on the sequencing and annotation of the genome of *Shewanella oneidensis* strain MR1.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Hydrothermal Organic Synthesis

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Hydrothermal Organic Synthesis***
Project Investigators:	***James Bischoff , George Cody , Robert Hazen , Russell Hemley , Hatten Yoder, Jr.***

Project Progress

Task 1. Hydrothermal Organic Chemistry (Cody, Boctor, Brandes, Hazen, Yoder)

Over the past year Cody and colleagues have continued their research into hydrothermal protometabolic chemistry. Building on their previous studies, they have now demonstrated a viable pathway for the formation of alanine and aspartic acid (Figure 1). They have shown that the presence of transition−metal sulfides enhances these reactions, presumably by operating as a hydrogenation catalyst to enhance the reductive amination reaction. The group also carried out experiments coupling active nitrogen into the previously defined protometabolic carbon−fixation pathways with the aim of establishing evidence of pathways that may lead to pyrimidine synthesis, one threshold to the "RNA−world."

Hazen and Brandes also performed a number of prebiotic synthesis experiments involving simple molecules in hydrothermal environments, including measurements of the conversion of nitrate and nitrite to ammonia at elevated pressures (to 0.2 GPa) and temperatures (to 250°C)

Task 2. Amino Acid Synthesis Under Hydrothermal Conditions (Bischoff, Ross, Lemke)

The U.S. Geological Service (USGS) group's activities include study of oligomerization and decarboxylation of amino acids in hydrothermal media, as well as modeling the fate of amino acids arriving in impacting cometary bodies. They showed that, while in accord with literature accounts, the formation of glycine dipeptide in hydrothermal media is endergonic by 2−4 kJ/mole, and the next step to the tripeptide is exergonic by 10−12 kJ/mole. This value is presumably applicable to all subsequent growth steps. The downhill swing of up to 16 kJ/mole provides an answer to the long−standing question of the spontaneous formation of polypeptides on the early Earth, and kinetics estimates at 25°C suggest that considerable levels of oligomerization would be expected over periods of a few millions of years in local regions of high

concentrations. Since life probably began within a 100−million−year span following the end of heavy bombardment, an open ocean scenario with amino acid concentrations below the mM range is not possible, inasmuch as kinetics estimates show the entire period would be required for just the first step to the dipeptide.

This obstacle has led to an exogenous alternative that provides a surprisingly facile course to functional, chiral polypeptides utilizing polyamino acids derived directly from incoming comets. The group's present estimates, developed in collaboration with Elizabetta Pierazzo at the University of Arizona, suggest that for some impacts the amino acids in the collider survive the event and then quickly form polymers during cooling. Beginning with this "jump start" to biochemistry the group's analysis employs statistical estimates of random chiral segments in the racemic polymers. Kinetics estimates for the hydrolysis of achiral and homochiral peptide segments then reveal the hydrolytic stability of the latter, which in turn can provide chiral, self−replicating and autocatalytically functional polypeptides within 40 to 50 million years.

Task 3. Stability of Organic Compounds at Very High Pressure (Hemley, H. Scott)

Over the past year Hemley and NAI postdoctoral fellow Henry Scott have used diamond anvil cells (DACs) to make in situ observations of the oxidation and reduction of carbon at simultaneously high pressures and temperatures. It is likely that planetary bodies accrete large amounts of reduced carbon, but it is not known how well organic species withstand hydrothermal processing at the elevated pressures of planetary interiors. Hemley and Scott conducted studies on the stability of polyethylene at a range of pressures (up to 10 GPa), temperatures, and oxygen environments. With the addition of $CaSiO_3$ (wollastonite) to the system of polyethylene plus water, production of carbonate at the expense of the organic species is observed. Also frequently documented is a reversal reaction in the system FeO + $CaCO_3$ + water by producing methane at 5 GPa pressure and temperatures greater than 1800 K.

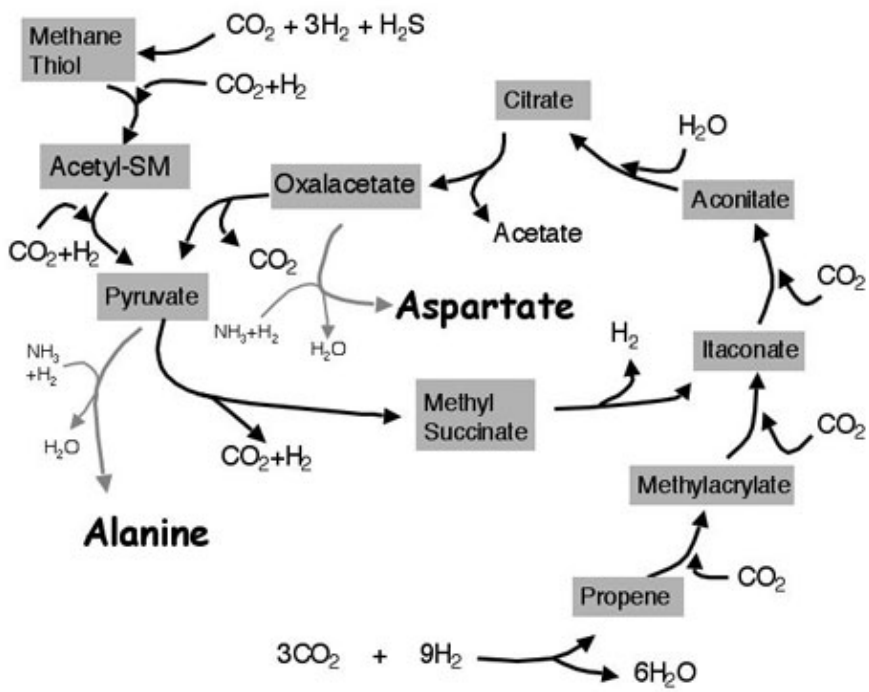

Figure 1. *A composite of various* abiotic *("protometabolic") carbon− (and nitrogen−) fixation reactions promoted or catalyzed in the presence of transition−metal sulfides and in aqueous media. This reaction network shares superficial similarities with intermediate anabolic strategies of certain anaerobic autotrophs, e.g., methanogens and acetogens. A reaction network such as this may have provided the primitive world with the essential biochemicals necessary to ?jump start? an emergent chemical system, e.g., RNA world. The apparent complexity shown in this diagram does not, by any means, reflect a limit for abiotic chemistry; rather it records what has been observed to date in a very limited reaction space explored by Co−I Cody and other researchers in experimental protometabolic chemistry.*

Highlights

- A robust abiotic chemical pathway from citrate to aspartate has been demonstrated. This pathway requires that citrate undergoes a retro−aldol reaction to form oxalacetate and that the oxalacetate has sufficient (albeit low) stability to remain long enough to be "trapped"' as aspartate. Aspartate lies on the path toward pyrimidine synthesis and hence is a threshold into the ribonucleic acid (RNA) world.

- The facile conversion of nitrate and nitrite to ammonia at elevated pressures (to 0.2 GPa) and temperatures (to 250°C) has been documented in the presence of 20 different transition−metal oxide and sulfide minerals.

- A surprisingly facile, straightforward course to chirality and functional polypeptides has been proposed. The pathway stems from the creation and survival of polyamino acids in impacting cometary bodies, a statistical demonstration of large fractions of chiral segments in the

racemic polymers, and hydrolysis kinetics analyses showing the sole survival of the chiral segments.

- A reversal reaction has been demonstrated in the system FeO + $CaCO_3$ + water by producing methane at 5 GPa pressure and temperatures greater than 1800 K. Such a result may have important implications for the generation of hydrocarbons in the hot, deep interiors of terrestrial planets.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Isotopic and Molecular Tracers of Life

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Isotopic and Molecular Tracers of Life***
Project Investigators:	***Conel Alexander , George Cody , James Farquhar , Marilyn Fogel , Douglas Rumble , Andrew Steele***

Project Progress

Task 1. Molecular Spectroscopic Investigations into Ancient Biochemistry (Cody, Fogel, Hazen)

Cody, Fogel, and Hazen have collaborated with NAI postdoctoral fellow Kevin Boyce and Andrew Knoll at Harvard University and scientists in Australia and South Africa on studies of the chemical, isotopic, and molecular characterization of a variety of ancient organic fossils. Recent results include isotopic, chemical, and morphological evidence for the oldest known microbial mats from a sandy marine environment and chemical evidence of specific structural biopolymers in Earth's most ancient vascular plants (Figure 1).

Boyce and CIW colleagues have made a preliminary determination of the biological affinities of a bizarre Paleozoic fossil, Prototaxites, which produced enormous tree−like trunks composed of intertwined, 50−micrometer−diameter tubes. On the basis of carbon and nitrogen isotopic analyses, specimens cluster into two discrete populations of carbon isotopic values. Pending further organic analyses to rule out the possibility of diagenetic artifacts, this isotopic disparity may reflect heterotrophy upon isotopically distinct sources, suggesting that Prototaxites was a twenty−foot−tall fungus.

Task 2. Life Detection in Extraterrestrial Materials (Steele, Fogel, Toporski)

Steele, in collaboration with postdoctoral fellow Jan Toporski, has continued to explore the use of commercial antibodies for printing protein microarrays and testing these microarrays against defined antigens and unknown samples of solar system exploration relevance such as Martian regolith simulant and samples from Haughton crater and the Enspel Formation. Steele and collaborators are characterizing populations of bacteria in the above samples as well as terrestrially contaminated meteorites (Figure 2) by use of polymerase chain reaction (PCR), cloning, and sequencing. Furthermore, Steele and Toporski continue to refine extraction protocols for biomarkers from

the above samples and to explore the survival of biomarker molecules through the fossilization process. Fogel, Steele, and Toporski have applied stable isotopes (carbon and nitrogen) to unravel the trophic structure of the ancient ecosystem preserved in the Enspel Formation, Germany.

Task 3. Mass−Independent Sulfur Isotope Fractionation in Archean Rocks (Farquhar, Rumble, J. Scott, Wang)

Sulfur isotopic geochemistry enjoys the unique power to record information on both ancient biochemistry and ancient atmospheric photochemistry. Experimental data are needed, however, in order to interpret isotope compositions in terms of atmospheric versus metabolic mechanisms. The fractionation of sulfur isotopes by microbial enzymatic catalysis has been well−studied in terms of $^{34}S/^{32}S$ fractionations, but published data on ^{33}S and ^{36}S are lacking. Rumble, J. Scott, and postdoctoral fellow Pei−Ling Wang are measuring the fractionation of multi−sulfur isotopes by pure cultures of 11 species of microbes. The study is focused on microbes that are able to metabolize elemental sulfur, because native sulfur is believed to be an important component of the Archean atmosphere. Preliminary results on five species show no evidence that microbes imitate the "mass−independent" fractionation characteristic of atmospheric photochemistry. This is an important result, because it simplifies the interpretation of sulfur isotope analyses of ancient rocks. Additional experiments on the full range of microbial species and under a variety of environmental conditions are continuing.

A highly resolved stratigraphic record of sulfur isotope fractionations transecting such pivotal geologic epochs as the Archean−Proterozoic boundary and the episode of Paleo−Proterozoic glaciation is sought, because it will provide insight into evolutionary changes in Earth's atmosphere. Drill core samples have been collected from several continents covering these time intervals. Farquhar, Rumble, postdoctoral fellows Wang and Shuhei Ono, together with collaborators from the Harvard NAI team, have been analyzing the samples. A study of the Fortescue and Hamersley Groups, Australia, shows strong correlation between depositional environments and sulfur isotope systematics. There is evidence of microbial activity as an important factor causing the precipitation of pyrite and thus preserving an isotopic record of atmospheric photochemistry.

Farquhar's group has described the mass transfer of sulfur through biosynthetic networks associated with sulfate reduction and disproportionation. They demonstrated that sulfur isotope fractionations for ^{32}S, ^{33}S, and ^{34}S during dissimilatory sulfate reduction can be explained as a direct consequence of distillation effects associated with the sulfate reduction pathways. They further carried out vibrational calculations for equilibrium sulfur isotope fractionations to provide a reference frame for evaluating biological and abiological sulfur isotope fractionation effects.

Farquhar's laboratory at the University of Maryland has installed and is in the final stages of testing a Finnigan MAT 253 gas−source mass spectrometer for sulfur isotope analyses. Coupled to this instrument is an SF6 preparation manifold for fluorination of samples by laser and conventional techniques.

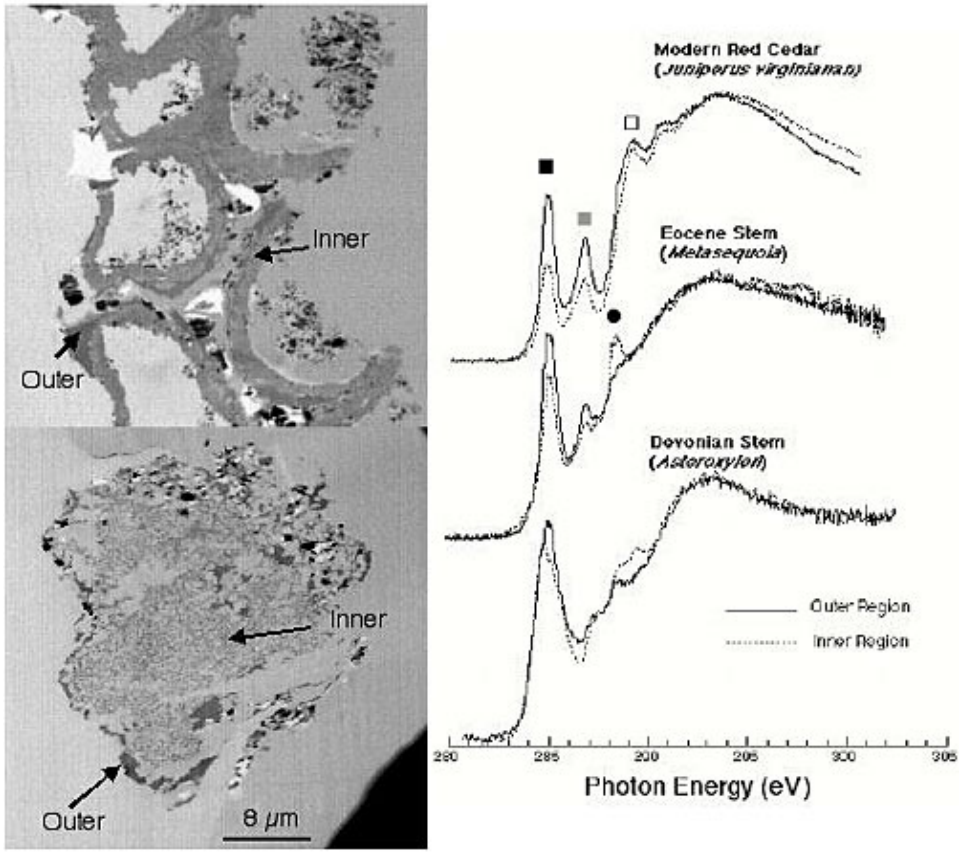

Figure 1. *High−resolution scanning transmission X−ray microscope images obtained by Co−Is Cody and Hazen (left) of preserved tracheid cells of ancient vascular plants,* Metasequoia milleri *(top), preserved in the ~ 40−Ma Princeton Chert, and* Asteroxylon mackiei *(bottom), preserved in the ~ 400−Ma Rhynie Chert. These high−resolution (40−nm spot size) X−ray images (with the photon energy tuned to 286 eV) reveal a mechanically resistant, strongly absorbing outer region and a weakly absorbing inner region. Comparison of the carbon X−ray absorption near edge spectra from each region (shown on the right) reveals significant differences in the carbon chemistry distinguishing the differentiated regions of the cell membrane even in the 400−Ma fossil. The squares and circles highlight specific absorption bands corresponding to organic functional groups diagnostic of ligno−cellulosic and altered ligno−cellulosic material.*

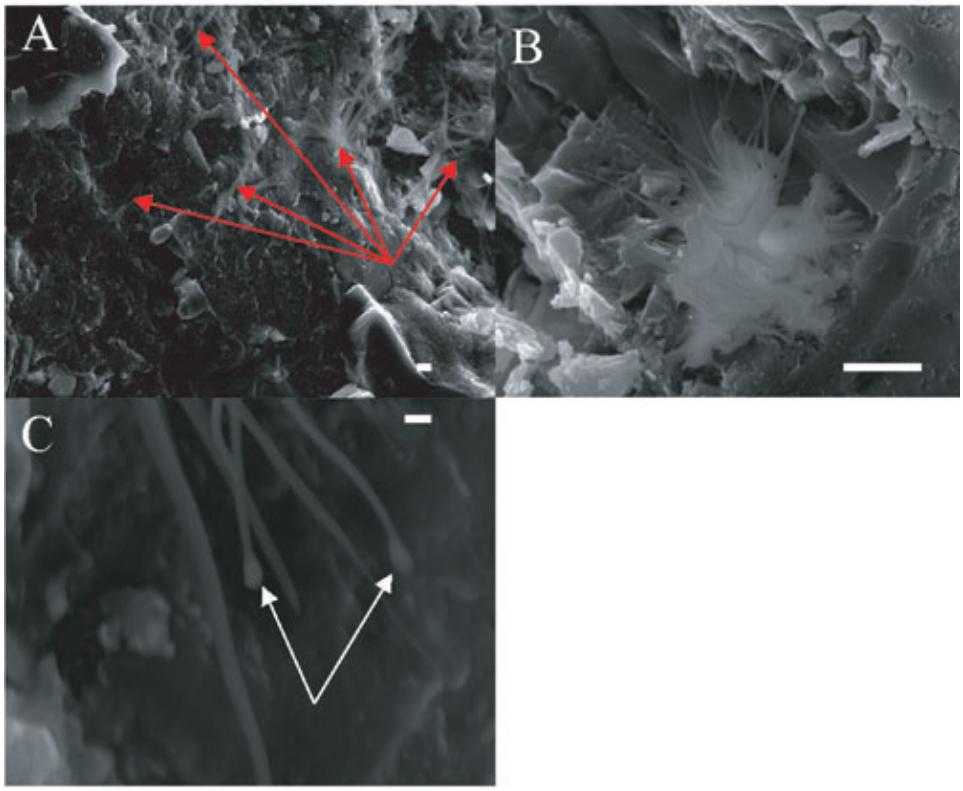

Figure 2. *Terrestrial microbes growing on the surface of chips of Martian meteorite Nakhla as seen in field−emission gun scanning electron microscope images obtained by Co−I Steele. A displays the extent of the contamination by terrestrial microbiota (red arrows) on a fractured surface. B shows a single cell that, on the basis of morphology, may be* Hyphomicrobium sp. C *depicts buds at the ends of stalked hyphael−like objects (white arrows) indicative of this class of bacteria (K. Nealson, personal communication, 2003). These samples are being used to test a range of new techniques and methodologies for life detection both in−situ and on returned samples. Scale bars are 1 ¼m.*

Highlights

- There is chemical evidence that the ancient (400−My−old), now extinct, vascular plant *Asteroxylon milleri* had the biochemical capability for lignin synthesis, whereas the slightly more primitive *Aglaophyton* did not. Identifying the point in the evolution of plants when lignin synthesis arose may provide insight into the vital evolutionary step that aided colonization of the continents by plants.

- The trophic interactions that characterized the ancient ecosystem preserved in the now−fossilized Enspel Formation in Germany have been reconstructed from the stable isotopic abundances of carbon and nitrogen.

- Preliminary data on five microbial species show mass−dependent fractionation of sulfur isotopes.

- Mass−independent sulfur isotope anomalies correlate with depositional environments of 2.5− to 2.7−Ga black shale and dolomite deposits from the Hamersley and Fortescue Groups, Western Australia.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Pilbara, Hamersley, Fortescue, and Duck Creek Groups, 3.5 to 1.9 Ga	
Start Date: 20 Aug 2002	***End Date:*** 12 Sep 2002
Continent: Australasia	***Country:*** Australia
State/Province: W. Australia	***Nearest City/Town:***
Latitude: various	***Longitude:*** various
Name of site(cave, mine, e.g.): transect	***Keywords:***
Description of Work: Investigated evidence of ancient life. Collected rock samples for istopic analysis.	
Members Involved: James Farquhar	

Field Trip Name: Enspel Formation	
Start Date: July 2002	***End Date:*** Aug. 2002
Continent: Europe	***Country:*** Germany
State/Province:	***Nearest City/Town:***
Latitude: various	***Longitude:*** various
Name of site(cave, mine, e.g.): Espel	***Keywords:*** fossil locality
Description of Work: Sample collection for laboratory analysis.	
Members Involved: Jan Toporski	

Cross Team Collaborations

Cody, Fogel, and Hazen have maintained an active collaboration with Kevin Boyce and Andrew Knoll of the Harvard NAI team on the chemical and isotopic analysis of ancient fossils.

Rumble collaborates with researchers from the NAI team at Pennsylvania State University (Jennifer Eigenbrode, Katherine Freeman, James Kasting, and Pushker Kharecha, as well as Alexander Pavlov, who is now at the University of Colorado) on the atmospheric sulfur signal in Archean strata. He is also collaborating with members of the Harvard NAI team (Heinrich Holland and Audrey Bekker) on the analysis of drill core samples from Archean black shales from South Africa.
Farquhar has collaborated with the UCLA NAI team on an ion microprobe investigation of sulfur isotopes in diamonds. These measurements provided strong evidence to support a recycled sulfur component in the diamonds analyzed.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Oxidation of Organic Carbon Under High Pressure Hydrothermal Processing

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Oxidation of Organic Carbon Under High Pressure Hydrothermal Processing***
NAI−NRC Postdoctoral Fellow :	***Henry Scott***

Project Progress

We are experimentally investigating the oxidation and reduction of carbon compounds at high pressures and temperatures. Specifically, we are working at temperatures ranging from ambient to 1500°C and pressures from ambient to 10 GPa. Our aim is to investigate the uppermost stability limits for organic compounds in planetary interiors. During Year Four our focus was on the oxidation of initially reduced carbon species; during Year Five we have approached the reaction from the opposite direction. In our current experiments we are using $CaCO_3$−calcite as the carbon source, and observe that at pressures greater than 5 GPa and temperatures of approximately 1500°C carbon is reduced to form methane. These experiments also include H_2O and FeO, which is oxidized to form Fe_3O_4−magnetite.

Highlights

- Methane production is observed by the high−pressure reduction of carbonates; methane is a potential hydrocarbon source in deep planetary interiors.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Re−Os study of hydrothermal processes in ordinary chondrites

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Re−Os study of hydrothermal processes in ordinary chondrites***
NAI−NRC Postdoctoral Fellow :	***Michael Smoliar***

Project Progress

The primary aim of this work is to place constraints on the timing and chemical processes of hydrous alteration and thermal metamorphism of asteroids, the parent bodies of meteorites, using the abundances and isotopic compositions of the highly siderophile (HSE, metal−loving) elements. Previous work had suggested that these elements are particularly sensitive to post−formation alteration processes in chondritic meteorites. I measured high concentrations of HSE in non−metal fractions from the chondrite Ochansk (H4), which demonstrates that these elements were removed from metal during metamorphism. Ochansk (H4) yielded a precise internal Re−Os isochron that directly dates the redistribution of these elements by metamorphism, and suggested that this metamorphism occurred very early in its history. These results demonstrate the sensitivity of the HSE to even mild alteration processes, and that such processes in chondrites can be precisely dated.

Highlights

- The Re−Os isochron obtained for H−chondrite Ochansk is the first internal Re−Os isochron for meteorites. The achieved age resolution (±25 Ma) demonstrates the capabilities of Re−Os system for studies of post−formation events on chondrite parent bodies.

- The HSE patterns, determined along with Re−Os, allow us to attribute the isochron age to a specific planetary event − thermal metamorphism. We showed that HSE distribution in chondrite components is very informative for interpretation of Re−Os ages.

- We found that substantial fraction of PGE (up to 20% for Os, Ir, and Ru) in chondrites is hosted by non−metal minerals. This fact has important implications for terrestrial geochemistry, especially for upper mantle studies, in providing an alternative explanation for high PGE content for mantle rocks.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Studies of Organic Matter and Water in Meteorites

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Studies of Organic Matter and Water in Meteorites***
Project Investigators:	***Conel Alexander , George Cody , David Emerson , Erik Hauri , Larry Nittler***

Project Progress

Task 1. Chondrule Formation and Solar Nebula Chemistry (Desch)

The mechanisms that produced chondrules and CAIs were important, energetic processes in the early Solar System that would also have led to complex gas−phase chemistry. This chemistry may have influenced the composition of organic matter in meteorites and may produce telltale signatures that would be observable in developing planetary systems.

In the past year, postdoctoral fellow Steven Desch and collaborators have made progress in determining some of the chemical effects of chondrule−melting shock waves on the gas in the solar nebula. They used their previously published chondrule formation model to constrain the pressures and shock speeds in the chondrule formation region. For likely shock speeds of 7 km/s, they demonstrated that ammonia is readily dissociated. Slightly stronger shocks can also dissociate molecular nitrogen. The liberated nitrogen was shown to be incorporated into radicals such as NO and into nitriles. These results have inspired an observational effort underway now at Department of Terrestrial Magnetism (DTM) to observe NO in protoplanetary disks. The nitriles are likely to participate in the organic chemistry that results in the macromolecular material found in meteorites.

Task 2. Chemical Structure of Meteoritic Macromolecule (Alexander, Cody, Tera)

The organic matter in primitive chondritic meteorites has attracted considerable attention, not only because it retains a record of synthesis in the interstellar medium and possibly the solar nebula, but also because it may have been an important component of the prebiotic organic matter on the early Earth and other Solar System bodies.

Alexander, Cody, and Tera continued their studies of extraterrestrial organic matter contained within carbonaceous chondrites. They prepared high−purity residues from a suite of meteorites that experienced a range of parent body

conditions. These include the CMs Cold Bokkveld, ALH 83001, and Y86720; the CRs EET 92042 and GRA 95229; and the COs ALH77307 and ALH 83108. Solid−state (1H and 13C) Nuclear Magnetic Resonance (NMR) has revealed considerable diversity in the compositions of the organic matter in these meteorites (Figure 1). The NMR results are supported by Gas Chromatography Mass Spectroscopy, as well as by isotopic and elemental analysis. The results suggest that if, as seems likely, there was a common source of organic matter in chondrites, this primordial material would have most closely resembled the organic matter found in CR chondrites. Aqueous alteration and/or thermal metamorphism under a variety of conditions on the different chondrite parent bodies produced the range of compositions now observed.

Cody recently collaborated with Monica Kress and Donald Brownlee (University of Washington) to assess the extent to which micrometeorites would have provided organic molecules to Earth's early atmosphere. Their approach was to flash−heat (500 K/s) fine−grained samples of Murchison (a CM2 carbonaceous chondrite) up to ~ 1000 K. The organic matter thermally evolved during flash heating is chemically complex, including numerous single− and double−ring aromatic compounds (variously functionalized with oxygen− and sulfur−containing functional groups). A large influx of such extraterrestrial matter would have had profound influence on the early Earth's atmosphere by providing both partial ultraviolet (UV) shielding and potentially interesting photochemistry.

Task 3. Interplanetary Dust Particles (Nittler, Mukhopadhyay)

Interplanetary dust particles (IDPs), collected in the stratosphere, are believed to have been an important contributor of organics to the early Earth. IDPs are known to contain large and variable isotopic enrichments of deuterium and 15N, believed largely to reflect incomplete processing of presolar organic material from the Sun's parental molecular cloud.

Larry Nittler and Sujoy Mukhopadhyay are using ion probe techniques to constrain the characteristics and origins of organic matter in IDPs. Isotopic imaging of H, C, and N isotopes in fragments of seven IDPs with ~1 micron spatial resolution has revealed a number of distinct components with different H and N isotopic compositions (Figure 2). Both H and N are isotopically heterogeneous on a micron scale. Although the highest D/H and 15N/14N ratios are always associated with carbonaceous material, there is little correlation between the two isotope systems. In fact, the highest 15N/14N ratios are associated with material with relatively modest D enrichments. Moreover, ion imaging has revealed for the first time clear evidence for a D−rich, but C−poor, component in IDPs. This material most likely consists of hydrated minerals such as phyllosilicates and has a D/H ratio remarkably similar to that observed in cometary water. Transmission electron microscopy and synchrotron analyses are planned to determine the precise chemical makeup of the isotopically analyzed IDPs. Mukhopadhyay and Nittler have also recently performed the first sulfur isotopic measurements of IDPs. No large isotopic variations indicating preservation of presolar material have been identified.

Task 4. Hydrogen Isotope Signature of Minerals and Melt Inclusions in Martian Meteorites (Alexander, Boctor, Hauri, Wang)

The H isotopic composition of water in Martian meteorites has the potential for providing information about the origin and evolution of water on Mars.

Boctor and colleagues completed and published an initial survey of 7 Martian meteorites whose ages span much of Martian history (180−4,000 Myr). In all of them even nominally anhydrous minerals often contained deuterium−rich water, indicative of exchange with the Martian atmosphere. There is a factor of two increase in the maximum measured D−enrichments from the oldest to the youngest meteorites. However, at present it is not clear whether this indicates a progressive change in the Martian atmospheric composition over time or is due to some combination of shock processing and/or variable terrestrial contamination.

Task 5. Iron Isotope Measurements of Terrestrial Rocks and Meteorites (Hauri, Emerson, Kehm)

The possibility that metabolic processing of Fe can produce measurable isotopic fractionation has stimulated wide−ranging efforts to measure such effects in various terrestrial settings. Kehm and Hauri recently developed a technique for measuring precisely the relative abundances of ^{54}Fe, ^{56}Fe, and ^{58}Fe in natural samples. The technique uses an Inductively Coupled Plasma (ICP) mass spectrometer operated at reduced plasma temperatures to produce a stable ion beam with minimal isobaric interferences from molecular species indigenous to the Ar plasma gas.

Results of this initial project include the demonstration of homogenous Fe isotope compositions among both differentiated and undifferentiated bulk meteorites and terrestrial Hawaiian basalt samples. However, variations ranging up to ^{56}Fe = −0.5‰ relative to terrestrial basalt Fe were observed in meteoritic chondrules from an ordinary chondrite. Such variations can plausibly result from rapid Fe condensation in the solar nebula and thus may ultimately provide important constraints on chondrule formation and alteration models.

Since this work, Kehm, Hauri, and Emerson have undertaken a related project to determine the extent of possible isotopic mass fractionation of Fe associated with Fe−metabolizing bacterial colonies around hydrothermal vents on the Loihi seamount. These measurements have indeed revealed isotopically heavy Fe (^{56}Fe ranging up to +0.5‰) in a number of Fe−rich sediments. Currently the group is extending these measurements to a new suite of Loihi bio−precipitates in order to verify and definitively quantify the range of the effects. Their ongoing studies of Fe mass fractionation in chondrules include analyses of chondrules from meteorites from different parent bodies in an effort to determine whether the observed isotopic mass fractionations are parent body or nebular in origin.

Figure 1. *^{13}C solid−state NMR spectra of organic solids derived from four*

different carbonaceous chondrites by Co−Is Cody and Alexander. Note the enormous differences in the carbon chemistry across the meteorite groups. The fraction of aromatic carbon (F_{AR}) exhibits the greatest variation.

Figure 2. *Images of a cluster interplanetary dust particle (IDP) fragment collected in the Earth's stratosphere and analyzed by Co−I Nittler. Left panel: secondary electron image. The IDP consists of carbonaceous material intermixed with fine−grained silicate and sulfide minerals. Right panel: Hydrogen isotope image of IDP generated by ion microprobe. The D/H ratio is highly variable on a micrometer scale. D/H ratios much higher than terrestrial values are associated both with C−rich and C−poor material, indicating partial preservation of interstellar organic material and cometary water.*

Highlights

- Chondrule formation may produce observable chemical signatures in a circumstellar disk.
- CR chondrites contain the most primitive organic matter yet studied from meteorites. The range of compositions seen in chondrites results from aqueous alteration and/or thermal metamorphism under a variety of conditions on the different chondrite parent bodies.
- Pyrolysis of organic matter in interplanetary dust particles during atmospheric entry may have had an important influence on atmospheric chemistry early in Earth's history.
- Ion imaging has revealed for the first time clear evidence for a D−rich, but C−poor, component in IDPs. This material most likely consists of hydrated minerals such as phyllosilicates and has a D/H ratio similar to that observed in cometary water.
- There is a hint that Martian meteorites preserve a record of the evolution of the Martian atmosphere, but the potential influences of shock and/or terrestrial contamination in the meteorites need to be better understood.
- Measurements have revealed isotopically heavy Fe (^{56}Fe ranging up to +0.5‰) in Fe−rich sediments associated with Fe−metabolizing bacterial colonies around hydrothermal vents on the Loihi seamount. This result holds out the promise that Fe isotopes will be a useful biomarker.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Stardust	Analysis techniques
1	Genesis	Analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

CIW has recently purchased, in part with funding from NASA's Sample Return Laboratory Instrument and Data Analysis Program, a field−emission scanning elctron microscope that will be used by Nittler and Alexander to examine cometary and interstellar dust returned by the Stardust mission. Nittler and Alexander are also collaborating with colleagues at the Naval Research Laboratory to improve an accelerator mass spectrometer there to enable high−sensitivity elemental analyses of solar−wind particles to be returned by the Genesis mission.

Cross Team Collaborations

Cody is collaborating with members of the NAI team at the University of Washington (Don Brownlee and Monica Kress) on the experimental simulation of micrometeorite delivery of organic material to the early Earth.

In independent work, Cody is collaborating with Gene McDonald of the JPL NAI team on the chemical structure of tholins, materials suggested to be present on icy bodies in the Solar System.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Studies in Planetary Formation and Evolution

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Studies in Planetary Formation and Evolution***
Project Investigators:	***Alan Boss , R. Paul Butler , Wesley Huntress , Sara Seager , Sean Solomon , Alycia Weinberger , George Wetherill***

Project Progress

During the course of the last five years, the Department of Terrestrial Magnetism (DTM) astronomy group has become perhaps the leading group worldwide studying the detection, formation, and evolution of planetary systems, with a special emphasis on systems containing habitable planets. The addition of staff members Paul Butler, Alycia Weinberger, and Sara Seager during this period, with the anticipated arrival of new staff member John Chambers in early 2004, coupled with a strong contingent of postdoctoral fellows, has buttressed the ongoing theoretical efforts of George Wetherill and Alan Boss to understand the formation of the Solar System in particular and of habitable planets in general. The DTM astronomy group continues to make major contributions to Carnegie's astrobiology research efforts.

Task 1. Detection and Characterization of Extrasolar Planets (Boss, Butler, Haghighipour, McCarthy, Rivera, Seager, von Braun, Weinberger)

Over the last year Butler, postdoctoral fellow Chris McCarthy, and their colleagues have discovered 10 planets from the Lick, Keck, and Anglo−Australian Planet Search programs, which rely on high−precision radial velocity measurements to detect planets indirectly through the wobble of the host star about the center of mass of the star−planet system. These discoveries include two new multiple planet systems, two new sub−Saturn−mass planets, and a planet orbiting at 3.3 AU in a circular orbit. This last system is the closest analogue to the Solar System found to date. Giant planets in circular orbits beyond 3 AU appear to be rare, this being only the second one known.

Butler's goal is to survey the nearest 2,000 solar−type and lower mass stars within 50 parsecs in preparation for the next generation of space−based missions designed to detect and study extrasolar planets, such as NASA's James Webb Space Telescope (JWST), Space Interferometry Mission (SIM), and Terrestrial Planet Finder (TPF), and the European Space Agency's (ESA's) Global Atmospheric Integration for Astrobiology (GAIA) and Darwin

missions. Toward this goal, Butler inaugurated the Magellan Planet Search in December 2002 at Carnegie's Las Campanas Observatory (LCO), adding 500 new Southern Hemisphere stars to his program. Butler and McCarthy are currently surveying a total of 1,700 stars from Lick−Keck in the north and AAT−Magellan in the Southern Hemisphere.

Seager is co−leading a search for short−period giant planets by the transit technique, where the planet's presence is inferred by the dimming of the host star's light when the planet passes in front of the star. The radius of each transiting planet can be determined from the known radius of the star and the amount of its dimming; the radius (together with the mass) is a key constraint on planetary evolution models. Seager's group has three planet candidates for which follow−up radial velocity observations were made during the reporting period. Data analysis is in progress. In addition, Seager and postdoctoral fellow Kaspar von Braun have started a new planet transit search in open star clusters in the southern hemisphere using the Carnegie Swope telescope at the LCO.

Seager has also been working on considering what the Earth would look like if viewed as an extrasolar planet, by interpreting data taken of Earthshine reflected off the dark side of the Moon. These measurements capture the Earth's spatially unresolved spectrum. This work is important for NASA's TPF mission, which will observe similarly spatially unresolved planetary spectra.

Boss and Weinberger have begun a long−term astrometric planet search on LCO's DuPont telescope, starting with a six−night run in May. The goal is to be able to detect long−period Jupiter−mass planets around nearby solar−type and lower mass stars by looking for the positional wobble of the host star as it orbits around the system's center of mass. Astrometric detections are complementary to Butler's radial velocity detections, as astrometry is preferentially sensitive to long−period planets and is able to determine the true mass of the planet, rather than a lower limit on the mass. By determining which of the nearest stars are orbited by Jupiter−like planets in Jupiter−like orbits, this astrometric planet search is intended to help refine the target list for NASA's TPF mission, simplifying the search for Solar System analogues.

Postdoctoral fellow Eugenio Rivera has been performing dynamical fits to the radial velocity data of a few stars with more than one planetary companion. Most of Rivera's work has been on the GJ 876 system, for which the inclusion of the mutual planetary perturbations in the fits to the radial velocity data results in a significantly improved solution. Eventually, it is hoped that these types of fits will strongly constrain the orbital inclinations (and thus the masses) of the planets in this system. Most recently, Rivera was able to put a constraint on the relative inclination between GJ 876's two known planets under the assumption that the recent astrometrically determined inclination of the outer planet was correct.

In collaboration with Rivera, postdoctoral fellow Nader Haghighipour has studied the long−term stability of Earth−like planets in the known extrasolar planetary systems of 47 UMa and 55 Cnc. They found that although 47 UMa's planetary configuration resembles a three−body system similar to that of the

Sun, Jupiter, and Saturn, an Earth−like planet could not have a stable orbit in this system since it would be in an unstable (1:3) resonance with the innermost giant planet. Their work is a part of an ongoing, larger study of the possibility of habitable planets in known extrasolar planetary systems.

In a collaborative research project with members of the NAI team at UCLA, Haghighipour searched for stable, periodic orbits at the location of different orbital resonances with other planets in the system. The idea is to apply the results to extrasolar planetary systems in order to search for regions where habitable planets could have stable orbits for long times (e.g., for the age of the Solar System). The initial focus of this work was on searching for stable orbits in a system with two giant planets in a 1:2 orbital resonance, since the results would then be applicable to the planetary system of GJ 876.

Task 2. Formation of Planetary Systems (Boss, Haghighipour, Roberge, Weinberger, Wetherill)

Weinberger pursued several searches for circumstellar disks around young stars using the W. M. Keck Observatory and the new 6.5−m Magellan Telescopes at LCO. She is using deep 10− and 20−micron imaging to detect reprocessed stellar energy as thermal emission from dusty disks (Figure 1). Weinberger has now surveyed over 50 stars younger than 100 Myr and within 100 pc of Earth. Disks with substantial material in the terrestrial planet region around stars older than 5 Myr seem to be quite rare. This means either that terrestrial planet formation will not take place or that it has already progressed to the point where collisions that generate substantial dust are rare.

In the coming months Weinberger will complete her mid−infrared surveys of the nearby Beta Pictoris and TW Hydrae associations. In July, with postdoctoral fellow Aki Roberge, she will undertake a search for Herbig−Haro objects associated with rather old circumstellar disks. Whether these older stars have outflows will be important to interpreting data on molecular hydrogen to be returned by NASA's Space Infrared Telescope Facility − does this emission arise from an outflow or from a potentially planet−forming disk?

The formation mechanism of Uranus and Neptune is uncertain. A new hypothesis was presented in the last year by Boss, Wetherill, and Haghighipour, envisioning rapid formation of several gaseous protoplanets in a marginally gravitationally unstable protoplanetary disk, coagulation and settling of dust grains within the protoplanets to form rock and ice cores, followed by loss of the outer disk gas and the gaseous envelopes of the protoplanets through extreme ultraviolet (EUV) photoevaporation driven by nearby OB stars. In the past year Boss demonstrated that the first part of this new scenario for ice giant planet formation is feasible in a disk with a gas density similar to that believed to be necessary to form the gas giant planets. A three−dimensional gravitational hydrodynamics code, including a full treatment of thermodynamics and radiative transfer in the diffusion approximation, was used to show that a disk is likely to form two or more gravitationally bound clumps, with masses on the order of 2 Jupiter masses, between 20 AU and 30 AU from a solar−mass star (Figure 2). Such protoplanets could be sufficiently massive to explain the production of the ice giant planets Uranus and

Neptune, following photoevaporation of most of their gaseous envelopes. This new scenario implies that planetary systems similar to our own could form even in seemingly hostile regions of high−mass star formation. This scenario, if correct, has important implications for the frequency of habitable planetary systems, as it raises the likelihood of finding such systems by roughly a factor of five, because most stars are believed to form in regions of high−mass star formation.

Haghighipour has been studying the combined effect of gas drag and pressure gradients in expediting the formation of planetesimals in a marginally gravitationally unstable protoplanetary disk. Because the disk gas is partially supported against gravity by the gas pressure gradient, the disk gas orbits faster than Keplerian for orbits inside that of a local pressure maximum in the disk and slower than Keplerian outside a local pressure maximum, producing gas drag forces on solids that lead to tailwinds and headwinds, respectively. As a result, solids migrate toward local pressure maxima, where they can collide and grow larger. Haghighipour has generalized this work to three dimensions by considering a non−negligible height for the disk and including the fully three−dimensional motions of solids. The results indicate an increase in the rate of the vertical and radial migration of solids toward the location of local density enhancements in the midplane of a non−uniform disk. The immediate implication is a shorter time for the formation of planetesimals and thus somewhat hastened formation of habitable planets similar to the Earth.

Task 3. Evolution of Planetary Water (Solomon)

One of the long−term goals of this NAI project is to assess the likelihood, timing, and physical and chemical environments of hydrothermal systems on Solar System objects other than Earth. Solomon's efforts on this project during the past year have focused on Mars, primarily because of the influx of new data from the Mars Global Surveyor (MGS) and Mars Odyssey missions. An important contribution has been the development of the suggestion that the pattern of paleomagnetic anomalies on Mars may have been strongly influenced by hydrothermal alteration of magnetic carriers, as a result of processes similar to those that occur in very young oceanic crust on Earth. In particular, his suggestion is that the paucity of magnetic anomalies discernible by orbiting spacecraft in the northern lowlands and young impact basins on Mars may be the result of chemical alteration and consequent lowered magnetization enabled by deep hydrothermal circulation beneath prominent drainage basins on Mars. Beyond its potential importance for constraining the history of the Martian crust and dynamo, this hypothesis may provide a basis for assessing the depth of penetration of hydrothermal activity in the Martian crust and the locus and timing of areas of such activity.

Figure 1. *False−color image of the disk around the star Beta Pictoris taken at wavelengths around 18 microns by Co−I Weinberger (top) and the same image after computer deconvolution with the Lucy−Richardson algorithm (bottom), showing dust heated by the star to temperatures of 150−500 K. A radius of 1 arcsecond corresponds to 20 AU. A tilt of the inner disk, out to 1 arcsec, is revealed for the first time in these images. The dust may be*

perturbed in this way by planets orbiting within the disk.

Figure 2. *False−color representation of the midplane density in Co−I Boss?s three dimensional radiative hydrodynamics model of a marginally gravitationally−unstable disk with a radius of 30 AU. Blue−red regions are high−density clumps of gas and dust that formed within less than 1000 years of disk evolution. Such clumps could become protoplanets that serve as the predecessors of the ice giant planets, following removal of the bulk of their gaseous envelopes by EUV radiation from nearby massive stars.*

Highlights

- Ten new planets were discovered by high−precision radial velocity surveys, including the closest known analogue to our Solar System.
- A transit−planet search yielded three promising candidates for new extrasolar planets.
- Orbital stability of Earth−like, habitable planets in known extrasolar planetary systems has been constrained by theoretical modeling.
- Observations of suspected protoplanetary disks imply that planet formation must occur faster than previously thought.
- A new scenario for Solar System formation raises the estimated frequency of habitable planetary systems by a factor of five.
- A new hypothesis to account for the pattern of crustal magnetic anomalies on Mars suggests that these features may provide a basis for assessing early hydrothermal activity and hence possibilities for early life on Mars.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Co−I, MOLA
1	MESSENGER	PI

1	Kepler	Science Team member
1	SIRTF	Co−I; background research
1	MOST	Support Scientist
2	TPF	SWG member (2)
2	CSR	Co−I
2	Venus Orbiter and Probe	PI

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Solomon is a member of the Mars Orbiting Laser Altimeter (MOLA) team on the Mars Global Surveyor mission.

Solomon is the PI for the MESSENGER Discovery mission to Mercury, to be launched next year.

Boss is a member of the Science Team for the Kepler mission to search for transiting planets.

Seager is a Co−Investigator for the Legacy Program and the Galactic Plane Survey on the Space Infrared Telescope Facility (SIRTF).

Weinberger will be carrying background research for SIRTF by identifying circumstellar disks for follow−up SIRTF observations at wavelengths inaccessible from the ground.

Seager is a Support Scientist for the Microvariability and Oscillations of Stars (MOST) Microsatellite, to be launched by the Canadian Space Agency.

Boss and Seager are members of the Scientific Working Group for the Terrestrial Planet Finder (TPF) mission.

Huntress is a Co−Investigator on a team preparing to propose a Comet

Surface Sample Return mission to the NASA New Frontiers Program, and he's probe PI for a team preparing to propose a Venus Orbiter and Probe mission to the NASA Discovery Program.

Field Expeditions

Field Trip Name: DuPont Telescope, Las Campanas Observatory	
Start Date: May 2003	***End Date:*** May 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Boss and Weinberger have begun a long−term astrometric planet search, complementary to the radial velocity searches underway by Butler. This observing trip initiated the search with 6 nights on the 2.5−m DuPont telescope.	
Members Involved: Alan Boss	

Field Trip Name: W. M. Keck Telescope	
Start Date: July 1, 2002	***End Date:*** June 30, 2003
Continent:	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:***
Latitude: 19o 49.7' N	***Longitude:*** 155o 28.7'
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Butler observing (stellar radial velocity measurements to search for extrasolar plaents): July 30−August 1, August 27−28, September 17−21, October 24−27, November 21−23, 2002; January 11, January 12−13, February 9, February 11, February 14−15, and March 12−13, 2003. Weinberger observing (mid−infrared imaging of young stars to detect their dusty disks): November 13−14, 2002.	
Members Involved: R. Paul Butler	

Field Trip Name: Anglo−Australian Telescope	
Start Date: July 1, 2002	***End Date:*** June 30, 2003
Continent:	***Country:***
State/Province: New Southe Wales	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Butler and McCarthy observing (stellar radial velocity measurements to search for extrasolar planets); July 20−21, November 13−16, November 19−21, 2002; April 15−22, and May 24−27, 2003.	
Members Involved: R. Paul Butler	

Field Trip Name: Magellan Baade Telescope, Las Campanas Observatory	
Start Date: July 1, 2002	***End Date:*** June 30, 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude: 29o 0.2'	***Longitude:*** 70o 42.1' W
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Butler observing (stellar radial velocity measurements to search for extrasolar planets): December 15−18, 2002; January 20−23, May 18−21, and June 15−17, 2003. Weinberger observing (mid−infrared imaging of young stars to image their dusty disks): August 24−29, 2002. von Braun observing (spectroscopic follow−up work of planetary transit candidates from previous photometric monitoring surveys): February 8−10, 2003.	
Members Involved: R. Paul Butler	

Field Trip Name: VLT2	
Start Date: July 1, 2002	***End Date:*** June 30, 2003
Continent:	***Country:***

State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Butler observing (asteroseismology): May 16, 2003	
Members Involved: R. Paul Butler	

Field Trip Name: Kitt Peak 4−m Telescope	
Start Date: October 12, 2002	***End Date:*** October 29, 2002
Continent: North America	***Country:*** USA
State/Province: Arizona	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: von Braun observing (photometric monitoring of a rich galactic field ("EXP3") to search for planetary transits).	
Members Involved: Kaspar Von Braun	

Field Trip Name: Las Campanas Swope 1−m Telescope	
Start Date: February 10, 2003	***End Date:*** April 23, 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: von Braun observing (photometric monitoring of open clusters to search for planetary transits): February 10−28, April 9−23, 2003.	
Members Involved: Kaspar Von Braun	

Field Trip Name: Cerro Tololo Interamerican Observatory 4−m Telescope	
Start Date: June 7, 2003	***End Date:*** June 20, 2003

Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: von Braun observing (photometric monitoring of a rich galactic field ("EXP4") to search for planetary transits.	
Members Involved: Kaspar Von Braun	

Cross Team Collaborations

Boss, as a member of the Science Working Group for the Kepler mission, is collaborating with members of the NAI teams at NASA Ames (Jack Lissauer) and the University of Washington (Don Brownlee).

Haghighipour is collaborating with members of the UCLA NAI team (William Moore and Farenc Varadi) in his searches for possible stable orbits for habitable planets in known extrasolar planetary systems.

Huntress is a Co−Investigator on the JPL NAI team led by Victoria Meadows. On that team he serves as an interface between theoretical planetary atmospheric modeling efforts and laboratory work at CIW and elsewhere on chemical processes included in the models.

Solomon is collaborating with Bruce Jakosky of the University of Colorado NAI team on the evolution of Martian water and its implications for Martian hydrothermal activity.

Weinberger continues her long−term collaboration with Eric Becklin, Ben Zuckerman, and Andrea Ghez of the UCLA NAI team on infrared observations of young stars.

Two staff changes next year will involve the movement of individuals from one NAI team to another. John Chambers, now on the Ames NAI team, will be joining the Carnegie Insitution as a member of the Research Staff in the spring of 2004. Steven Desch, now on the CIW NAI team, will be joining the faculty at Arizona State University this fall. Both appointments will present new opportunities for cross−team collaboration.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Theoretical Studies of Hydrothermal Synthesis Reactions

Lead Team:	***Carnegie Institution of Washington***
Project Title:	***Theoretical Studies of Hydrothermal Synthesis Reactions***
Project Investigators:	***Everett Shock , Harold Morowitz***

Project Progress

Task 1. Thermodynamics of Hydrothermal Organic Reactions (Shock, Zolotov)

During the last year Shock and Zolotov modeled the potential for microbial metabolism on Europa. Thermodynamic calculations were used to examine the possibility that sulfate reduction might be a metabolic strategy allowed by the complex chemical processes thought to occur on Europa. The model employs a sulfate−bearing ocean, originating from quenched hydrothermal fluids generated during differentiation, which interacts with hydrogen (H_2) released by hydrothermal fluids. The resulting energy is on the order of a few kilojoules per kilogram of water and is limited either by low H_2 or sulfate concentrations. This process represents an irreplaceable source of energy early in the history of Europa, owing to the likely decline of hydrothermal processes that generate H_2. If sulfate reduction remains a viable strategy for Europa, a source of reductant(s) other than H_2 would be required, including organic compounds.

Task 2. Theoretical Analysis of the Energetic Landscape of Ecosystems (Shock)

Because hydrothermal systems are populated by the deepest−branching organisms in the universal phylogenetic tree, they are the oldest continuously inhabited ecosystems on Earth. There is a clear interest in juxtaposing the genetic diversity with the geochemical (energetic) diversity in such systems. If such a relationship can be established, the results may reveal how ecosystems originate and evolve.

Highlights

- Thermodynamic calculations support the possibility that sulfate reduction may be metabolically viable on Europa given the complex chemical processes thought to occur there.

Roadmap Objectives

- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

NASA ASTROBIOLOGY INSTITUTE
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Fellowships: Carnegie Institution of Washington

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Henry Scott
Project Title: Oxidation of Organic Carbon Under High Pressure Hydrothermal Processing
Advisor: Russell Hemley, Project Investigator
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: July 2002

Recipient: Michael Smoliar
Project Title: Re−Os study of hydrothermal processes in ordinary chondrites
Advisor: Conel Alexander, Advisor
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: September 2002

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

EPO: Carnegie Institution of Washington

These are the Education and Public Outreach activities for the Carnegie Institution of Washington.

Capital Science Lectures

To make science more accessible to the general public, the Carnegie Institution began the Capital Science Lectures in the fall of 1990. These free public talks are designed to help nonscientists understand scientific thinking and to appreciate the importance of basic research in our lives today. For the past four years, speakers have been chosen to focus on the Institution's interest in Astrobiology. The 2002/2003 series featured talks by such scientists as Marilyn Fogel, Kip Thorne, Peter Grant and Jennifer Doudna. The series also featured a premier of the movie Cosmic Africa, which follows South African astrophysicist Thebe Medupe in a journey across Africa, examining indigenous mythologies and cosmologies and how these beliefs and practices mix with modern astronomy. The series is also attended by students of local high schools. They meet with the presenter before the lecture to discuss the research and to have personal interaction with the scientist. Students from several area schools have been attending since the inception of the lecture series.

Astrobiology Educator Presentations

The Carnegie Institution provided an Astrobiology workshop at the National Convention of the National Science Teachers Association in Philadelphia, PA in March 2003. The hands−on workshop for elementary teachers featured the NAI Astrobiology Educator's Guide, the 'Discovering New Worlds of Life' poster and the 'Ice in the Solar System' education module. Dr. Andrew Steele also presented a talk entitled 'How to Spot a Martian' as part of the Astrobiology Short Course at the same convention.

Astrobiology Presentations for the General Public and Special Interest Groups

The Carnegie Institution of Washington offered the following presentations for the general public and special interest groups:

−George Cody presented at the 'Astrophysics of Life' conference at the space telescope institute in Baltimore, MD. He also presented a public seminar at UCLA.
−Alan Boss contributed an article 'They Might be Gaints' to Mercury, the

magazine of the Astronomical Society of the Pacific.
−Paul Butler contributed to the Summer Science Programs in Ojai, CA (Aug 2002) and Socorro, NM (June 2003) and gave the Carnegie Observatories Centennial lecture in Pasadena, CA (May, 2003).
−Sara Seager presented to the National Capital Astronomers Club, Washington DC (April, 2003).
−Robert Hazen presented to the Learning in Retirement Institute in Fairfax, VA. He was also invited to talk to the American Chemical Society in New Orleans, LA.
−Sarah Stewart presented a talk entitled 'When Worlds Collide or " Comet Busting'" to the University of Maryland Small Bodies Group in January, 2003.
−Alycia Weinberger presented a talk entitled 'Circumstellar Disks and their Clues for Planet Formation' to the National Capital Astronomers Club, Washington DC (June 2003).
−Henry Scott presented a talk 'The Chemical Stratification and habitability of Jupiter's Ganymede' to the meeting of the Geological Society of Washington (January 2003). He also presented a talk entitled 'High−Pressure Hydrothermal Processing in Large Icy Satellites' to the American Geophysical Union (San Francisco, CA, December 2002).
−Nader Haghighipour presented an invited lecture to the National Science Foundation entitled 'Challenges in Theoretical Astronomy.'
−Sara Seager presented a talk entitled 'Future Research Directions and Visions for Astronomy' at the Society of Professional Industrial Engineers conference (August 2002).

Carnegie Academy for Science Education Summer Institute

An intensive five−week graduate science institute for elementary teachers in the District of Columbia Public Schools, this Institute is organized around a broad theme of science. In 2002, part of the Institute was organized around the theme of Astrobiology. Teachers experience a range of activities, concepts, and content that enable them to teach science and mathematics more effectively. Astrobiology−related themes included microbes, hydrothermal vent morphology and biology, extra−solar planets, planetary geology, and mission design. Scientists contribute to the work of classroom educators by highlighting scientific discoveries and leading activities. Participating scientists in 2002 included James Scott and Marilyn Fogel.

Astrobiology Coursework

Robert Hazen developed and taught a two−semester graduate seminar entitled "The Literature of Astrobiology" as part of the new Astrobiology PhD program at George Mason University. This course surveyed more than 200 primary articles in Astrobiology on wide−ranging topics: prebiotic chemistry, molecular phylogeny, extremophiles, Precambrian geology and paleontology, current planetary exploration missions and more. This course will be repeated in alternate years.

Astrobiology Conferences and Committees

The Carnegie Institution of Washington was a member of the following committees:

− Co−Chair, National Research Council (NAS) Committee on the Origins and Evolution of Life in the Universe (2000−2003)
−NASA's Terrestrial Planet Finder scientific working group;

The Carnegie Institution of Washington co−organized and co−convened the James Web Space Telescope Astrobiology Workshop, Washington DC, in May 2003.

Carnegie Seminar Series

The Department of Terrestrial Magnetism and the Geophysical Laboratory each hold weekly scientific seminars. Speakers include visitors and members of the staff, with topics ranging from astrophysics and planetary sciences to geochemistry and seismology. The seminars are announced to the community with monthly schedules sent to 214 institutions and individuals in the Washington metropolitan area.
The following seminars were given by scientists associated with the NASA Astrobiology Institute, and by speakers on subjects related to Astrobiology.

2002

July 10 Steven J. Desch
Department of Terrestrial Magnetism
Carnegie Institution of Washington
"Melting of Chondrules by Solar Nebula Shocks"

July 17 Carey M. Lisse
Department of Astronomy
University of Maryland
"On the Evolution and Extinction of Comets as Sources of Interplanetary Dust Cloud and Near Earth Objects?"

November 6 Michael J. Mumma
NASA Goddard Space Flight Center
"A Current View of Organic Volatiles in Comets"

December 4 Nader Haghighipour
Department of Terrestrial Magnetism
Carnegie Institution of Washington
"Rapid Migration of Small Solids in a Non−Uniform Solar Nebula"

December 18 Bosmat A. Cohen

Rutgers, The State University of New Jersey
"The Formation of Chondrules by Open−system Melting of Nebular Condensates"

2003

January 8 Richard W. Carlson
Department of Terrestrial Magnetism
Carnegie Institution of Washington "Early Solar System Chronology"

January 15 Eugenio J. Rivera
Department of Terrestrial Magnetism
Carnegie Institution of Washington
"The Dynamical Evolution of the Earth−Moon Progenitors"

January 29 Marc J. Kuchner
Harvard−Smithsonian Center for Astrophysics
"Reading the Resonant Signatures of Planets in Debris Disks"

February 26 Qing−zhu Yin
Harvard University
"Resetting the Clock on Planet Formation"

March 3 Steven J. Desch
Department of Terrestrial Magnetism
Carnegie Institution of Washington
"Magnetic Fields during Star Formation"

March 5 Michael C. Liu
University of Hawaii
"Young Brown Dwarfs and Exoplanets"
March 10 Kevin L. Luhman

March 10 Kevin L. Luhman
Smithsonian Astrophysical Observatory
"The Number Distributions of Stars, Brown Dwarfs, and Planets"

March 27 John E. Chambers
NASA Ames Research Center
"Delivery of Volatiles to Habitable Planets"

April 23 Scott J. Kenyon
Harvard Smithsonian Center for Astrophysics
"Dusty Rings: Signposts of Recent Planet Formation"

May 2 Maria Schönbächler
ETH−Zürich
"Nb−Zr Chronometry and Early Solar System Development"

May 28 Natasha M. Johnson
Goddard Space Flight Center

"Venus, Water and Tremolite"

June 18 John Gizis
University of Delaware
"Observations of Brown Dwarfs"

GL SEMINARS

The following seminars were given by GL scientists, Postdoctoral Fellows and Invited Guest Speakers from other Universities.

2002

July 1 Martin Brasier, Oxford University, and John Lindsay, NASA JSC, Houston, TX
"Questioning Evidence of Earth's Earliest Fossils"

October 7 Sarah Russell
Natural History Museum, London
"Isotopic Constraints on the Formation of Chondrules"

October 28 Hyman Hartman
Massachusetts Inst. of Technology
"The Origin of Life: A Simple Solution"

November 21 Antonio Salgado Serrano Centro de Astrobiologia, Spain
"Development of Novel Biosensors: Use of Highly Functionalized Derivatives of D−Glucosamine as Versatile Spacers in DNA−Chips"

2003

February 24 Steven D'Hondt
University of Rhode Island
"Life Beneath the Seafloor"

March 3 Jackie Dixon
University of Miami
"Temporal Evolution of Water in the Mantle"

March 17 Pan Conrad
Jet Propulsion Laboratory
"The Effect of Microbial Attachment on Carbonate Dissolution"

March 26 Jim Lyons
UCLA
"Mass−independent Fractionation of Oxygen Isotopes in the Modern Atmosphere"

March 31 Patricia Foster
Indiana University/Biosciences − Genetics
"Mutation Under Stress: Insights from the Study of Adaptive Mutation in E. Coli"

May 5 Craig Manning
UCLA
"The Deep Blue Planet: Aqueous Chemistry in the Earth's Lower Crust and Mantle"

May 12 Rhonda Stroud
Naval Research Laboratory
"Focused Ion Beam and Electron Microscopy of Presolar Grains"

May 19 Freeman Dyson
Princeton − Institute for Advanced Study
"Looking for Life in Unlikely Places: Reasons Why Planets May Not Be the Best Places to Look for Life"

May 22 Alexandre I. Tsapin
Jet Propulsion Laboratory, Life Detection Group
"New Approach to Life Detection: Chirality as a Biomarker"

June 16 Graham Cairns−Smith
University of Glasgow
"The Origins of Life: Putting Natural Selection First"

Carnegie Summer Intern Program

The Carnegie Summer Intern Program in Geoscience brings about 20 college students, competitively selected, to our campus every summer for an intensive 10−week experience in original scientific research. At a symposium held at the end of the program, students report on the results of their research. Several interns have been lead authors of related articles later published in scientific journals.
Interns who worked on astrobiology topics included:

Denise M. Akob, St. Mary's College of Maryland, Biology
"Constructing Food Webs of Mangrove Invertebrates Using Stable Isotopes"

Hugh Churchill, Oberlin College
"pH−Dependent Relative Surface Charge of Quartz Measured with Atomic Force Microscopy (AFM): Implications for Amino Acid Adsorption"

Leah Hutchison, Massachusetts Institute of Technology
"Mineralogy of Silicate Dust Grains in Circumstellar Disks around T Tauri Stars"

Stephen Lin, Montgomery Blair High School

"An Investigation into the Chemical Formation of Organic Macromolecules in Carbonaceous Chondritic Meteorites"

Rebekah Miller, Swarthmore College
"Nitrogen in Studies of Prebiotic Chemistry: The Formation of Amino Acids and Highly Conjugated Systems"

Laura Mitterman, University of Pennsylvania
"Preservation of Fossils in Two Lacustrine Environments of Southwest Germany"

Eric Nadal, University of British Columbia
"Type I Migration and Dynamical Friction; a Possible Scenario for the Capture of the Gliese 876 Planets in a 2:1 Resonance"

James Norwood, Harvey Mudd College
"Investigation of the Effects of a Stellar Companion upon the Stability of the Planetary System of Upsilon Andromedae"

Maia Schweizer, Princeton University
"Reconstructing Enspel: Using Stable Isotopes to Investigate an Oligocene Lacustrine Ecosystem"

Astrobiology: Discovering New Worlds of Life Poster (Interactive)

An interactive version of the award−winning poster, Astrobiology: Discovering New Worlds of Life (published in 2002) has been produced. The poster is mounted on a touch−sensitive screen, connected to a computer hard drive and a flat screen monitor. When touched, several of the features on the poster activate the monitor to display exciting video footage of life in hydrothermal vents, the scientists and their research of such communities, piloting the Alvin and more. This product is portable, occupies little space and may be set up by a single individual. It will be made available to all members of the NAI scientific and EP/O teams to be displayed at conferences, schools, universities and public lectures. It will then be made available to museums, science centers and libraries for public display on a rotational basis.

Mineralogical Society of America 'Distinguished Lecturer': Lectures on Astrobiology in the US and Germany

Robert Hazen was named the Mineralogical Society of America's "Distinguished Lecturer" for 2002−2003. He delivered one or more of 3 lectures on Astrobiology themes (26 lectures total) at 18 colleges and universities in North America and Europe. These venues include: Mary Washington College, VA; LaSalle University, PA; LaFayette University, PA; UC Berkeley; University of Puget Sound; California State University, Fresno;

Washington University, MO; University of Southern Illinois; University of Missouri; University of Southern Georgia; Georgia State University; Tennessee Technological University; University of Kiel, Germany; University of Greifswald, Germany; University of Freiberg, Germany; University of Bochum, Germany; University of Cologne, Germany; University of Muenster, Germany.

Robert Hazen serves on the boards of NOVA (WGBH, Boston), Encyclopedia Americana, the Carnegie Council, and Earth Sky. He is also a member of the American Association for the Advancement of Science (AAAS) Committee for the Public Understanding of Science and Technology.

Astrobiology Articles in the Spectrum Newsletter

A quarterly publication of the Carnegie Institution of Washington for staff and interested members of the general public regularly features articles about Astrobiology research. Articles also appear on the Institution's Web site. The most recent issue featured such articles as "Scientists Trap Hydrogen Gas in Ice 'Cages'" and "The CO2 Puzzle."

Astrobiology Invited Lectures

Alan Boss gave a series of invited lectures to the Seventh Cycle of Special Courses, National Observatory, Rio de Janiero, Brazil from July 2002 to November 2002. These were:

`Discovery of Extrasolar Planets' July 2002.

`Triggering the Formation of the Solar System' July 2002.

'Gas Giant Planet Formation' July 2002.

'Terrestrial and Ice Giant Planet Formation' July 2002.

He also presented the following public lecture:
'A Heretic's Approach to Solar System Formation' (public lecture), Benjamin Dean Lecture Series on "Dissecting Solar Systems,"California Academy of Sciences, San Francisco, California, November 2002.

'Ice in the Solar System' Interactive CD

An interactive CD entitled 'Ice in the Solar System' has been developed. The CD is designed for both students and teachers of Grade levels Pre−K to 5. The CD provides a series of lessons and experiences that build a conceptual understanding of ice here on Earth and beyond. The lessons progress through eight major conceptual strands: Ice as an immediate experience; Ice is water;

Ice has structure; Ice is both rock and mineral; Ice in motion; Ice and energy transfer; Ice in layers; Ice and life; Ice in space. Each strand contains lessons for students in grades K−2 and 3−5 that are aligned with the National Science Education Standards and the American Association for the Advancement of Science (AAAS) Benchmarks for Science Literacy. Each strand also has engaging student activities and interactive quizzes for independent learning and exploration. In addition, the CD contains a glossary linked to a gallery of over 50 video or still images which help to illustrate the topics covered in each of the eight conceptual strands and lead to deeper understanding.

The framework of the lessons was designed by Richard Shope, an Education and Public Outreach Coordinator of the Jet Propulsion Laboratory. The CD was designed and programmed by Crabtree and Company of Falls Church, VA. The CD will be distributed through Science Scope, a magazine of the National Science Teachers Association (NSTA), at NSTA and other conferences at which the Education and Public Outreach Division of NAI or other NASA funded group is presenting, by direct mail upon request and through the NAI EP/O team members.

Astrobiology Features in the Popular Media

Carnegie Institution of Washington scientists and their Astrobiology research were featured in a number of publications for the general public:
−National Geographic ran a sidebar in its July, 2002 issue that talked about Carnegie's centennial and its Astrobiology work. James Scott was quoted about his research with extremophiles.
−Sean Solomon was quoted in Astronomy Magazine about Mercury and the MESSENGER Mission.
−A monumental roundup on the state of cosmology that appeared in the July 23, 2002 edition of the New York Times featured several Carnegie scientists.
−The work of Alan Boss, George Wetherill and Nader Haghighipour dealing with the origins of Uranus and Neptune was featured in the July 2002 issue of Sky Telescope, Astrobiology Magazine and SPACE.com. Images from Boss's model on planet formation were featured in the August 2002 Sky Telescope.

Astrobiology Presentations to Students

The Carnegie Institution presented a number of talks or workshops to students.
−Sara Seager presented colloquia to the Institute for Astronomy, University of Hawaii (August 2002) and the University of Virginia (April 2003). She also gave seminars at Shawnee State University, Ohio (October 2002) and Goddard Space Flight Center (May 2003). In addition she presented informal talks to the UCLA Astronomy Journal club and to the Evolution group (April 2003).
−Alycia Weinberger presented to the 'Young Engineers and Scientists Seminar' lecture series (March 2003) and to the NSF Summer Interns (July 2002). She had a presentation 'So you want to be an Astronomer?' at the Elementary School career days at Rock Creek Park Elementary School, MD (July 2002) and at Florham Park, NJ (June 2003).

−Nader Haghighipour presented an invited talk 'One Hundred Other Solar Systems: How Planetary Systems are Formed' at George Mason University, VA. He also presented an invited lecture 'Extrasolar Planetary Systems: Theoretical Challenges' to the Department of Commerce Science and Technology Fellowship Program.
−Robert Hazen presented at the Johns Hopkins University, MD and at Cornell University, NY.

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ANNUAL REPORT YEAR 5
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Members: Carnegie Institution of Washington

Team Members sorted by current team.

Name:	Michael Acierno
Email:	acierno@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Conel Alexander
Email:	alexander@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	John Baross
Email:	jbaross@u.washington.edu
Institution:	University of Washington
Name:	James Bischoff
Email:	jimb@octopus.wr.usgs.gov
Institution:	USGS Menlo Park
Name:	Nabil Boctor
Email:	n.boctor@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Alan Boss
Email:	boss@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Jay Brandes
Email:	brandes@utmsi.edu
Institution:	University of Texas, Austin
Name:	Billy Brazelton

Email:	braz@u.washington.edu
Institution:	University of Washington
Name:	R. Paul Butler
Email:	paul@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	James Cho
Email:	cho@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Ines Cifuentes
Email:	icifuentes@pst.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Mary Coder
Email:	coder@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	George Cody
Email:	g.cody@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Albert Colman
Email:	a.colman@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Steven Desch
Email:	desch@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Janice Dunlap
Email:	dunlap@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Julie Edmonds

Email:	jedmonds@pst.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	David Emerson
Email:	demerson@gmu.edu
Institution:	George Mason University
Name:	James Farquhar
Email:	jfarquhar@ucsd.edu
Institution:	University of Maryland
Name:	Marilyn Fogel
Email:	fogel@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Nader Haghighipour
Email:	nader@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Shaun Hardy
Email:	hardy@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Erik Hauri
Email:	hauri@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Robert Hazen
Email:	r.hazen@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Russell Hemley
Email:	r.hemley@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Mary Horan

Institution:	Carnegie Institution of Washington
Name:	Julie Huber
Email:	huberja@u.washington.edu
Institution:	University of Washington
Name:	Brooke Hunter
Email:	hunter@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Wesley Huntress
Email:	whuntress@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	David Johnston
Email:	dtj@geol.umd.edu
Institution:	University of Maryland
Name:	Jonathan Kaye
Email:	jzkaye@u.washington.edu
Institution:	University of Washington
Name:	Karl Kehm
Email:	kkehm2@dtm.ciw.edu
Institution:	Washington College
Name:	Sandra Keiser
Email:	keiser@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Kono Lemke
Email:	klemke@pangea.stanford.edu
Institution:	Stanford University
Name:	M. Mahmood
Email:	mmahmood@howard.edu

Institution:	Howard University
Name:	Jake Maule
Email:	Jake.g.maule1@jsc.nasa.gov
Institution:	Carnegie Institution of Washington
Name:	Christopher McCarthy
Email:	mccarthy@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Mausmi Mehta
Email:	mausmi@u.washington.edu
Institution:	University of Washington
Name:	D'Arcy Meyer−Dombard
Email:	darmeyer@artsci.wustl.edu
Institution:	Washington University
Name:	Harold Morowitz
Email:	morowitz@gmu.edu
Institution:	George Mason University
Name:	Sujoy Mukhopadhyay
Email:	sujoy@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Larry Nittler
Email:	nittler@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Shuhei Ono
Email:	s.ono@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Eugenio Rivera
Email:	rivera@dtm.ciw.edu

Institution:	Carnegie Institution of Washington
Name:	Aki Roberge
Email:	roberge@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	David Ross
Email:	dross3@yahoo.com
Institution:	USGS Menlo Park
Name:	Douglas Rumble
Email:	d.rumble@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Gotthard Saghi−Szabo
Email:	g.saghi−szabo@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Matthew Schrenk
Email:	mos@u.washington.edu
Institution:	University of Washington
Name:	Maia Schweizer
Email:	m.schweizer@gl.ciw.edu
Institution:	Princeton University
Name:	Henry Scott
Email:	h.scott@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	James Scott
Email:	Scott@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Sara Seager
Email:	seager@dtm.ciw.edu

Institution:	Carnegie Institution of Washington
Name:	Anurag Sharma
Email:	a.sharma@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Everett Shock
Email:	eshock@asu.edu
Institution:	Arizona State University
Name:	Michael Smoliar
Email:	smoliar@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Sean Solomon
Email:	scs@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Terry Stahl
Email:	stahl@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Andrew Steele
Email:	a.steele@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Robin Sutka
Email:	rsutka@atcc.org
Institution:	George Mason University
Name:	Fouad Tera
Email:	tera@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Jan Toporski
Email:	j.toporski@gl.ciw.edu

Institution:	Carnegie Institution of Washington
Name:	Harri Vanhala
Email:	hvanhala@challenger.org
Institution:	Challenger Center
Name:	Kaspar Von Braun
Email:	vonbraun@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Richard Walker
Institution:	University of Maryland
Name:	Jianhua Wang
Email:	wang@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Pei−Ling Wang
Email:	p.wang@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Alycia Weinberger
Email:	alycia@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	George Wetherill
Email:	wetherill@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Merri Wolf
Email:	wolf@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Hatten Yoder, Jr.
Email:	h.yoder@gl.ciw.edu
Institution:	Carnegie Institution of Washington

Name:	Misha Zolotov
Email:	zolotov@zonvark.wustl.edu
Institution:	Washington University

Harvard University
Executive Summary
Principal Investigator: Andrew Knoll

Introduction

The Harvard NAI team was constituted in 1998 as an interactive group of biogeochemists, paleontologists, sedimentary geologists, geochemists, and tectonic geologists assembled with the common goal of understanding the coevolution of life and environments in Earth history. The team originally proposed to focus multidisciplinary research on four critical intervals of planetary change: the early Archean (>3000 million years ago) when life began, the early Paleoproterozoic (2400−2200 Ma) when oxygen began to accumulate in the atmosphere and surface ocean, the terminal Proterozoic and Early Cambrian (750−525 Ma) when animal life radiated, and the Permo−Triassic boundary (251 Ma) when mass extinction removed some 90 percent of Earth's species diversity, permanently altering the course of evolution. Given reduced funding levels in years 1 and 2, however, the team chose to focus on the latter three intervals; over the past five years, team members have made substantial contributions to each research area. Fortunately, increased funding in years 3 to 5 and strong interest by additional colleagues at Harvard and MIT enabled us to expand both our membership and intellectual purview. Thus, to the three projects funded from the outset (and approached in fresh ways by our newest co−investigators), we have added four additional research foci. John Hayes' research at the interface of microbiology and biogeochemistry expanded as a result of incremental funding that enabled his group to undertake a substantial collaborative effort with the NAI Team at MBL; the addition of Dan Schrag (Harvard) in year 2 and Roger Summons (MIT) in year 4 further bolstered our team's collaborative research in biogeochemistry. In association with the Spanish Center for Astrobiology, Andrew Knoll completed research on Neogene iron formations in southern Spain that will play a direct role in guiding exploration of Mars hematites by the recently launched Mars Explorer Rovers (MERs). Charles Marshall pursued statistical analyses of molecular sequence and biostratigraphic data as part of the NAI Focus Group on Evogenomics. Lastly, Dan Schrag initiated collaborative research with MIT's Maria Zuber that addresses the enigma of Mars' carbonate−poor surface and, hence, the history of water on the red planet.

Scope of Team Activities in 2003−2004

Research by the Harvard team is interdisciplinary, attracting broad

participation by scientists within the five member institutions (Harvard, MIT, WHOI, Rochester, Smithsonian Institution). We have also been successful in promoting cross−team collaborations −− research projects have been undertaken with colleagues from the Carnegie, MBL, Rhode Island, Penn State, NASA Ames, and JPL teams, as well as both the Spanish and Australian astrobiology centers. Moreover, our team participated actively in the Evogenomics Focus Group and took a leadership position in the Mission to Early Earth Focus Group (A. Anbar). Team members are active in research on novel biosignatures and digital mapping technologies that can be applied to solar system research; A. Knoll and J. Grotzinger are members of the 2003 Mars MER science team; and R. Summons serves on Mars Exploration Program Assessment Group (MEPAG) and the Astrobiology Science Strategy Group, committees charged with defining astrobiological research strategies for upcoming Mars missions. Equally important, research by Harvard team members on sedimentary and geochemical biosignatures as well as early states of Earth's atmosphere will directly influence plans for continuing planetary exploration and the projected Terrestrial Planet Finder mission.

During the past year, Harvard team members conducted field research in Australia, southern Africa, Svalbard, the Canadian Rocky Mountains, China, and Oman. We also taught actively at three universities and in the International Geobiology course, a summer course in geobiology for graduate students and postdoctoral fellows, sponsored by the Agouron Institute. In year 5, much of our Education and Public Outreach (EPO) effort focused on university teaching, but we also helped to develop a traveling museum exhibit on biology and Earth history, in partnership with the Harvard Museum of Natural History, and individual team members lectured to K−12 and adult groups.

Research Accomplishments in 2003−2004

Subproject 1: The Proterozoic Oxidation of the Earth's Surface

The history of oxygen in the oceans and atmospheres is thought to have played a key role in Earth's long term biological evolution. Ongoing research by Harvard team members addresses the initial oxygenation of the atmosphere and surface ocean 2400−2200 million years ago (Ma), renewed oxygen influx near the end of the Proterozoic Eon, and life and environments between those two events.

Research by H.D. Holland and colleagues has sharply constrained the timing of Earth's initial atmospheric oxygenation. Measurements of the isotopic composition of sulfur in pyrites from the Timeball Hill and Rooihogte formations, South Africa, show both a considerably larger range in ^{34}S than older sulfides and the absence of a significant signal of mass independent fractionation of the sulfur isotopes. These observations provide strong evidence for the presence of oxygen in the atmosphere at the time these sediments were deposited. Re−Os dating of the pyrites yielded an age of 2,322 ± 15 Ma and an initial $^{187}Os/^{188}Os$ ratio of 0.1087 ± 0.0063. The former value shows that the loss of a major ^{33}S signal in the atmosphere occurred between 2,450 and 2,322 ± 15 Ma, indicating that O_2 appeared in the

atmosphere between these dates. The latter number is essentially equal to that of the mantle at 2,322 Ma, indicating that the input of riverine Os to the oceans was minor, an inference consistent with the absence of Re enrichment in highly carbonaceous shales from this period. This, in turn, suggests that 2322 million years ago atmopsheric oxygen levels were sufficiently high to eliminate the MIF signal in sulfur but sufficiently low to preclude significant oxidative weathering of Re and Os on the continents.

Research on mid−Proterozoic rocks by the Anbar and Knoll labs further contributes to our growing understanding of the redox development of the atmosphere and oceans. In 1998, Donald Canfield proposed that the cessation of iron formation deposition ca. 1850 Ma reflected the expansion of sulfidic deep oceans and not, as traditionally understood, the spread of oxygen throughout ocean basins. Research on the iron chemistry of the ca. 1500−1400 Ma Roper basin in northern Australia, completed by NRC postdoctoral fellow Yanan Shen, Knoll, and Australian Centre for Astrobiology colleague Malcolm Walter Research, demonstrated the presence of a strong redoxcline within this ancient marine basin. Indeed, Shen and colleagues have now shown that all northern Australian basins formed between 1730 and ca. 1400 Ma show evidence of basinal anoxia. The strong facies dependence of sulfur isotopic composition in Roper pyrites further supports the hypothesis that midway through recorded Earth history, marine sulfate levels remained well below their modern level. The Roper basin also contains abundant and exceptionally well preserved microfossils. Research in the Knoll lab showed that these fossils preserve complex wall ultrastructures, imaged by transmission electron microscopy (TEM), that document a moderate diversity of eukaryotic life in coastal environments of the mid−Proterozoic ocean. In complementary research, Ariel Anbar showed (1) that Mo isotopes can be used as paleotracers of redox conditions that integrate over the global ocean and (2) that Mo isotopic measurements of Roper samples support the hypothesis of relatively widespread anoxia in mid−Proterozoic oceans.

Subproject 2: Neoproterozoic−Cambrian environmental change and evolution

This subproject has enjoyed the broadest participation of Harvard team members, and for good reason. The Proterozoic−Cambrian transition witnessed remarkable changes in tectonics, climate, atmospheric composition, and especially life. This is the interval during which animal life −− and, hence, the prospect of intelligence −− radiated on Earth. Harvard team researchers are studying the paleontology (Knoll, Grotzinger, Erwin), geochronology (Bowring, Grotzinger), tectonics (Hoffman, Bowring), and environmental changes (Hoffman, Schrag, Bowring, Grotzinger) of this interval, with an eye to constructing models of integrated change in the Earth system.

Using new carbon isotope data from carbonate−rich Neoproterozoic and Early Cambrian sections in Svalbard, Namibia and Morocco, Paul Hoffman's group compiled the first high−resolution C−isotopic curve for Neoproterozoic−Cambrian seawater. The curve highlights a series of high−amplitude biogeochemical anomalies that have no parallel in Phanerozoic (543 Ma to present) or earlier Proterozoic time. Two of these anomalies correspond to the Sturtian and Marinoan snowball Earth episodes,

which were preceded uniquely by long intervals when fractional organic burial exceeded 0.4, or twice the modern value. Hoffman's group also found low−temperature equilibrium fractionation of carbon and oxygen isotopes between coexisting dolomite and calcite in the Marinoan cap carbonate sequence in Namibia and northwestern Canada. This suggests that dolomite formed in contact with seawater, unlike the normal Phanerozoic and Neoproterozoic ocean in which dolomite precipitation was kinetically inhibited. As sulfate ion is a known inhibitor of dolomite above 2mM concentration (versus 28 mM in modern seawater), Hoffman and students proposed that low sulfate concentrations, evolved in an ice−covered ocean, led to sea−floor dolomite formation during post−glacial transgression. Unlike normal marine carbonate phases, dolomite is stable and should be a more faithful carrier of isotopic information.

The dramatic diversification of animal phyla during early Cambrian time has fueled debate regarding the mechanisms of early animal evolution for over a century. What is now clear is that intrinsic catalysts, such as the innovation of developmental genetic mechanisms, as well as extrinsic processes involving environmental change, are both critically important in accounting for this major event in the history of life. Research by John Grotzinger and Sam Bowring on biostratigraphic, geochemical and geochronometric data from Oman lends strong support to the hypothesis that environmental perturbation near the Proterozoic−Cambrian boundary facilitated the Cambrian radiation of bilaterian animal phyla. Biostratigraphic, carbon isotopic, and uranium−lead zircon geochronological data from Ara Group of Oman indicate an abrupt last appearance of latest Proterozoic calcified metazoans coincident with a large−magnitude, but short−lived negative C−isotopic excursion. U−Pb zircon age data from an intercalated ash bed directly constrain this negative excursion to be 542 Ma, consistent with previous constraints from Siberia and Namibia. The absence of calcified fossils in carbonate units above this negative excursion contrasts strongly with their great abundance in carbonate units below the negative excursion. Combined with the global biostratigraphic record, these new data strengthen hypotheses invoking mass extinction within terminal Proterozoic ecosystems at or near the Precambrian−Cambrian boundary.

Subproject 3: Permo−Triassic mass extinction and its consequences

At the end of the Permian Period, 251 million years ago, more than ninety percent of marine species disappeared; land ecosystems were similarly devastated. Harvard team members seek to understand the causes and evolutionary consequences of this greatest of all mass extinctions. During the past year, D. Erwin and S. Bowring have continued field and laboratory research on the timing of P−Tr mass extinction. During the same period, team member John Marshall and colleagues examined old models and developed new models of the oxygen cycle in the past and present oceans. In an earlier publication from this project, they demonstrated how it is difficult to achieve a widespread, sustained anoxia in models of the Late Permian Ocean. This has resulted in a dialog with a group at Penn State on the representation of the oxygen cycle in ocean models. Marshall and colleagues have used a model of the modern ocean circulation and biogeochemistry to explore the implications

of the simplified parameterizations that are under scrutiny, finding that allowing negative oxygen concentrations is misleading, though it might be interpreted as "total oxidant," since it leads to large and erroneously identified regions of anoxia in modern ocean simulations. In addition to better parameterization, models of oxygen distribution in ancient oceans will require more detailed representations of oceanic nutrient and oxygen cycles. Marshall's team is developing such representations in the context of an atmosphere−ocean box model.

Subproject 4: Molecular and isotopic approaches to microbial ecology and Biogeochemistry

Ancient organic matter provides a rich source of biological and environmental information about the early Earth, as well as a potentially informative source of insights about Mars and other planets. John Hayes' group continued their investigations of the biogeochemistry of hydrogen isotopes, and this year completed meticulous analyses that demonstrate the quantitative nature of hydrogen isotopic "exchange" between organic matter and water. Hayes also completed field research on the Lost City hydrothermal system, using the research submarine Alvin to gather samples of lipid−rich fluids for biomarker and isotopic analysis. Team member Roger Summons continued his exploration of lipids in living microorganisms and ancient sedimentary rocks, characterizing the lipids of new isolates of extremophilic bacteria and archaeans and discovering molecular biomarker evidence for basinal anoxia in mid−Proterozoic basins from northern Australia (see above). Working together, Hayes, Summons, and MIT colleague Dan Rothman have proposed a novel explanation of the unusual record of C−isotopes in Neoproterozoic marine basins (see above). Their model suggests that high concentrations of dissolved organic matter in anoxic deep waters governed the isotopic composition of Neoproterozoic oceans.

Team member Dan Schrag focused on rates of methanogenesis in sediments from the South American continental margin. Vigorous upwelling off the west coast of South America leads to the deposition of organic rich sediments, creating chemical potential gradients that are host to diverse microbial communities. Ocean Drilling Program Leg 201 drilled several sites from this region last year. Degradation of organic matter generates extremely high alkalinity as well as large concentrations of dissolved ammonium and phosphate. High alkalinity drives the shallow precipitation of authigenic carbonate, resulting in depletions of dissolved Ca that mask that released by calcite dissolution (as indicated by increases with depth in dissolved Sr). Dolomite precipitation causes significant negative excursions of dissolved Mg from background down−core trends that are due to uptake during clay alteration. These excursions are coincident with sharply defined minima in Ca. Isotopic analysis of dissolved inorganic carbon carried out by our laboratory shows a pattern characteristic of sites dominated by methanogenesis. ^{13}C values decrease sharply with depth in the first 10 to 50 meters, reaching values as low as −30 per mil, indicating organic matter oxidation as well as methanotrophy. Values increase below the zone where sulfate disappears, reaching a plateau at values between 0 and +15 per mil. In some cases, the sulfate content of the pore fluid increases again, because sulfate rich brine

flows through the basaltic basement rock. Schrag is currently working with numerical models to calculate the rates of methanogenesis and methanotrophy to begin to ask questions about what limits the biological activity in these environments.

Subproject 5: Geobiology of Neogene hematitic sedimentary rocks

In 2003, NASA launched two rover missions to Mars. One of the rovers is slated to touch down in Meridini Planum, a region marked by aqueous hematite deposition. If we are to maximize the scientific opportunities of this mission, we must first complete careful studies of analogous systems on Earth, where biological and physical processes can be tied directly to paleobiological and geochemical patterns in deposited iron−rich sediments. The Rio Tinto drainage area of southern Spain offers just such an opportunity. During the past funding year, team member Andrew Knoll and colleagues from the Spanish Center for Astrobiology and the Johnson Space Center completed laboratory research on previously collected samples of present day Rio Tinto sediments and diagenetically stabilized iron rocks formed over the past two million years. The samples show how coarse grained hematites can arise during diagenesis of originally goethitic and jarositic sediments, and detail the macroscopic and microscopic textures that record biosignatures in hematitic rocks.

Subproject 6: Evogenomics (Collaborative focus group research)

Research by team member Charles Marshall focused on improving confidence intervals in paleontological estimates of evolutionary first and last appearances of taxa and on reconciling molecular clock and paleontological estimates of evolutionary divergence times. Research has also continued on the construction of a global database for the fossil record that will enable paleontologists to understand the history of biological diversity and facilitate the differentiation of the biological from geological signals in Phanerozoic marine diversity studies.

Subproject 7: Water and carbonates on the early surface of Mars

Although liquid water is not stable at the surface today, a large number of observations suggest that liquid water existed at least episodically at various times throughout Martian history. Although most morphological evidence for liquid water on Mars is consistent either with episodic and rapid release of water at the surface, or else with liquid water in the subsurface that results in chemical weathering reactions, the presence of valley networks and the degradation of impact craters on ancient surfaces of late Noachian age imply weathering and erosion by liquid water at the surface for substantial amounts of time. One particularly interesting aspect of Martian surface geology is the apparent discrepancy between the geological evidence for water on Mars during the Noachian and the lack of calcium carbonate on the surface. If a large body of liquid water on Mars persisted for millions of years or longer, the high CO_2 atmosphere would form carbonic acid, and react with the silicate crust, producing calcium carbonate. However, carbonate minerals have not yet been detected on the surface in sufficient quantities to be consistent with this

hypothesis.

Team member Dan Schrag and MIT colleague Maria Zuber have begun to address this problem, hypothesizing that climate episodes warm enough to maintain an active hydrologic cycle endured only long enough to produce the erosional features, not long enough for calcium carbonate to reach saturation. They are currently modeling this scenario for different ocean volumes and different atmospheric CO_2 concentrations.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Environmental changes in the context of biological evolution during Neoproterozoic on the Yangtze Platform, a snowball Earth?

Lead Team:	***Harvard University***
Project Title:	***Environmental changes in the context of biological evolution during Neoproterozoic on the Yangtze Platform, a snowball Earth?***
NAI−NRC Postdoctoral Fellow :	***Yanan Shen***

Project Progress

Project description:

The S−isotopic data of biogenic pyrite and the fractionation between sulfide and coeval seawater sulfate are instrumental in elucidating sulfate concentration in Precambrian oceans and evolution of atmospheric oxygen. The small fractionations (±5‰) between sedimentary sulfide and sulfate from Archean oceans may have been produced at low sulfate concentrations, implying low atmospheric oxygen. The increase in fractionation up to 40‰ between late Archean and early Proterozoic may signal the increased accumulation of seawater sulfate possibly coupled with the rise of atmospheric oxygen. However, wide spread but ^{34}S values of sedimentary pyrites during middle Proterozoic provide little compelling evidence on seawater sulfate levels. Likewise, the redox state of middle Proterozoic ocean remains controversial. A three−box model in combination with major disappearance of early Precambrian banded iron formations (BIFs) around 1,850 million years ago (Ma) hypothesizes sulfidic deep waters in middle Proterozoic ocean, suggesting atmospheric oxygen could be no more than 25% of Present Atmospheric Level (PAL). By contrast, oxic ocean model favors much higher oxygen in the atmosphere. Therefore, seawater sulfate concentration, redox state of the ocean, and eventually atmospheric oxygen level during middle Proterozoic remains elusive.

In the context of evolving middle Proterozoic atmosphere and ocean, microfossils exhibited a distinctive picture of Proterozoic biosphere. Though prokaryotes display extraordinary low rate of evolutionary change, eukaryotes indeed diversified by early Proterozoic. But only until early Mesoproterozoic, abundant acritarchs from Roper group of ~1,500 Ma, McArthur Basin in northern Australia show remarkable details of morphological development and diversification for eukaryotes. Furthermore, for the first time in Precambrian

record, Roper microfossils display clear onshore−offshore pattern of decreasing abundance, declining diversity, and changing dominance of eukaryotic microfossils, stressing biological selection with natural environment. Therefore, Roper group is of great temptation to illuminate ocean chemistry and its interaction with middle Proterozoic life.

Progress report:

In collaborating with Malcolm Walter, the director of Australian Astrobiology Center, we have performed Fe−S systematic study on sedimentary rocks of the Roper group. Our sulfur isotopic records of biogenic pyrites from the Roper Group reveal a remarkable face−dependent isotopic fractionation. Euxinic deep waters in the Roper seaway, as evidenced by Black Sea−type iron enrichment, provided favorable sites for microbial sulfate reduction, producing sulfides with ^{34}S values of −20.7~+21.2‰. In a low sulfate water body, the preferential burial of ^{32}S in the basinal environment would drive isotopic values of dissolved sulfate in upper water columns to more positive values. Combined with the diffusion of sulfate into shelf sediments, this would have resulted in heavy ^{34}S values up to +50‰ for shelf pyrites. Biogeochemical signature of the Roper sedimentary rocks provides a wonderful window on our understanding of Proterozoic ecosystems.

Our results have been recently published in *Nature* (June 5 issue, 2003).

Highlights

- For the first time, we identify faces−dependent S−isotopic fractionation over Precambrian records. Also, our Fe−S data from the Roper group have provided compelling evidence for low sulfate and euxinic nature of middle Proterozoic oceans. Moreover, our S−isotopic data provide vital information for the interpretation of Precambrian sulfur isotopic records.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Cross Team Collaborations

Malcolm R. Walter, Australian Astrobiology Center.

Outcome: Shen, Y., Knoll, A.H., Walter, M.R., 2003. Evidence for low sulfate and anoxia in a mid−Proterozoic marine basin. 423: 632−635. *Nature*.

Roger Buick, Astrobiology Center at University of Washington in Seattle.

Outcome: Shen, Y., Buick, R. 2003. The antiquity of microbial sulfate reduction. *Earth−Science Reviews* (in press).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Evogenomics Focus Group

Lead Team:	***Harvard University***
Project Title:	***Evogenomics Focus Group***
Project Investigator:	***Charles Marshall***

Project Progress

In year 5, Co−I Charles Marshall continued his statistical analyses of the fossil record as part of the Evogenomics Focus Group. Among other things, this focus group seeks to understand the molecular divergences among organisms and calibrate rates of molecular divergence using the fossil record. This exercise requires that the relationship between fossil discoveries and total stratigraphic range of extinct taxa be quantified. Marshall and colleagues contributed new techniques for evaluating the completeness of the fossil record, constraining estimates of primate divergence and providing sharper tools for estimating the positions of mass extinctions in stratigraphic sections.

Figure 1. *Present day iron deposition along the Rio Tinto, Spain*

Highlights

- New statistical techniques show place constraints on the timing of primnate divergence, given the incomplete record of fossil pirmates.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

Cross Team Collaborations

We collaborated with members of the Ecogenomics Focus Group, led by B. Hedges at Penn State.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Isotopic and molecular approaches to microbial ecology and biogeochemistry (The evolution of organic matter)

Lead Team:	***Harvard University***
Project Title:	***Isotopic and molecular approaches to microbial ecology and biogeochemistry (The evolution of organic matter)***
Project Investigators:	***John Hayes , Roger Summons , Roger Summons , Daniel Schrag***

Project Progress

In Hayes' group, Alex Sessions has continued work on hydrogen−isotopic biogeochemistry. During the period covered by this report, we have prepared a manuscript that deals with the "exchange" of hydrogen atoms between organic compounds and water (or surface−bound hydroxyl groups). Measurements completed in previous years have shown that the isotopic composition of "non−exchangeable" H (for example, H bound to C in hydrocarbons) can change much more rapidly than expected. The phenomenon has been traced to processes different from those involved in classical exchange reactions. Examples include carbon−skeletal rearrangements and stereochemical inversions in which the hydrogen inventory of a molecule does not change but in which C−H bonds are broken and remade. It has been necessary to erect a new "taxonomy" of processes that can affect D/H ratios in organic molecules.

Hayes, Sylva, Hinrichs, and Summons continued reconnaissance analyses of lipids from the Lost City hydrothermal vent system. The system is of interest because the vent fluids are rich in H_2 and may thus resemble settings on the primitive Earth. The samples were provided by Prof. Deborah Kelley of the University of Washington and had been collected in the course of only two Alvin dives at the site in 2000. Quantities of extractable lipids proved to be too low to allow detailed molecular and isotopic analyses. Accordingly, Hayes joined this year's much longer Atlantis/Alvin cruise to the site (18 dives, 20 days on station). Together with Alex Bradley, a graduate student now beginning studies with Prof. Summons, he made shipboard survey analyses that identified high−lipid materials and that resulted in the focused collection of many kilograms of suitable samples.

Hayes and Summons continued collaborations with Dan Rothman, a specialist in non−linear modeling techniques and a member of the faculty at MIT. Work has focused on the carbon isotopic records (both carbonate and organic) from the late Proterozoic (see highlights below and bridge−fund proposal). Our research explores two broad themes. The first is the chemical and isotopic

characterization and biogeochemical significance of lipids from cultured microbes and environmental samples with well characterized microbiota. The second is a search for fossil analogues in ancient sedimentary environments (0.5 to 2.7Ga).

In collaboration with Linda Jahnke and Victoria Orphan (NASA Ames), Helen Sturt at WHOI, Kai Hinrichs (Univ. Bremen) and a research group at the University of Regensburg, Germany (Dr Robert Huber, Dr Harald Huber and their graduate students), Roger Summons has characterized the lipids of new isolates of extremophilic bacteria (*Aquificales sp.*, *Thermovibrio ruber* and *Thiovolum*) and archaea (e.g. *Ignicoccus sp.*, *Nannoarchaeum equitans*, *Methanococcus sp.*) using a combination of LC−MS−MS to determine intact lipids degradation to precisely identify hydrocarbon skeletons.

On the ancient sediment side, Summons is studying two important and well preserved sequences in Oman and Australia for evidence of environmental change through the Proterozoic Eon. In studies that draw on his earlier hydrocarbon work in the 1.7−1.4Ga McArthur Basin of Northern Australia, Summons and colleagues have discovered evidence for photoic zone anoxia by way of biomarkers diagnostic for the green and purple sulfur bacteria (*Chlorobiaceae* and *Chromatiaceae*) in the Barney Creek Formation. They are now evaluating the stratigraphic and lithological relationships between these markers and those of oxygenic phototrophs in order to develop a model of the redox evolution of the basin system. In studies of the latest Neoproterozoic sequence from the Oman Salt Basin, Summons is studying chemostratigraphic relationships and characterizing organofacies (eg. stromatolitic, thrombolitic and deep basin sapropel) in rocks that bridge the Cambrian−Precambrian boundary, with the aim of discriminating global secular and local environmental effects.

Dan Schrag has been studying rates of methanogenesis in sediments from the South American continental margin. Vigorous upwelling off the west coast of South America leads to the deposition of organic rich sediments, creating chemical potential gradients that are host to diverse microbial communities. Ocean Drilling Program Leg 201 drilled several sites from this region last year. Degradation of organic matter generates extremely high alkalinity as well as large concentrations of dissolved ammonium and phosphate. High alkalinity drives the shallow precipitation of authigenic carbonate, resulting in depletions of dissolved Ca that masks that released by calcite dissolution (as indicated by increases with depth in dissolved Sr). Dolomite precipitation causes significant negative excursions of dissolved Mg from background downcore trends that are due to uptake during clay alteration. These excursions are coincident with sharply defined minima in Ca. Isotopic analysis of dissolved inorganic carbon carried out by our laboratory shows a pattern characteristic of sites dominated by methanogenesis. ^{13}C values decrease sharply with depth in the first 10 to 50 meters, reaching values as low as −30 per mil, indicating organic matter oxidation as well as methanotrophy. Values increase below the zone where sulfate disappears, reaching a plateau at values between 0 and +15 per mil. In some cases, the sulfate content of the pore fluid increases again, because sulfate rich brine flows through the basaltic basement rock. Schrag is currently working with numerical models to calculate the rates of methanogenesis and

methanotrophy to begin to ask questions about what limits the biological activity in these environments.

Highlights

- Rothman, Hayes, and Summons (in press, PNAS) have shown that abundances of ^{13}C in late Proterozoic carbonate and organic carbon are consistent with a global biogeochemical system much different from that prevailing today. In the absence of animals, organic material survived in the ocean for long times. The resulting relationship between carbonate and organic carbon − very different from that during the last 500 million years − can yield isotopic records like those observed in the late Proterozoic without requiring planet−wide, ocean−sealing glaciers.

- Lipids of a range of extremophilic bacteria have been found to have conventional hydrocarbon chains but are otherwise distinctive in their polar head−groups.

- Biomarkers diagnostic for photic zone anoxia have been discovered in the 1.64 Ga Barney Creek Formation, and they have a lithofacies−specific occurrence.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: R/V Atlantis cruise AT 7−34	
Start Date: : 21 April 2003	***End Date:*** 22 May 2003
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude: 30N	***Longitude:*** 42 W
Name of site(cave, mine, e.g.): Lost City	***Keywords:***

Description of Work: Determine abundances of microbial lipids in more than 50 different samples returned by 18 Alvin dives to the Lost City hydrothermal vent field.

Members Involved: John Hayes

Cross Team Collaborations

Collaboration with Linda Jahnke, Victoria Orphan and Tsegereda Embaye of the NASA Ames Team has characterized a new suite of lipid biomarkers for thermophilic and halophilic methanogens. We have also continued our long−term study of cultured cyanobacteria and related environmental samples for information of their diagnostic biomarkers and environmental controls on lipid biosynthetic pathways.

Collaboration with Dr Helen Sturt and Dr Kai Hinrichs of the URI−WHOI Team has resulted in new LC−MS−MS methods for the direct analysis and identification of intact lipids of extremophiles and characterization of a range of cultured bacteria and archaea.

Collaboration continues with Jennifer Eigenbrode and Katherine Freeman of the Penn State Team. Jennifer is studying Archean and Early Proterozoic sediments of the Pilbara Craton for the presence of diagnostic molecular biosignatures in rocks of different lithologies.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Planetary Context of Biological Evolution
Subproject: Carbon Cycle and Climate Dyanamics of Mars

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution Subproject: Carbon Cycle and Climate Dyanamics of Mars***
Project Investigators:	***Andrew Knoll , Daniel Schrag***

Project Progress

The surface of Mars preserves the record of a past climate in which liquid water was stable and apparently abundant. We seek to understand the planetary−scale control of climate through the study of climatic perturbations and their relationship to the carbon cycle on Earth, making basic geological and geochemical observations and then comparing these data with simple models of biogeochemical cycles.

Water is an essential ingredient for regulating climate. On Mars, as on Earth, there is substantial water on the surface at present, but it exists not as liquid water but as polar ice caps. The CO_2−rich atmosphere of 6 mb is inadequate to keep Martian surface temperatures above freezing, (except, in the current epoch, for local equatorial areas for brief periods). What has limited the accumulation of atmospheric CO_2 is not silicate weathering but the lack of a modern volcanic source of CO_2. If volcanism existed on Mars today as it likely does on Venus, CO_2 would accumulate in the atmosphere until the ice caps melted. This in turn would limit the continued rise of atmospheric CO_2 through the silicate weathering feedback.

Although liquid water is not stable at the surface today, there are a large number of observations that suggest that liquid water existed at least episodically at various times throughout Martian history. Although most morphological evidence for liquid water on Mars is consistent either with episodic and rapid release of water at the surface, or else with liquid water in the subsurface that results in chemical weathering reactions, the presence of valley networks and the degradation of impact craters on ancient surfaces of late Noachian age imply weathering and erosion by liquid water at the surface for substantial amounts of time. One particularly interesting aspect of Martian surface geology is the apparent discrepancy between the geological evidence for water on Mars during the Noachian and the lack of calcium carbonate on the surface. If a large body of liquid water on Mars persisted for millions of

years or longer, the high CO_2 atmosphere would form carbonic acid, and react with the silicate crust, producing calcium carbonate. However, carbonate minerals have not yet been detected on the surface in sufficient quantities to be consistent with this hypothesis.

A potential explanation for the observations is the possibility that climate episodes warm enough to maintain an active hydrologic cycle endured only long enough to produce the erosional features, but not long enough for calcium carbonate to reach saturation. We are currently modeling this scenario for different ocean volumes and different atmospheric CO_2 concentrations. The calculations assume simple calcium silicate chemistry for the crust and use equilibrium constants appropriate for the system $CaO-CO_2-H_2O$. The critical assumption made here is that volcanic outgassing at this time was not ongoing at a sufficient rate to replace whatever CO_2 was lost from the atmosphere by ocean uptake. We are presenting our results in July, and a paper is in preparation.

Highlights

- New research reconciles evidence for water but the lack of evidence for carbonate rocks on the ancient Martian surface.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1,2	Mars MER, furutre Mars exploration	Background research on Mars? volatile history

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

This research brings together Harvard team member Dan Schrag and leading Mars researcher Maria Zuber, from MIT.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Planetary Context of Biological Evolution Sub project: Geobiology of Neogene hematitic sedimentary rocks

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution Sub project: Geobiology of Neogene hematitic sedimentary rocks***
Project Investigators:	***Andrew Knoll , Ariel Anbar***

Project Progress

We completed laboratory analyses of samples of iron deposits collected along the Rio Tinto basin, southwestern Spain (Fig. 1). Analyses included x−ray diffraction (XRD), Moessbauer, petrological, and paleontological investigations of collected samples. In consequence, we can now show how the primary iron deposits in the Rio Tinto system −− hydronium jarrosite, shcwertmannite, and poorly ordered goethite −− are transformed through diagenesis to produce iron deposits rich in coarse−grained hematite. Of relevance to Mars, the hematite forms as a stable product of diagenesis over a two million year span, not as an initial precipitate.

We also demonstrated that fossils, including fungal and bacterial microfossils, can be preserved in remarkable detail by goethites in the basin, although subsequent digenetic alteration to hematite commonly obliterates preserved fossils. Finally, we demonstrated that sedimentary features observable with Mars Explorer Rover's (MER's) pancam and navcam imagers include features identifiable as biological signatures. Foremost among these are streamers, created by the adherence of iron precipitates to filamentous microorganisms.

The Rio Tinto project provides a terrestrial analog to the Mars Meridiani Planumhematite landing site −− indeed the only terrestrial analog in which both initial and diagenetically stabilized deposits have been studied.

Figure 1. *Present day iron deposition along the Rio Tinto, Spain*

Highlights

- Analyses of diagenetically stabilized iron deposits along the Rio Tinto, southwestern Spain, provide a guide to the search for biological signatures in anicent iron−bearing rocks on Mars.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars MER 2003	Science Team members (Knoll and Grotzinger)

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission

Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

See description of research above. The Rio Tinto research directs constrains and informs in situ exploration of iron−rich rocks on Mars.

Cross Team Collaborations

We collaborated with the Spanish Center for Astrobiology (David Fernandez−Remolar and Ricardo Amils) and with Richard Morris at the Johnson Space Center.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Planetary Context of Biological Evolution Subproject: Neoproterozoic−Cambrian Environmental Change and Evolution

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution Subproject: Neoproterozoic−Cambrian Environmental Change and Evolution***
Project Investigator:	***Andrew Knoll***

Project Progress

Subproject 2, Neoproterozoic−Cambrian environmental change and evolution, has enjoyed the broadest participation of Harvard team members, and for good reason. The Proterozoic−Cambrian transition witnessed remarkable changes in tectonics, climate, atmospheric composition, and especially life. This is the interval during which animal life −− and, hence, the prospect of intelligence, radiated on Earth. Harvard team researchers are studying the paleontology (Knoll, Grotzinger, Erwin), geochronology (Bowring, Grotzinger), tectonics (Hoffman, Bowring), and environmental changes (Hoffman, Schrag, Bowring, Grotzinger) of this interval, with an eye to constructing models of integrated change in the Earth system. Specific progress in Year 5 includes the following:

Using new carbon isotope data from carbonate−rich Neoproterozoic and Early Cambrian sections in Svalbard, Namibia and Morocco, Paul Hoffman's group compiled the first high−resolution curve for Neoproterozoic−Cambrian seawater (Fig. 1). It highlights a series of high−amplitude biogeochemical anomalies that have no parallel in Phanerozoic (543 Ma to present) or earlier Proterozoic time. Two of these anomalies correspond to the Sturtian and Marinoan snowball Earth episodes, which were preceded uniquely by >100 myrs when fractional organic burial exceeded 0.4, or twice the modern value.

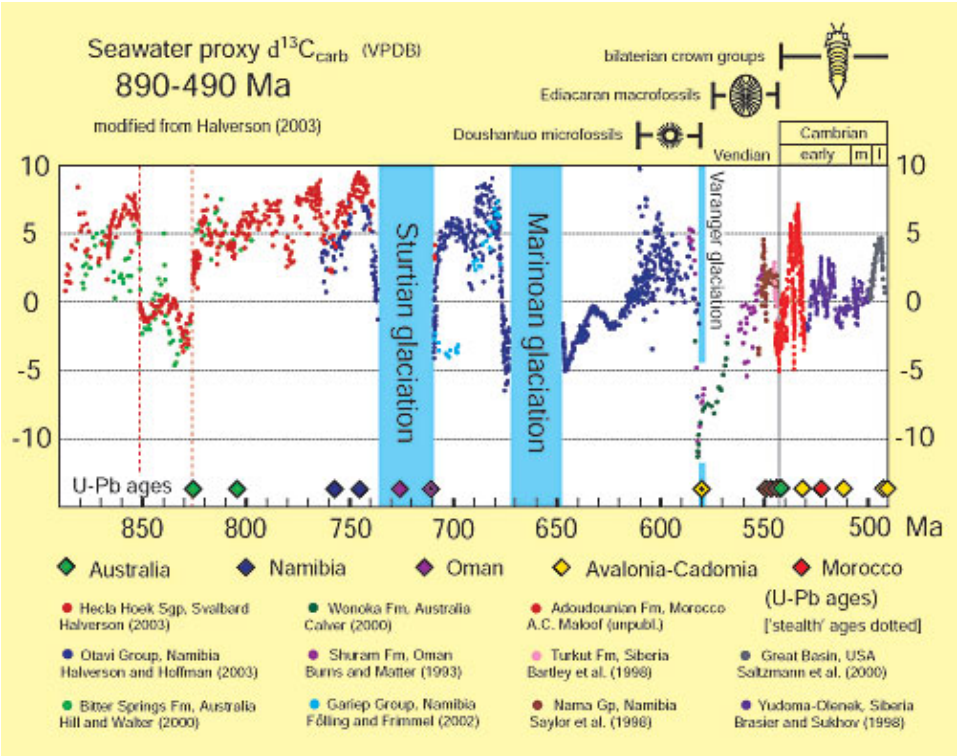


Figure 1.

Evidence for open water during Neoproterozoic glacial periods in different areas has been cited in opposition to the snowball Earth hypothesis. In Svalbard, Hoffman's team documented an evaporitic carbonate lagoonal sequence within the Marinoan glacial sequence (Fig. 2). The stratigraphic and sedimentological contexts of this sequence suggest that it represents an oasis on snowball Earth. It formed when tropical sea−surface temperatures reached the melting point, causing shorefast ice to melt away, while the tropical ocean remained ice covered because of the inflow of thick sea ice ('sea glaciers') from higher latitudes. The glacial record of snowball Earth involves the different histories of three ice−mass types (Fig. 2): sea glaciers, shorefast sea ice (sikussak), and terrestrial ice domes.

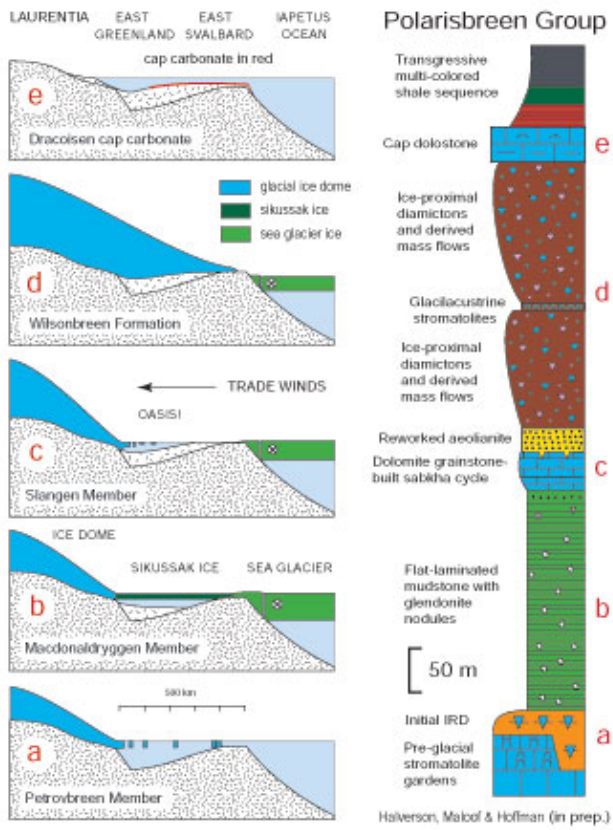
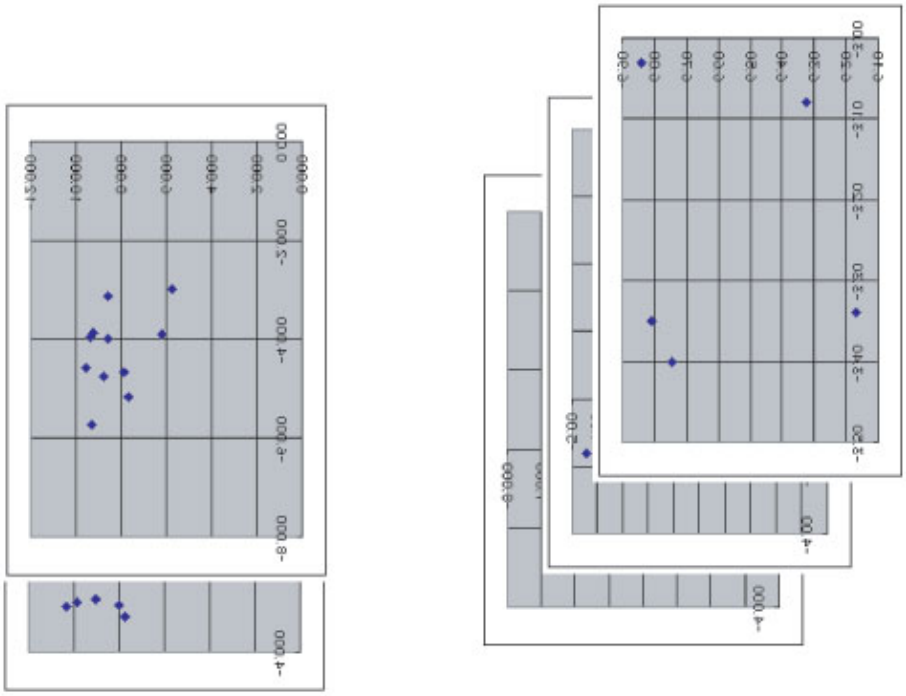


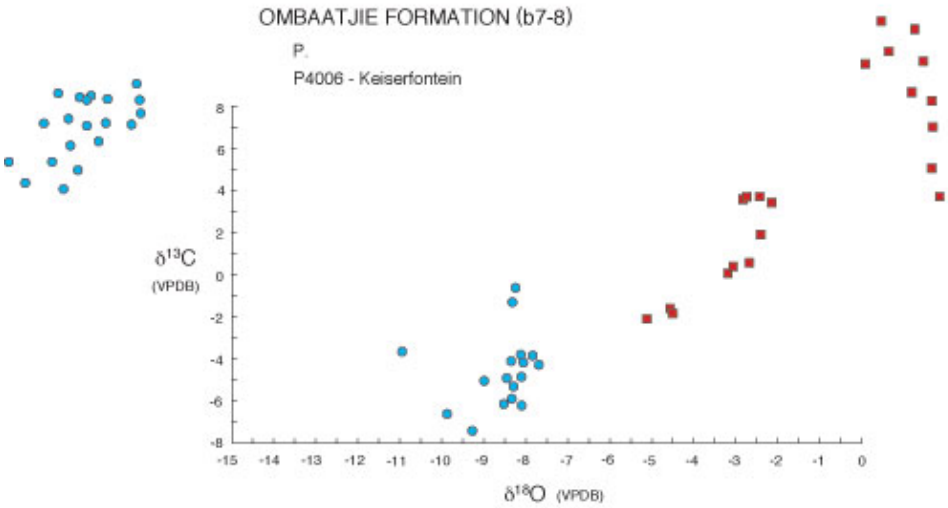
Figure 2.

The existence of sand−wedge polygons formed in periglacial soils situated close to the paleo−equator during the Marinoan glaciation has long been cited as evidence for a high (>54 degrees) obliquity of the ecliptic during pre−Phanerozoic time, providing an alternative explanation to snowball Earth for low−latitude glaciation. A low−obliquity orbit does not produce sufficient seasonality at the equator to form 3−m deep cracks as observed. However, mechanical analysis reveals that such deep cracks can form by crack−propagation under diurnal forcing if soils are perpetually frozen (i.e., no summer active layer), as would be expected on a snowball Earth due to its high albedo. Thus, the observed sand wedges do not require high obliquity for their formation, which is not supported by any other data.

Hoffman's group also finds low−temperature equilibrium fractionation of carbon and oxygen isotopes between coexisting dolomite and calcite in the Marinoan cap carbonate sequence in Namibia (Fig. 3 upper panel) and northwestern Canada. This suggests that dolomite formed in contact with seawater, unlike the normal Phanerozoic and Neoproterozoic ocean in which dolomite was kinetically inhibited. No similar fractionation is observed in other stratigraphic units (e.g. Fig. 3 lower panel). As sulfate ion is a known inhibitor of dolomite above 2 mM concentration (versus 28 mM in modern seawater), Hoffman proposes that low sulfate concentrations, evolved when the ocean was ice covered, led to sea−floor dolomite formation during the post−glacial

transgression. Unlike normal marine carbonate phases, dolomite is stable and should be a more faithful carrier of isotopic information.




OMBAATJIE FORMATION (b7-8)
P.
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δ18O (VPDB)

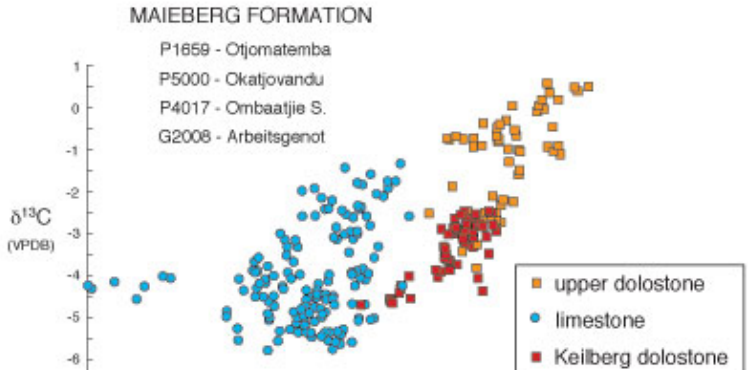
MAIEBERG FORMATION
P1659 - Otjomatemba
P5000 - Okatjovandu
P4017 - Ombaatjie S.
G2008 - Arbeitsgenot
δ13C
(VPDB)
upper dolostone
limestone
Keilberg dolostone

Figure 3.

Dan Schrag continued geochemical and geophysical modeling of the Neoproterozoic climate. The Snowball Earth hypothesis proposes that Neoproterozoic glacial deposits and associated "cap" carbonates represent a series of global glaciations followed by extreme greenhouse conditions. In the context of the hypothesis, a runaway ice−albedo feedback causes a global glaciation, with near−complete sea−ice cover, and a greatly reduced hydrologic cycle dominated by sublimation. Escape from this frozen state requires several to several 10's of millions of years for carbon dioxide, released by magmatic outgassing, to build up in the ocean/atmosphere system, providing adequate radiative forcing to overcome the high planetary albedo. Meltback would be extremely rapid (i.e., hundreds of years), transforming the Earth from frozen to ultra−greenhouse conditions.

A research effort involving two members of our Astrobiology Group (Grotzinger, Bowring) has been able to provide important new constraints on biogeochemical events at the Precambrian−Cambrian boundary in Oman. Globally significant events of faunal turnover, tectonic reorganization, and biogeochemical change are now widely regarded to have closely coincided with the Precambrian−Cambrian boundary. Over the past decade, research on the boundary has provided constraints on the age and duration of these events, the possible phylogenetic relationships between faunal assemblages, and the magnitude and significance of contemporaneous shifts in the trace element and isotopic composition of the oceans. In turn, these results enable tighter focus on the links that existed between global biogeochemical events and episodes of faunal extinction and radiation. Biostratigraphic, carbon isotopic, and uranium−lead zircon geochronological data from Ara Group of Oman indicate an abrupt last appearance of Cloudina and Namacalathus coincident with a large−magnitude, but short−lived negative excursion in the carbon−isotopic composition of seawater that is globally coincident with the Precambrian−Cambrian boundary. U−Pb zircon age data from an intercalated ash bed directly constrain this negative excursion to be 542 Ma, consistent with previous constraints from Siberia and Namibia. The Oman age of 542 Ma constitutes the best independent evidence that this anomaly is global in extent. The stratigraphically highest fossiliferous sediments in Oman, which directly underlie the strata containing the negative excursion, contain an ash bed yielding an age of 543.2 ± 0.5 Ma. The absence of Cloudina and Namacalathus fossils in carbonate units above this negative excursion contrasts strongly with their great abundance in carbonate units below the negative excursion. Combined with the global biostratigraphic record, these new data strengthen hypotheses invoking mass extinction within terminal Proterozoic ecosystems at or near the Precambrian−Cambrian boundary. The most likely explanation −− that Cloudina and Namacalathus disappeared as part of a global extinction −− can account for the absence of those fossils in carbonates above the negative excursion in Oman. The simplest interpretation of the data presented here is that extinction occurred globally at the Precambrian−Cambrian boundary coincident with a global biogeochemical event marked by the negative isotope excursion. Given the extreme difficulty in preserving Ediacaran soft−bodied organisms as fossils, their stratigraphic distribution across the Precambrian−Cambrian boundary has provided

ambiguous constraints on evolutionary models. In contrast, the disappearance of calcified Cloudina and Namacalathus above this critical level, despite constant depositional and taphonomic conditions, provides a more clearly resolved image of this global extinction.

A second research effort has resulted in the development of a digital model of a Proterozoic Thrombolite reef complex in Namibia. A terminal Proterozoic isolated carbonate platform resided downdip on a carbonate ramp of the Nama Group of southern Namibia. The overall geometric evolution of the studied platform from flat−topped to bucket with elevated margins is recorded in many Proterozoic and Phanerozoic isolated carbonate platforms with similar dimensions. The terminal Proterozoic, microbial−dominated, isolated carbonate platform of this study clearly illustrates that the answer to accommodation changes was already familiar among carbonate platforms before the dawn of metazoan−dominated platforms. The stratigraphic evolution of the platform was digitally reconstructed from an extensive dataset that was compiled by using digital surveying technologies. The platform comprises three accommodation cycles in which each subsequent cycle experienced progressively greater influence of a long−term accommodation increase. Aggradation and progradation during the first cycle resulted in a flat, uniform, sheet−like platform. The coarsening and shallowing−upward sequence representing the first cycle is dominated by columnar stromatolitic thrombolites and massive dolostones with interbedded mudstone−grainstone at the base of the sequence grading into cross−bedded dolostones. The second cycle features aggradation, formation of a distinct margin containing thrombolite mounds and domes, and the development of a bucket geometry. Columnar stromatolitic thrombolites dominate the platform interior. The final stage of platform development shows a deepening trend with initial aggradation and formation of well−bedded, thin deposits in the interior and mound development at the margins. While the interior drowned, the platform margin kept up with rising sea level, and a complex pinnacle reef formed containing fused and coalesced thrombolite mounds flanked by bioclastic grainstones (containing Cloudina and Namacalathus fossils) and collapse breccias. A set of isolated large thrombolite mounds flanked by shales indicates the final stage of the carbonate platform. During a progressive increase in accommodation, a flat−topped isolated carbonate platform becomes aerially less extensive by either backstepping or formation of smaller pinnacles or a combination of both.

In the past year, Sam Bowring's group has worked on refining the history of glaciation in Newfoundland as well as in Namibia and Oman. At present we have evidence for glacial deposits that are >760 Ma, 711 Ma, 650−630 Ma, and 580 Ma. The out standing question is whether these are global or snowball glaciations or whether some are "normal" high−latitude glaciations. The other big question concerns synchronicity and duration. As reported last year and at the annual Astrobiology meeting in Tempe, the Gaskiers glacial deposit in Newfoundland has duration of less than 1 Ma, a duration at odds with models for snowball glaciation. While it could be dismissed as a non−snowball glaciation, it does have an associated cap carbonate and a low paleolatitude (30°). Another major effort has been to constrain the age and significance of the Cambrian/Precambrian boundary in Oman. Significantly, the boundary or extinction horizon corresponds to a sharp negative excursion

in carbon isotopes that has duration of less than 1 Ma. It is quite possible that like other major extinctions in Earth history, post−extinction time was characterized by a period of rapid evolutionary change, which is often described as the Cambrian explosion. In complementary research, team member Knoll joined French colleagues in the radiometric analysis of Neoproterozoic phosphates from China. The rocks contain the oldest known fossil remains of animals; their recorded Pb−Pb age of 596+/−4 million years supports the hypothesis that, at 580 Ma, the brief Gaskiers glaication belongs to a third ice age that postdated the globally extensive Sturtian and Marinoan events.

Highlights

- New data were used to compile the first high−resolution C−isotope curve for Neoproterozoic and Cambrian seawater (890 to 490 Ma). The compilation provides context for the Sturtian and Marinoan snowball Earth episodes, and confirms that high fractional organic burial was sustained for >100 myrs preceding glaciation.

- Cap dolomites are 'primary' dolomite, based on low−temperature isotopic equilibrium with coexisting calcite. Low seawater sulfate concentrations are thought to have allowed sea−floor dolomite formation in the immediate aftermath of the Marinoan snowball Earth.

- Integrated stratigraphic, geochemical, and geochronological data from Oman provide empirical support for the hypothesis that end−Proterozoic mass extinction facilitated the Cambrian diversification of bilaterian phyla.

- New radiometric dates constrain the timing and number of Neoproterozoic ice ages, as well as the age of the earliest known animal fossils.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	High resolution field mapping of Mars	Developing digital mapping techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The digital mapping techniques under development by Grotzinger will be applicable to any serious investigation of Martian geology undertaken in lander expeditions in 2009 and beyond. Understanding the physical environmental of Earth during, before, and after snowball glaciation is also immediately relevant to the astrobiological characterization of extrasolar planets, currently under development by NASA.

Field Expeditions

Field Trip Name: Namibia	
Start Date: June 10, 2002	***End Date:*** July 19, 2002
Continent: Africa	***Country:*** Namibia
State/Province: Kunene	***Nearest City/Town:*** Otavi Group
Latitude: 20.5degS	***Longitude:*** 14.5degE
Name of site(cave, mine, e.g.):	***Keywords:*** Neoproterozoic Snowball Earth
Description of Work: Regional scale stratigraphic studies and sampling for stable isotopes.	
Members Involved: Paul Hoffman	

Field Trip Name: Newfoundland	
Start Date: July 13,2002	***End Date:*** July 19, 2002
Continent: North America	***Country:*** Canada
State/Province: Newfoundland	***Nearest City/Town:***
Latitude: 50degN	***Longitude:*** 56degW
Name of site(cave, mine, e.g.): Betts Cove	***Keywords:*** Ophiolite, seawater evolution, oxygen isotopes
Description of Work: Collected samples of the earliest Ordovician (489 Ma)	

Betts Cove ophiolite for oxygen isotope analysis. The samples will be used to test evidence of secular change in the oxygen isotope composition of Paleozoic and Precambrian seawater.
Members Involved: Paul Hoffman

Field Trip Name: Svalbard	
Start Date: July 22, 2002	***End Date:*** August 17, 2002
Continent: Europe	***Country:*** Svalbard
State/Province: Ny Friesland, Nordaustlandet	***Nearest City/Town:***
Latitude: 80degN	***Longitude:*** 20degE
Name of site(cave, mine, e.g.): Hecla Hoek Succession	***Keywords:*** Neoproterozoic Snowball Earth
Description of Work: Regional scale stratigraphic studies and sampling for stable isotopes and palemagnetism.	
Members Involved: Paul Hoffman	

Field Trip Name: Namibia	
Start Date: June 1, 2003	***End Date:*** July 4, 2003
Continent: Africa	***Country:*** Namibia
State/Province: Kunene	***Nearest City/Town:***
Latitude: 20.5degS	***Longitude:*** 14.5degE
Name of site(cave, mine, e.g.): Otavi Group	***Keywords:*** Neoproterozoic Snowball Earth
Description of Work: Regional scale stratigraphic studies and sampling for stable isotopes and paleomagnetism.	
Members Involved: Paul Hoffman	

Field Trip Name: Oman	
Start Date: May 1, 2003	***End Date:*** May 22, 2003

Continent: Asia	***Country:*** Oman
State/Province: Muscat	***Nearest City/Town:***
Latitude: 23 N	***Longitude:*** 55 E
Name of site(cave, mine, e.g.):	***Keywords:*** Neoproterozoic, Cambrian, mass extinction
Description of Work: Multidisciplinary studies of the Neoproterozoic−Cambrian transition	
Members Involved: John Grotzinger	

Field Trip Name: Namibia	
Start Date: August 3, 2002	***End Date:*** September 5, 2003
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** Neoproterozoic geochronology, paleoclimates
Description of Work: Collected ash beds for U−Pb zircon analysis	
Members Involved: Dan Condon	

Cross Team Collaborations

Matt Hurtgen (Penn State Team) accompanied our team for field work in northeast Svalbard. Results from Hurtgen's 2001 field work with our team in northern Namibia were reported (see Abstracts). Hurtgen's work involves sulfur isotopes of trace sulfate in carbonate strata associated with Neoproterozoic snowball Earth episodes. Hurtgen will accompany our team for field work in July 2003 in the Arctic Canadian Cordillera, prior to taking up an NAI post−doc fellowship at Harvard in September 2003.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Planetary Context of Biological Evolution: Subproject: Permo−Triassic mass extinction and its consequences

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Subproject: Permo−Triassic mass extinction and its consequences***
Project Investigators:	***Andrew Knoll , Douglas Erwin , Sam Bowring***

Project Progress

During this period John Marshall's group has been examining and developing models of the oxygen cycle in the past and present oceans. In an earlier publication from this project, they demonstrated how it is difficult to achieve a widespread, sustained anoxia in models of the Late Permian Ocean. This has resulted in a dialog with a group at Pennsylvania State University on the representation of the oxygen cycle in ocean models. Marshall's group has used a model of the modern ocean circulation and biogeochemistry to explore the implications of the simplified parameterizations that are under scrutiny. They find that allowing negative oxygen concentrations is misleading, though it might be interpreted as "total oxidant", since it leads to very large and erroneous regions of anoxia in modern ocean simulations. A manuscript is in preparation concerning these results.

More detailed representations of oceanic nutrient and oxygen cycles are necessary and we have continued to develop such representations in the context of an atmosphere−ocean box model (Follows, in collaboration with Paul Falkowski at Rutgers).

Team member Douglas Erwin continued his research on the Permo−Triassic extinction. Planned field work in South China to acquire samples for a blind test of the suggested impact at the Permo−Triassic boundary was delayed by the outbreak of SARS, but is now scheduled for October 2003. Also a detailed database of species level fossil occurrences of Permian and Triassic gastropods is nearing completion for a planned analysis of extinction and recovery patterns. Erwin also continues to develop models of post−extinction biotic recovery and has nearly completed a book on the extinction for the general public (expected Sept. 2003).

Highlights

- In order to better understand the possibility of widespread ocean anoxia, more comprehensive models of the coupled ocean nutrient and oxygen cycles are required.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The Planetary Context of Biological Evolution Subproject: The Proterozoic Oxidiation of the Earth's Surface

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution Subproject: The Proterozoic Oxidiation of the Earth's Surface***
Project Investigator:	***Andrew Knoll***

Project Progress

The history of oxygen in the oceans and atmospheres is thought to have played a key role in Earth's long term biological evolution. Ongoing research addresses the initial oxygenation of the atmosphere and surface ocean 2.4−2.2 Ga, renewed oxygen influx near the end of the Proterozoic eon, and, increasingly, the nature of the biosphere between those two events.

In Year 5, Ariel Anbar's lab continued development of the Mo stable isotope system for paleoredox investigations in natural samples and laboratory experiments. The most significant new result was the laboratory determination of the fractionation factor for Mo isotopes during adsorption to Mn oxides (previous lab studies had determined only that such fractionation occurs). Anbar's results indicate that this is an equilibrium isotope effect and that it dominates Mo isotope fractionation in the oceans. This places his proposed use of Mo isotopes as paleoredox tracers on more solid ground. Anbar and A.H. Knoll also published a paper in *Science* in which they explored the biological implications of trace metal scarcity in sulfidic Proterozoic oceans.

Anbar's lab also advanced several Fe isotope projects in collaboration with the PSU Team and with new collaborators in the Center for Environmental Bioinorganic Chemistry at Princeton University. Highlights include: Interpretation of Fe isotope effects associated with mineral weathering (w/PSU); assessment of a new technique (high mass resolution MC−ICP−MS) for Fe isotope studies; and calculation of the equilibrium fractionation factor between Fe(II) and Fe(III) hexaquo complexes using ab initio molecular modeling. The latter study brings theory into agreement with experimental determination of this fractionation factor for the first time.

National Research Council (NRC) postdoctoral fellow Yanan Shen, Andrew Knoll, and Australian collaborator Malcolm Walter added new data to the debate about Proterozoic environments, showing that the 1500−1400 Ma

Roper Basin had oxic surface waters but was anoxic at depth. Shen et al. also demonstrated that sulfur isotopic values of syngenetic and early diagenetic pyrite in Roper rocks vary as a strong function of depth in the basin. These findings support the hypothesis that 1500−1400 million years ago sulfate levels remained well below modern values. Knoll's lab also showed that microfossils in Roper shales preserve diverse and complex ultrastructures (as visualized by transmission electron microscopy (TEM)), recording moderate levels of eukaryotic diversity in coastal environments.

The most exciting new discoveries in H.D. Holland's lab concern the composition of pyrite in the Timeball Hill and Rooihogte formations in South Africa. Measurements of the isotopic composition of sulfur in these pyrites have shown a considerably larger range in ^{34}S than in older sulfides, and the absence of a significant signal of mass independent fractionation of the sulfur isotopes. These observations and the presence of hematitic iron ore in the upper part of the Timeball Hill Formation are strong evidence for the presence of oxygen in the atmosphere during the deposition of these sediments. Re−Os dating of the pyrites has yielded an age of 2,322 ± 15 Ma and an initial 187Os/188Os ratio of 0.1087 ± 0.0063. The age shows that the loss of a major Ä33S signal in the atmosphere occurred between 2,450 and 2,322 ± 15 Ma. This indicates that O_2 appeared in the atmosphere between these dates.

The initial $^{187}Os/^{188}Os$ ratio in the pyrites is essentially equal to that of the mantle at 2,322 Ma. This indicates that the input of riverine terrestrial Os was very minor, an inference that is consistent with the absence of Re enrichment in highly carbonaceous shales from this period. The O_2 content of the atmosphere was apparently sufficiently high at 2,322 ± 15 Ma to eliminate the MIF signal in sulfur but sufficiently low to prevent a significant amount of oxidative weathering of Re and Os on the continents.

Finally, Anbar remained active as co−chair of the Mission to Early Earth Focus Group. This work included facilitating the development of the "Archean Biosphere Drilling Project" to oversee the Mission to Early Earth's (MtEE's) Archean drilling project in Western Australia, now planned for summer, 2004.

Highlights

- Laboratory Mo isotope experiments support hypotheses of mid−Proterozoic sulfidic seas.

- Independently, measurements of iron speciation chemistry and sulfur isotopes document deep water anoxia and low sulfate levels in a mid−Proterozoic marine basin.

- Re−Os dating of pyrite from the Timeball Hill and Rooihogte formations, South Africa, has shown that they were deposited 2,322 ± 15 Ma. The absence of significant mass independent fractionation in the sulfur of these pyrites together with the presence of large quantities of hematitic iron ore indicates that O_2 was present in the atmosphere 2,322 ± 15 Ma. Its appearance is now bracketed between 2,450 and 2,322 ± 15 Ma.

- The initial $^{187}Os/^{188}Os$ in the pyrites of the Timeball Hill and Rooihogte formations is equal to that of the mantle at 2,322 Ma. This indicates that the input of riverine Os from the continents at that time was very small, and hence that O_2 levels in the atmosphere were still minor.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF and related	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The search for life on extrasolar planets will, inevitably, begin with the interpretation of remotely−sensed chemical signatures in planetary atmospheres. Such interpretation requires an understanding of the linkages between atmospheres and biopspheres. Because most biospheres are likely to be primitive, we have no choice but to develop this understanding by examining the ancient record of life and environment on Earth. Our focus on environmental redox is particularly appropriate for future TPF−type missions because of the potential importance of ozone (and, hence, oxygen) as an atmospheric biosignature. Our work will help us to understand the prospects for life under a low−O_2 atmosphere.

Field Expeditions

Field Trip Name: Archean and Paleoproterozoic geology the Great Lakes	
Start Date: 5/21/03	***End Date:*** 6/12/03
Continent: North America	***Country:*** Canada and USA
State/Province: WI,MI,MN,ON	***Nearest City/Town:*** (Marquette, Duluth, Thunder Bay, Sudbury, Ottawa nearest towns)
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** shale, pyrite, Archean, geology
Description of Work: Collected pyritiferous [SPELLING] shales for geochemical analysis	
Members Involved: Audrey Bekker	

Field Trip Name: Archean and proterozoic Geology of South Africa	
Start Date: 6/12/02	***End Date:*** 8/5/02
Continent: Africa	***Country:*** South Africa
State/Province: Transvaal	***Nearest City/Town:*** (near Johannesburg)
Latitude: 26 degrees S	***Longitude:*** 28 degrees E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collected samples of carbonaceous shales with pyrite, chert with pyrite, carbonates.	
Members Involved: Audrey Bekker	

Cross Team Collaborations

The Fe isotope biosignature studies outlined above are collaborative with JPL/Caltech and PSU Teams.

Mission to Early Earth Focus Group is collaborative with several Teams (PSU, UW, UC, etc.).

Dr. Andrey Bekker has been working with Dr. D. Rumble and Dr. S. Ono of the Carnegie NAI team, measuring the isotopic composition of sulfur in

Precambrian pyrite.

Holland's group continued its close contact with Professor J. Kasting of the Penn State NAI team regarding the evolution of the atmosphere and on the redox controls of the mantle. These controls have an important bearing on theories of the appearance of atmospheric O_2 during the Paleoproterozoic. Holland also works closely with Washington NAI team member Roger Buick, citing Buick as a key source of geologic information and of samples for his research.

Knoll's lab continues to work closely with Malcolm Walter of the Australian Centre for Astrobiology. In the past year, this has resulted in papers in *Nature* and *PNAS*.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: The use of living plants and fossil chemistry to study the morphological patterns and developmental processes of land plant evolution

Lead Team:	***Harvard University***
Project Title:	***The use of living plants and fossil chemistry to study the morphological patterns and developmental processes of land plant evolution***
NAI−NRC Postdoctoral Fellow :	***Charles Boyce***

Project Progress

My research takes advantage of the unique opportunities of plants, including cellular preservation in fossils and the repeated evolution of similar morphological structures, to study the evolution of development and physiology in geologic time. Previous investigations of morphologically similar leaves in distantly related plant lineages have demonstrated that the evolution of convergent morphological patterns involves the evolution of convergent developmental processes and that morphological diversity through time has been shaped by developmental constraints. Work in the last year has demonstrated that these multiple independent evolutionary experiments have also involved detailed convergence of leaf functional attributes. Additional physiological studies have provided an understanding of how environmental stresses such as water deficits impose morphological changes during leaf growth. This may allow the use of fossil plants to assess important ecological parameters that are typically not available from the fossil record, such as plant architecture and placement within the forest canopy.

Collaborative work with the Carnegie Astrobiology team involves the application of emerging techniques of fine−scale chemical analysis to the study of the biology of fossil and extant organisms. In the last year this research has allowed us to identify several evolutionary shifts in the wall chemistry of vascular cells that have been involved in the diversification of complex land plants and correlated with the convergent evolution of leaves described above. Also, comparative analyses of the chemistry preserved in fossils have provided a preliminary determination of the biological affinities of a bizarre Paleozoic fossil, Prototaxites, which produced enormous tree−like trunks composed of intertwined, 50 micron−diameter tubes. Different specimens cluster into two discrete populations of carbon isotopic values. Pending further organic analyses to rule out the possibility of diagenetic artifacts, this isotopic disparity may well reflect heterotrophy upon isotopically

distinct sources, suggesting Prototaxites was a twenty foot tall fungus.

Highlights

- Chemical comparisons suggest that the 380 million year old fossil Prototaxites may have been a twenty foot tall fungus.
- Extreme evolutionary convergence of morphology, development, and physiology is present in the multiple independent evolutionary experiments of inventing a leaf among vascular plants.
- Evolutionary shifts in the wall chemistry of vascular cells and proliferation of vascular cell types have been involved in the rise of complex land plants.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life

Cross Team Collaborations

I am involved in an extensive, ongoing collaboration with members of the Carnegie Astrobiology team, George Cody, Marilyn Fogel, and Bob Hazen. Our work involves the application of emerging techniques of fine−scale chemical analysis to the study of the physiology and biochemistry of fossil and extant organisms. In the last year this research has allowed us to identify several evolutionary shifts in the wall chemistry of vascular cells that have been involved in the diversification of complex land plants and to make a preliminary determination of the biological affinities of enigmatic Paleozoic fossil, which appears likely to have been a twenty foot tall fungus.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: Harvard University

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Charles Boyce
Project Title: The use of living plants and fossil chemistry to study the morphological patterns and developmental processes of land plant evolution
Advisor: Andrew Knoll, Advisor
NAI Lead Team: Harvard University
Fellowship Began In: August 2002

Recipient: Yanan Shen
Project Title: Environmental changes in the context of biological evolution during Neoproterozoic on the Yangtze Platform, a snowball Earth?
Advisor: Andrew Knoll, Advisor
NAI Lead Team: Harvard University
Fellowship Began In: April 2, 2001

NASA ASTROBIOLOGY INSTITUTE
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[July 2002 - June 2003]

EPO: Harvard University

These are the Education and Public Outreach activities for the Harvard University.

Snowball Earth

Paul Hoffman
Lecture to students and faculty at Princeton University. Carbonate bounding glacial deposits: Evidence for snowball Earth glaciations and greenhouse aftermaths in the Otavi Group (Neoproterozoic) of northern Namibia.

Paul Hoffman
Worked with NHK TV (Japan) on a special program on Snowball Earth.

Paul Hoffman
Provided material to author Gabrielle Walker for her popular science book Snowball Earth: the story of the great global catastrophe that spawned life as we know it, Published by Random House, Inc.

Astrobiology Coursework

Earth and Planetary Sciences, 271r

Paul Hoffman
Problems in Precambrian Geology − course for 20 graduate students

Earth and Planetary Sciences 8

Paul Hoffman
Astrobiology−related course − compulsory course for all Earth and Planetary Science undergraduate concentrators at Harvard University.

Evolution: Investigating the Evidence

Charles Marshall
Invited Speaker for a National Workshop for Grade 6−16 Teachers, the Geological Society of America Annual Meeting, Denver, Colorado. November 2002.

Planetary Context of Biological Evolution

John Grotzinger
Gave 3 presentations to grade school science classes in the greater Boston area public school system.

John Grotzinger
Involved 8 Nambian scientists in digital mapping project in 2002 and 13 Omani scientists in mapping project in 2003. Among these groups were both practicing geologists and geologists in training.

Publications: Harvard University

Adams, E.W., Grotzinger, J.P., Schroder, S., Al−Siyabi, H., Amthor, J.E. McCormick, D.S. (2002). Shape, size, and distribution of microbial reefs in a carbonate−ramp setting (Nama Group, Namibia) [Abstract]. *16th International Sedimentological Congress, July 8−12, Johannesburg, Abstract Volume* (p. 6).

Adams, E.W., Schroder, S., Grotzinger, J.P. McCormick, D.S. (Submitted, 2003). Digital reconstruction and stratigraphic evolution of a microbial−dominated, isolated carbonate platform (terminal Proterozoic, Nama Group, Namibia). *Journal of Sedimentary Research*.

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Anbar, A. Knoll, A.H. (2002). Proterozoic ocean chemistry and evolution: A bioorganic bridge? *Science*, 297: 1137−1142.

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Arnold, G.L., Anbar, A.D. Barling, J. (2002). Oxygenation of proterozoic oceans: Insight from molybdenum isotopes [Abstract]. *12th Annual V. M. Goldschmidt Conference, Abstracts, Davos, Switzerland*.

Arnold, G.L., Anbar, A.D. Barling, J. (2002). Oxygenation of Proterozoic oceans: Insight from molybdenum isotopes [Abstract]. *12th Annual V.M. Goldschmidt Conference*, Davos, Switzerland.

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Bambach, R.K., Knoll, A.H. Sepkoski, J.J. (2002). Anatomical and ecological constraints on Phanerozoic animal diversity in the marine realm. *Proceedings of the National Academy of Sciences of the United States of America*, 99: 6954−6859.

Barfod, G., Alberede, F., Knoll, A.H., Xiao, S., Baker, J. Frei, R. (2002). New Lu−Hf and Pb−Pb age constraints on the earliest animal fossils. *Earth and Planetary Science Letters*, 201: 203−212.

Barfod, G.H., Albarede, F., Knoll, A.H., Xiao, S., Telouk, P., Frei, R. Baker, J. (2002). Implications for the Neoproterozoic biological and climatic history from dating of the Doushantuo phosphorites, South China [Abstract]. *Eos, Transactions of the American Geophysical Union*, 83(47, Fall Meeting Supplement). Abstract # B71B−0737.

Bekker, A. Eriksson, K.A. (2003). A Paleoproterozoic drowned carbonate platform on the southeastern margin of the Wyoming Craton: A record of the Kenorland breakup. *Precambrian Research*, 120: 327−364.

Bekker, A., Karhu, J.A., Eriksson, K.A. Kaufman, A.J. (2003). Chemostratigraphy of Paleoproterozoic carbonate successions of the Wyoming Craton: Tectonic forcing of biogeohemical change? *Precambrian Research*, 120: 279−325.

Bekker, A., Kaufman, A.J., Karhu, J.A., Beukes, N.J., Swart, Q.D., Coetzee, L.L. Eriksson, K.A. (2001). Chemostratigraphy of the Paleoproterozoic Duitschland Formation, South Africa: Implications for coupled climate change and carbon cycling. *American Journal of Science*, 301: 261−285.

Bowden, S.A., Love, G.D., Snape, C.E., Brocks, J.J., Logan, G.A. Summons R.E. (2002). Detection and significance of molecular fossils of Chlorobiaceae in Paleoproterozoic sediments [Abstract: NASA *Astrobiology* Institute General Meeting 2003]. *Astrobiology*, 2(4): 612−613.

Bowring, S.A. Schmitz, M.D. (In Press, 2003). High−precision U−Pb zircon geochronology and the stratigraphic record. In: J.M. Hanchar P.W.O. Hoskin (Eds.). *Zircon: Experiments, Isotopes, and Trace Element*

Investigations. Washington, DC: Mineralogical Society of America and The Geochemical Society Press.

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Bowring, S.M., Myrow, P., Landing, E., Ramezani, J. Grotzinger, J. (2003). Geochronological constraints on terminal Neoproterozoic events and the rise of Metazoans [Abstract]. EGS−AGU−EUG Joint Assembly 2003, Nice, France. *Geophysical Research Abstracts, Vol. 5, Geodynamics Programme*. Abstract EAE03−A−13219.

Bowring, S.M., Myrow, P., Landing, E., Ramezani, J., Condon, D Hoffmann, K.H. (Accepted, 2003). Geochronological constraints on Neoproterozoic glaciations and the rise of Metazoans [Abstract]. *Geological Society of America, Abstracts with Programs, Annual Meeting, Seattle, WA*.

Bowring, S.M., Ramezani, J. Grotzinger, J.P. (2003). High precision U−Pb zircon geochronology and the Proterozoic−Cambrian boundary [Abstract]. *New Frontiers in the Fourth Dimension: Generation, Calibration and Application of Geological Timescales. NUNA Conference, 15−18 March 2003, Quebec, Canada*.

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Boyce, C.K., Cody, G.D., Fogel, M.L., Hazen, R.M., Alexander, C.M.O'D. Knoll, A.H. (In Press, 2003). Chemical evidence for cell wall lignification and the evolution of tracheids in Early Devonian plants. *International Journal of Plant Sciences*.

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Boyce, C.K., Cody, G.D., Zweiniecki, M.A. Holbrook, N.M. (2003). Biochemical and physiological innovation during the proliferation of vascular cell types [Abstract]. *Botanical Society of America Annual Meeting, Mobile, AL*. Abstract #59.

Boyce, C.K., Zweiniecki, M.A. Holbrook, N.M. (2003). How to make a leaf? 400 million years of repeated developmental, physiological, and biochemical answers to the same evolutionary question [Abstract]. *Botanical Society of America Annual Meeting, Mobile, AL*. Abstract #62.

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Brocks, J.J., Buick, R., Summons, R.E. Logan, G.A. (In Press, 2003). A reconstruction of Archean biological diversity based on molecular fossils from the 2.78 − 2.45 billion year old Mount Bruce Supergroup, Hamersley Basin, Western Australia. *Geochimica et Cosmochimica Acta*.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Members: Harvard University

Team Members sorted by current team.

Name:	Michelle Allen
Email:	m.allen@unsw.edu.au
Institution:	University of New South Wales
Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Name:	G. Arnold
Email:	gail@earth.rochester.edu
Institution:	University of Rochester
Name:	Jane Barling
Email:	barling@earth.rochester.edu
Institution:	University of Rochester
Name:	Audrey Bekker
Email:	a_bekker@vt.edu
Institution:	Harvard University
Name:	Sam Bowring
Email:	bowring@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Charles Boyce
Email:	ckboyce@oeb.harvard.edu
Institution:	Harvard University
Name:	Susan Brantley

Email:	brantley@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Jochen Brocks
Email:	brocks@oeb.harvard.edu
Institution:	Harvard University
Name:	Roger Buick
Email:	buick@ess.washington.edu
Institution:	University of Washington
Name:	George Cody
Email:	g.cody@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Dan Condon
Email:	dcondon@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Jennifer Eigenbrode
Email:	eigenbro@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Douglas Erwin
Email:	erwin.doug@nmnh.si.edu
Institution:	Smithsonian Institution
Name:	David Fernández Remolar
Email:	dfernandez@trasto.cbm.uam.es
Institution:	Centro de Astrobiologia
Name:	Marilyn Fogel
Email:	fogel@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Mick Follows

Email:	mick@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Katherine Freeman
Email:	kate@essc.psu.edu
Institution:	Pennsylvania State University
Name:	S. Goldman
Email:	shawn@earth.rochester.edu
Institution:	University of Rochester
Name:	Paul Greenwood
Email:	p.Greenwood@exchange.curtin.edu.au
Institution:	Curtain University
Name:	John Grotzinger
Email:	grotz@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Galen Halverson
Email:	halvers@eps.harvard.edu
Institution:	Harvard University
Name:	John Hayes
Email:	jhayes@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Robert Hazen
Email:	r.hazen@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Kai−Uwe Hinrichs
Email:	khinrichs@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Paul Hoffman

Email:	hoffman@eps.harvard.edu
Institution:	Harvard University
Name:	N. Holbrook
Email:	holbrook@oeb.harvard.edu
Institution:	Harvard University
Name:	Heinrich Holland
Email:	holland@eps.harvard.edu
Institution:	Harvard University
Name:	Harald Huber
Email:	harald.huber@biologie.uni−regensburg.de
Institution:	University of Regensburg
Name:	Matthew Hurtgen
Email:	mhurtgen@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Ulrike Jahn
Email:	ulrike.jahn@biologie.uni−regensburg.de
Institution:	University of Regensburg
Name:	Linda Jahnke
Email:	ljahnke@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	A. Jarzecki
Email:	jarzecki@Princeton.EDU
Institution:	Princeton University
Name:	K. Klochko
Email:	katya@earth.rochester.edu
Institution:	University of Rochester
Name:	Andrew Knoll

Email:	aknoll@oeb.harvard.edu
Institution:	Harvard University
Name:	Graham Logan
Email:	Graham.Logan@ga.gov.au
Institution:	Geoscience Australia
Name:	Kathleen Londry
Email:	londryk@cc.umanitoba.ca
Institution:	University of Manitoba
Name:	Gordon Love
Email:	G.D.Love@newcastle.ac.uk
Institution:	University of Newcastle
Name:	Timothy Lyons
Email:	LyonsT@missouri.edu
Institution:	University of Missouri, Columbia
Name:	Adam Maloof
Email:	maloof@eps.harvard.edu
Institution:	Harvard University
Name:	Charles Marshall
Email:	cmarshall@oeb.harvard.edu
Institution:	Harvard University
Name:	Richard Morris
Email:	richard.v.morris1@jsc.nasa.gov
Institution:	Johnson Space Center
Name:	Thomas Olzewski
Email:	Olzewski.thomas@nmnh.si.edu
Institution:	Smithsonian Institution
Name:	Victoria Orphan

Email:	vorphan@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Ann Pearson
Email:	pearson@eps.harvard.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Kira Pratt
Email:	kpratt@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Jahan Ramezani
Email:	ramezani@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	J. Roe
Email:	jroe@mail.rochester.edu
Institution:	University of Rochester
Name:	Dan Rothman
Email:	dan@segovia.mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Rob Rye
Email:	rye@usc.edu
Institution:	University of Southern California
Name:	Daniel Schrag
Email:	Schrag@eps.harvard.edu
Institution:	Harvard University
Name:	Stefan Schroeder
Email:	stefan@erl.mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Alex Sessions

Email:	asessions@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Yanan Shen
Email:	yshen@oeb.harvard.edu
Institution:	Harvard University
Name:	Diane Sheridan
Email:	dsheridan@oeb.harvard.edu
Institution:	Harvard University
Name:	Christian Sidor
Email:	sidor.christian@nmnh.si.edu
Institution:	Smithsonian Institution
Name:	T. Spiro
Email:	spiro@Princeton.EDU
Institution:	Princeton University
Name:	A. Stewart
Email:	as005j@mail.rochester.edu
Institution:	University of Rochester
Name:	Helen Sturt
Email:	hsturt@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Roger Summons
Email:	roger.summons@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Sean Sylva
Email:	ssylva@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Elisabeth Valiulis

Email:	valiulis@nmnh.si.edu
Institution:	Smithsonian Institution
Name:	Malcolm Walter
Email:	malcolm.walter@els.mq.edu.au
Institution:	Macquarie University
Name:	S. Weyer
Email:	stefan.weyer@em.uni−frankfurt.de
Institution:	University of Frankfurt
Name:	Rong Zhang
Email:	Rong.Zhang@noaa.gov
Institution:	Geophysical Fluid Dynamics Laboratory (GFDL)
Name:	H Zimmermann
Email:	hzimmer@gwdg.de
Institution:	Gottingen University
Name:	M. Zuber
Email:	mzuber@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Maciej Zwieniecki
Email:	mzwienie@oeb.harvard.edu
Institution:	Harvard University

Jet Propulsion Laboratory
Executive Summary
Principal Investigator: Kenneth Nealson

The fifth year of the JPL/Caltech/USGS NAI group was a great success with regard to discovery, publication of seminal work, representation of the work to the public, and overall adherence to the roadmap objectives espoused by the NAI. The work was highlighted by several keynote publications in the areas of life detection and biosignature development and testing, and set the stage for future work in the area: work critical to the assessment and testing of instruments for life detection missions. Each Co−I trained several students and postdocs, presented papers at the NAI annual meeting, and many of them presented plenary lectures at national and international meetings. Some of these are highlighted below.

As has been stated previously, the goal of our program slowly evolved from that of the co−evolution of Earth and its life, to that of a goal focused more centrally on the definition of life, the development of methods for its detection, the testing of some of these methods, and the beginnings of moving these methods to mission readiness.

The Co−Is of the program in the last year included:

- G. Blake and Y. Yung, Caltech −− Isotopes of nitrogen oxides as biosignatures
- J. Kirschvink, Caltech −− Microbial magnetosomes as biosignatures
- T. Ahrens, Caltech −− The effect of impact on potential biosignatures
- G. McDonald, JPL −− Organic geochemical biosignatures
- M. Fogel and D. Rumble, CIW −− Stable isotopes of C and S as biosignatures
- C. Johnson, Univ. of Wisconsin −− Stable isotopes of Fe as biosignatures
- J. Banfield, UC Berkeley −− Mineral weathering as a biosignature
- A. Anbar, U. Rochester −− Stable isotopes of metals as biosignatures
- K. Nealson, JPL/USC −− Development of strategies for life detection

For each of these areas, significant progress was made, papers were published in major journals, as noted in the individual reports, and national and international presentations were made. Some of these are highlighted below:

Of particular note, and delineated in the individual progress reports, was the work of **Dr. J. Kirschvink**, who has been a proponent of microbial

magnetosomes as biosignatures. His work on magnetosomes produced a number of published papers, generated great interest in this area, and continues to be interpreted as a potential biosignature both in subsurface samples on Earth, and in extraterrestrial samples, when returned. This work involved collaboration and interactions with members of the NAI from several centers, and within our own group.

In addition, **Dr. Clark Johnson** has continued his work with stable isotopes of iron, one of the areas that represents one of the seminal discoveries of our NAI program, and one that has attracted major attention in the international arena.

Dr. Gene McDonald of the JPL made considerable progress using amino acids as biosignatures to study several different earthly sites, and developed several approaches for applying these methods to extraterrestrial samples. In addition, in collaboration with members of the CIW group, analyzed tholin compounds with the goal of modeling their production and properties for the upcoming Cassini mission.

Members of our team have been involved with a number of NASA groups including the roadmap writing exercise, Mars Exploration Assessment Group (MEPAG), as well as with several ongoing missions, including Mars Global Surveyor, Odyssey (Nealson is a Co−I on Thermal Emission Imaging System (THEMIS)), and have participated in the writing of several new proposals for missions.

Finally, members of the JPL−1 team have been outstanding in terms of public interactions, presenting major talks at many meetings, both national and international. These include plenary lectures at several conferences, many lead talks at Gordon Conferences, and talks at international meetings. These talks have ranged from general talks about life detection strategy to very specific talks involving individual biosignatures being studied by each PI.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Astrobiology Funding to US Geological Survey

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Astrobiology Funding to US Geological Survey***
Project Investigator:	***Jeffrey Plescia***

Project Progress

Visible to near−infrared reflectance data have been collected for hyperthermal mat communities and sinter associated with springs in Yellowstone National Park. Springs with a range of temperatures and acidities have been samples in order to examine a range of environments. Target sites include Octopus Spring, Black Sand Pool, Nymph Creek, Lemonade Creek, Norris Basin, and Mammoth areas. Reflectance spectra are acquired using a portable field spectrometer with an artificial light source. Data are collected of the mat in situ as well as on pieces of the mat that have been removed from the water. Each of the major mat communities that have been examined has a diagnostic spectral signature that is produced from its unique combination of chlorophylls, bacteriochlorophylls, and carotenoids. The variations between major communities is large compared with the variation within a community. Spectra acquired of the same type of community occurring at different springs show the same absorptions. Data have also been acquired of active and inactive sinter materials. These data show that the sinter retain some degree of the organic absorptions even after the mat ceases to be active.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Fe Isotope Biosignatures

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Fe Isotope Biosignatures***
Project Investigators:	***Clark Johnson , Brian Beard***

Project Progress

The field of Fe isotope geochemistry, which the UW−Madison group has been largely responsible for developing, has matured greatly in the last year. Over 2,500 Fe isotope analyses are now available, as compared to less than two dozen in 1999, and these data constrain the biologic and abiologic mechanisms for producing Fe isotope fractionations in the field and the laboratory, as well as provide a rapidly emerging picture of Fe biogeochemical cycling over the last 3 billion years of Earth history. This explosion in our understanding of this new isotope system contrasts dramatically with that at the beginning of the five−year grant, when it was not yet known if isotopic analyses of Fe could even be done.

The major focus of our group has been on development of Fe isotopes as a biosignature for detecting metabolic processing of Fe. For example, we have quantified the Fe isotope fractionations that are produced by anaerobic photosynthetic Fe oxidation, which appears to be unique as compared to equilibrium Fe isotope fractionations in abiologic systems. However, it is possible that kinetic isotope effects that occur during rapid oxidation in abiologic systems may produce similar isotopic effects, which would limit the effectiveness of Fe isotopes to detect this form of Fe metabolism in the ancient rock record on Earth or other planetary bodies. More distinct Fe isotope fractionations that are uniquely attributed to biology appear to occur during dissimilatory Fe(III) reduction, and a major effort in Year 5 has been to quantify these fractionations during formation of biogenic magnetite and Fe carbonates. These results show that the Fe isotope compositions of Archean Banded Iron Formations likely were produced by dissimilatory Fe(III) reduction, and the Fe isotope biosignature for this metabolic process may be traced back at least 3 billion years on Earth (Figure 1).

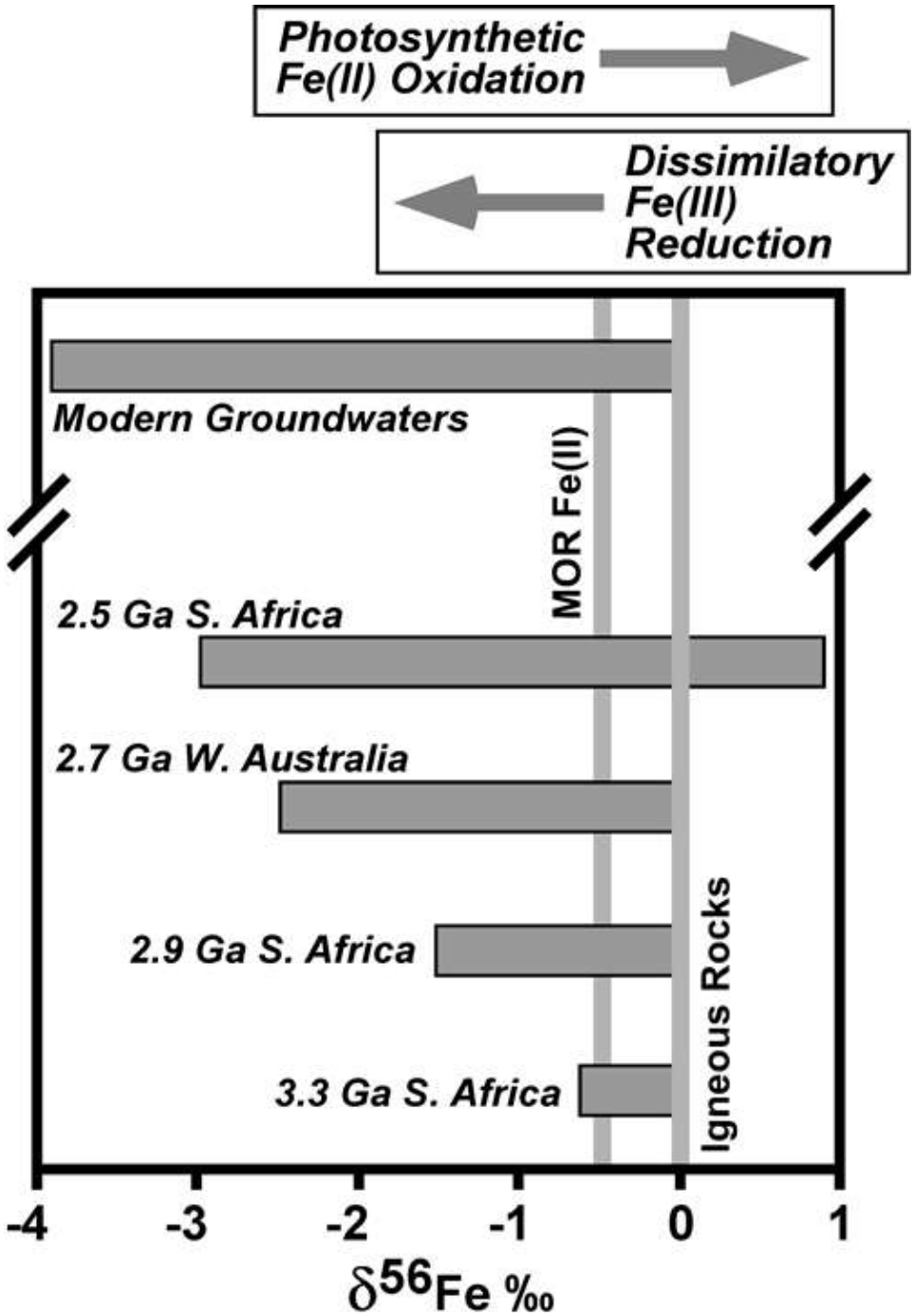

Figure 1. Summary of over 500 Fe isotope analyses for Archean sedimentary rocks and modern groundwaters. The low−^{56}Fe values beginning at ~2.9 Ga appear to be only explained by dissimilatory Fe(III) reduction, assuming formation in equilibrium with Mid−Ocean Ridge (MOR) sources of Fe(II). The isotopic signature for photosynthetic Fe(II) oxidation appears in 2.5 Ga Banded Iron Formations. Igneous rocks are isotopically invariant, at ^{56}Fe=0.00±0.05 ?, indicating that most sources of Fe, in the absence of biological processing, are isotopically homogeneous.

Highlights

- Fe isotope fractionations produced by metabolic processing of Fe are unique from those in abiologic systems, indicating that Fe isotopes may be used as a biosignature.

- Fe isotopes identify a likely role for metabolic processing of Fe by bacteria in Archean and Proterozoic Banded Iron Formations.

- Biological redox cycling of Fe is documented back to 3 billion years ago based on Fe isotope variations in clastic sedimentary rocks.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	*In−situ* measurement of isotopic biosignatures	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In collaboration with JPL scientists, we have been working on developing methods to analyze Fe isotope compositions *in situ* on Mars via a miniature mass spectrometer. Our work has focused on calibrating the Fe isotope measurements, including detailed assessment of the Fe isotope fractionations that may be produced during reduction of rock samples to Fe metal, followed by conversion to Fe pentacarbonyl.

Cross Team Collaborations

In addition to work with our lead NAI team JPL−1 (Ken Nealson), we have been working on the Archean rock record with the Penn State team (Hiroshi Ohmoto) and modern microbial mat systems with the NASA−Ames team (Dave Des Marais).

Our work with the Penn State team on Archean sedimentary rocks has produced the remarkable conclusion that biologically driven Fe redox cycling has occurred for at least 3 billion years on Earth. The primary evidence for this lies in Fe isotope compositions of magnetite− and Fe carbonate−rich clastic sedimentary rocks that underwent diagenesis in deep marine settings that can only be explained through dissimilatory Fe(III) reduction. This in turn implies that reactive ferric hydroxide minerals were in abundance at this time, and if the ambient atmospheric oxygen contents were low, as argued by many workers, anaerobic photosynthetic Fe oxidation would be a likely candidate for producing ferric hydroxides.

Fe cycling in modern microbial communities has been the focus of our work with the NASA−Ames team. We have found very large Fe isotope anomalies, the largest yet measured on Earth, to occur in concert with S cycling in the anaerobic portions of the sediment substrate of modern microbial mats. It seems likely that such Fe isotope signatures will be preserved in the rock record, raising the possibility that layered microbial communities might leave similar Fe isotope biosignatures in ancient deposits.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Fractionation of Transition Metal Isotopes

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Fractionation of Transition Metal Isotopes***
Project Investigator:	***Ariel Anbar***

Project Progress

The primary focus of this research is to determine if fractionations of transition metal isotopes can be used as biosignatures. Collaborations are pursued with the PSU Team and others outside the institute. We are also interested in the possible use of such fractionations to study changes in metal geochemical cycling, which could provide insight into environmental change and/or biochemical evolution. The latter applications are pursued primarily with the Harvard Team and non−NAI collaborators.

In Year 5, we continued examination of Fe and Mo isotopes.

Major Fe isotope results included developing a model to explain Fe isotope fractionation during hornblende weathering, finding evidence of Fe isotope fractionation during adsorption, and generating theoretical results (in collaboration with researchers at Princeton University) on the equilibrium fractionation factor between Fe(II) and Fe(III) aquo complexes that match experimental data. Major Mo isotope results included continued efforts to explain observed biogenic Mo isotope effects in cultures, and research into Mo isotope fractionation during abiotic aqueous chemistry− especially during interactions with Mn oxides. In collaboration with the Harvard Team, we continued development of Mo isotopes in ancient sediments for paleoredox investigations.

Highlights

- Iron stable isotopes constitute a complex and promising system with tantalizing, but elusive, biosignature potential.
- Quantum chemical modeling of Fe isotope fractionation between Fe(II) and Fe(III) complexes matches experimental determinations.
- With regard to Mo stable isotopes, there is a new toll to study changes in Precambrian ocean redox.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars sample return	Background research, techniques
1	Genesis	McKeegan, Co−I

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The search for signs of life in materials brought back from Mars in the future will require a suite of ?biosignature? tools. Fe isotopes, and isotopes of other metals, are potentially more robust carriers of biological information than are more traditional signatures such as C or S isotopes or organic molecules. Our work is primarily aimed at providing a context for the interpretation of Fe and Mo isotope variations that might be observed in future samples.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Impact Frustration and Subsequent Generation of Biologically Tenable Climates on Earth and Mars

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Impact Frustration and Subsequent Generation of Biologically Tenable Climates on Earth and Mars***
Project Investigators:	***Thomas Ahrens , Andy Shen , John O'Keefe , Michael Willis***

Project Progress

During the last year:

1. We have initiated study of the mechanical effects of shock deformation on bacteria living in fluids. Initial studies of e. coli at 3 and 15 GPa for 105 ns *in vivo* with TE buffer are designed to determine mechanical strains required for mortality. Extension of these experiments to lower shock stress, for longer durations, and higher stress, for shorter durations is planned. Studies of magnetotactic bacteria that have higher impedance (Fe_3O_4) structures within a low density matrix are planned.
2. Studies (in collaboration w/U. Arizona) of shock effects on the D/H ratio of water−bearing amphiboles, kaesuterite, similar to that found in SNC meteorites, reported at LPSC,2003 are designed to study the water budget of Mars. We obtained a surprising result that the D/H ratio of shocked (20−30 GPa) samples increased by 5%. Further work on samples will be done.

Project Goals for Next Year

- Continue to conduct detailed studies of the effect of the atmospheres on impact cratering on Mars
- Continue to conduct further speciation of impact vapor studies for minerals
- Continue to study the effect of impact on bacteria.

Highlights

- See #2 in Project Accomplishments

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Odyssey and Global Survey Missions	analysis of Mars craters

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Laboratory/Observational Studies of Biogenic Greenhouse Gases on the Early Earth

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Laboratory/Observational Studies of Biogenic Greenhouse Gases on the Early Earth***
Project Investigators:	***Geoffrey Blake , Yuk Yung***

Project Progress

Research by the Blake group as part of the NASA Astrobiology Institute effort led by P.I. K. Nealson centers on isotopic studies of biogenic greenhouse gases as evidence for life on the large scale appropriate for remote sensing approaches and on global biogeochemical investigations. Our early work in this area with the Nealson and Yung groups was concerned with the early and present biogeochemical evolution of the Earth. We have continued this largely theoretical study, but now are also developing new tools for the exploration of Mars and other extraterrestrial environments. Our particular tracer of emphasis is stable isotope fractionation, and we seek to understand whether or not these signatures can be reliably detected in extraterrestrial solar system bodies and exo−planetary systems. We have now characterized in detail the fractionation induced by the photolysis of NNO first predicted by Yung using a combination of non−linear spectroscopic light sources and mass spectrometry or Fourier transform infrared (FTIR) spectroscopy (Rahn et al. 1998, Zhang et al. 2000, Turatti et al. 2000), and have recently developed a novel theoretical approach that can be easily extended to other systems (Blake et al. 2003).

Neither of these approaches is compatible with the stringent space and weight requirements of in situ planetary exploration strategies. We are therefore developing new technologies that should enable the in situ measurements of important radiatively and biogenically active gases such as CO, CO_2, H_2O, CH_4, NNO, and H_2S to very high precision in order to examine the atmospheric dynamics and potential biogeochemistry on Mars, Titan, and other solar system bodies. Specifically, we are using laser diodes and sensors to image infrared (IR) laser induced fluorescence (IR−LIF). The support from NABI was used to conduct pivotal modeling tests of this approach, now under development primarily with Planetary Instrument Definition and Development Program (PIDDP) and ASTID program support in collaboration with JPL. We have recently combined microchip lasers with state−of−the−art HgCdTe detectors to investigate the sensitivity of IR−LIF under realistic planetary conditions, to optimize the optical pumping and filtering schemes for important species, and to apply the spectrometer to the non−destructive measurement of

stable isotopes in a variety of test samples. These studies form the necessary precursors to the development of compact, lightweight stable isotope/trace gas sensors for future planetary missions. Thanks to support from the ASTID program to Chris Webster, this coming summer we will complete the first combined laser absorption and emission tests using miniaturized, flight−compatible diode laser spectrometers at JPL. Within the NABI consortium, we will continue to work with the Nealson and Yung groups on modeling of the potential biological activity on Mars and the early Earth, and on the isotopic signatures of various model biospheres. This research is groundbreaking, and provides the necessary context for IR−LIF to be used as a robust diagnostic of extant or extinct (through its sampling of gases trapped in Martian soils and ice caps) biota on and underneath planetary surfaces.

Highlights

- We have verified that the stratospheric isotopic fractionation of nitrous oxide is caused by photolysis, and have developed a novel theoretical approach to photochemical fractionation that can be applied to other molecules and planetary atmospheres. This theory can now be widely applied to investigate the potential role of isotopic signatures as extrasolar biomarkers, particularly for Mars exploration.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
3	IR laser measurement of stable isotope ratios	Research and instrument/payload development, with support from the PIDDP and ASTID programs

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission

Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

Our collaborative work with the Yung group on nitrous oxide photolytic fractionation continues, leading to the submission of papers to Geophysical Research Letters and the Journal of Geophysical Research. The former is in press and should be released in July of 2003, the second is in the final stages of peer review. An additional, extensive, publication is in preparation that expands this technique to a wide variety of molecules and potential biomarkers.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Magnetic Biosignatures

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Magnetic Biosignatures***
Project Investigators:	***Kenneth Nealson , Joseph Kirschvink***

Project Progress

1. **ALH84001**: We have developed a successful detection strategy based on microwave ferromagnetic resonance for the identification of bacterial magnetofossils. On a series of control sediments that have been examined extensively with high−resolution transmission electron microscopy (HRTEM), this technique is able to rapidly distinguish those that do and do not contain magnetofossils. The basic principle exploits the magnetic anisotropy produced by linear chains of single−domain magnetite crystals, such as those produced intracellularly by the magnetotactic bacteria. Initial results on carbonate blebs from Martian meteorite ALH84001 are not incompatible with the presence of magnetofossils (Weiss et al., in review). Work is in progress to develop this procedure into a portable instrument that could be used in the field for magnetofossil and paleomagnetic studies, as well as possibly for eventual inclusion on a Martian lander.
2. **Microbial Genetics**: Our whole−genomic analysis of the nearly complete genomic sequence of two magnetotactic bacteria argues against lateral gene transfer as the acquisition mechanism for magnetotaxis (Nash et al., in review). Numerous clusters of conserved genes are at scattered locations around the physical genome in these two organisms. Magnetotaxis appears to have arisen very close to the root of the bacterial Domain, if not earlier. More recently, in samples of pure magnetotactic bacteria from the anoxic, hypersaline, hyperalkaline sediments from Mono Lake, California, we have detected two organisms with Archaebacterial ribosomal ribonucleic acid (rRNA). This is the first report of magnetotactic Archaebacteria and shows that magnetotaxis is a trait common to all three domains of life, further suggesting that the last common ancestor of all living organisms may have been magnetotactic. This is not inconsistent with the presence of putative magnetofossils in the 4 billion year old ALH 84001 carbonate globules from Mars and 2 billion year old terrestrial magnetofossils.
3. **The Paleoproterozoic Snowball Earth and the Great Oxygenation Event**: A detailed sedimentological and paleomagnetic investigation of the glaciogenic Huronian sediments in the Sudbury area of Canada

has demonstrated that low−latitude magnetizations once thought to be primary, and hence suggestive of low−latitude glaciation, are in fact secondary magnetic overprints that fail a small−scale paleomagnetic fold test (Hilburn et al., 2002). A detailed comparison of these units with those in South Africa (for which the youngest glacial event, the Makganyene diamictite, is low−latitude) suggests that all 3 Huronian glacial advances are older than the Makganyene event. Hence, there seems to have been only one clear Paleoproterozoic Snowball Earth episode. We have not been able to disprove the hypothesis that this event was triggered by the geologically sudden collapse of a methane−greenhouse atmosphere, perhaps in response to the evolution of O_2−releasing cyanobacteria. The concept that a discrete evolutionary event (like the evolution of O_2−releasing photosynthesis) could cause the destruction of an entire planetary ecosystem is a rather sobering thought.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Genesis and Stardust	Research/Analysis Techniques: SQUID Microscope imaging of returned materials may help to place thermal constraints on the particle capture process. Techniques are now being developed for these analyses. SQUID microscope studies of IDPs and cometary particles may allow for the first direct detection of cometary and extrasolar magnetization, as well as

		allow to make the first direct measurements of the the ancient protosolar magnetic field.
2	SCIM (Sample Collection for Investigation of Mars)	SQUID Microscope imaging of returned materials may help to place thermal constraints on the particle capture process. Also, Ferromagnetic resonance techniques may help identify magnetofossil−bearing sediments for return to Earth. Techniques are now being developed for these analyses. SQUID microscope and FMR studies of Martian dust could constrain mineralogy and mode of origin, as well as the timing and intensity of magnetic fields on Mars.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Understanding the thermal history of materials returned from space missions is crucial for understanding their geochemistry and petrology. SQUID Microscope imaging is a powerful tool for constraining such thermal events, as demonstrated by our previous work on the ALH 84001 meteorite.

Paleointensity studies of such samples can constrain the origin and timing of magnetic fields and dynamos in the early solar system, which in turn have implications for how the solar system formed, and the evolution of the interiors and atmospheres of planetary bodies.

Field Expeditions

Field Trip Name: Huronian Glaciation	
Start Date: July 29, 2002	***End Date:*** August 5, 2002
Continent: North America	***Country:*** Canada

State/Province: Ontario and Quebec	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Sudbury	***Keywords:***
Description of Work: Collection of oriented paleomagnetic samples for paleomagnetic and geochemical analysis, to determine the latitude of the glacial events and the redox state of the earth at the time they formed.	
Members Involved: Joseph Kirschvink	

Field Trip Name: Search for Magnetic Archaebacteria	
Start Date: : May 24, 2003	***End Date:*** : May 26, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Lee Vining
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Mono Lake	***Keywords:***
Description of Work: Collection of lake sediments from deep water and near shore localities for microbiological and genetic analyses, to determine the presence of novel magnetotactic microbial organisms.	
Members Involved: Joseph Kirschvink	

Cross Team Collaborations

We have been collaborating extensively with David McKay's group at the Johnson Space Flight Center in Houston, Texas, on the interpretation of the magnetite crystals in the ALH 84001 meteorite. Several publications are shown in the attached list.

We have also been collaborating extensively with Peter Ward's group at the University of Washington on the paleomagnetic calibration of the major extinction event at Permian Triassic boundary in South Africa. Two major manuscripts are in preparation.

We have also been collaborating with S. Mojzsis's group at the University of Colorado, Boulder in our magnetic studies of Hadean zircons.

We also have been collaborating with J. Grotzinger, A. Knoll, and S. Bowring in the Harvard−MIT group on three different projects: paleomagnetism of Precambrian−Cambrian boundary sediments in Oman (c.f. Amthor et al. 2003), deep drilling in the Kaapval craton across the Snowball Earth deposits (c.f. Evans et al. 1997), and zircon dating of the Sept Iles intrusive event, which will provide a key test of the Cambrian Inertial Interchange hypothesis (c.f. Kirschvink et al. 1997)

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Martian Biogenic Gases

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Martian Biogenic Gases***
Project Investigator:	***Yuk Yung***

Project Progress

If life exists beneath the Martian surface similar to terrestrial bacteria that obtain their energy by chemical reactions utilizing H_2 and CO, then it may be possible to infer the presence of subsurface life by observing metabolic by−products as trace gases in the Martian atmosphere. In this study we use a chemical model of the Martian atmosphere to study the fate of several organic trace gases. Although most of these gases have short chemical lifetimes, CH_4 has a chemical lifetime of about 300 yrs, and thus it will tend to be uniformly distributed in the Martian atmosphere. Using this model and the current observational upper limit on atmospheric CH_4, we deduce that global flux, from all sources, of CH_4 into the Martian atmosphere must be at least 1.2 x 10^5 times less than terrestrial value. If there are abiotic sources of CH_4 on Mars, then the biological component of the CH_4 must be even less. Furthermore, using current detection techniques, we estimate that it is possible to detect a Martian CH_4 source that is about 7 x 10^7 times less than the terrestrial source. This will provide the strictest test that we are aware of for a hypothetical subsurface biosphere on Mars.

Highlights

- Life could exist under the surface of Mars
- It is possible to set strong upper limits to life on Mars with current spectroscopic techniques.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Mineralogical Biosignatures

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Mineralogical Biosignatures***
Project Investigator:	***Jill Banfield***

Project Progress

The primary focus of the past 12 months has been on minerals generated by iron−oxidizing bacteria at neutral pH and on sulfate−reducing bacteria. We have continued to characterize the products of a diversity of iron−oxidizing bacteria and discovered that polymer mineralization can yield unexpected mineral phases with extreme morphologies not encountered in inorganic materials. Specifically, recrystallization on extracellular polymer strands generates akaganeite pseudo−single crystals with aspect ratios of > 1000:1. Until recently, we had presumed that these features arose due to polymer directed mineral growth. In the past few months we have analyzed these biogenic materials with two different X−ray microscopies and have been able to confirm the presence of organic carbon and establish that the polymers are predominantly saccharides. We have postulated a direct connection between mineralization and energy metabolism to explain the investment by bacteria in production of these polymers. Nature has encouraged submission of manuscript reporting these data. We have redeveloped oligonucleotide probes for detection of sulfate−reducing bacteria and used these to characterize biofilms. We have completed a description of the structure, microstructure, and aggregation state of metal sulfides formed as the direct result of sulfate−reducing bacteria (SRB) activity. The data imply episodic mineralization, possibly arising to oscillatory system behavior because of the effects of completing metabolic pathways for sulfate and organic carbon utilization. A manuscript reporting these data is about to be submitted.

Highlights

- Bacteria associated with iron oxidation at circum−neutral pH produce saccharide−based polymers that localize precipitation and template formation of novel phases.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Concept	Basic research:life detection

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The primary objective of our work is to develop an understanding of the nature of the record life leaves in minerals.

Field Expeditions

Field Trip Name: Sample collection in the subsurface	
Start Date: 2002	***End Date:***
Continent: North America	***Country:*** USA
State/Province: WI	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Piquette Mine	***Keywords:*** SRB and iron−oxidizing bacteria, subsurface
Description of Work: Sample collection: iron−oxide encrusted biofilms and decaying wood colonized by SRB, plus water sample collection and in situ measurements	
Members Involved: Clara Chan	

Cross Team Collaborations

Although we have not collaborated with NAI team members, we have collaborated with Pupa De Stasio.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Organic Molecules as Biosignatures

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Organic Molecules as Biosignatures***
Project Investigator:	***Gene McDonald***

Project Progress

We have continued our investigations into organic biogeochemistry in extreme environments on Earth and the implications for extraterrestrial organic biomarker searches. We are preparing to submit a manuscript describing our analysis of amino acid concentration vs. depth profiles in microbially colonized Antarctic sandstone rocks. We have found an interesting phenomenon in which one or more as yet unidentified molecules containing D−alanine and D−glutamic acid appear to pool at significant depths (up to 10 cm or more) inside the rock, while a second fraction containing D−aspartic acid and D−leucine is concentrated near the surface of the rock, at the level of highest biomass occurrence. These two contrasting profiles may be due to differential breakdown and aqueous transport of peptidoglycans or other biomacromolecules produced by the cryptoendolithic community. This discovery has important implications for the design of spacecraft amino acid analysis instrumentation that might be used to search for similar biological communities on Mars.

We are also extending our database of amino acid and lipid biomarker profiles from low−water−activity environments to include samples of possible Mojave Desert endoliths. These samples include rocks coated with desert varnish, a layer of metal oxides and clays that has been speculated to have a biologically mediated formation mechanism. A USC Geobiology graduate student, Rachel Schelble, is searching for bacterial fatty acid biomarkers in the varnish layers of these samples at JPL under a NASA Planetary Biology Internship.

We have also been investigating possible prebiotic organic chemistry on Titan through the use of laboratory−produced haze analog materials known as tholins. In collaboration with George Cody of the Carnegie Institution NAI team, we have obtained high−resolution ^{1}H, ^{13}C and ^{15}N nuclear magnetic resonance (NMR) spectra of one form of Titan tholin. We are currently in the process of assembling those data into a model chemical structure. This structure will give us greater insight into the chemistry that may occur when atmospheric organic haze particles interact with water, rock, or hydrocarbon phases on the surface of Titan.

Highlights

- We have developed improved understanding of amino acid biogeochemistry in Antarctic endolithic communities.

- We have obtained structural data on Titan aerosol haze analogs at much higher resolution than previously available.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Cross Team Collaborations

In collaboration with George Cody of the Carnegie Institution NAI team, we have obtained high−resolution ^{1}H, ^{13}C and ^{15}N NMR spectra of one form of Titan tholin. We are currently in the process of assembling those data into a model chemical structure.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Stable Isotope Biogeochemistry

Lead Team:	***Jet Propulsion Laboratory***
Project Title:	***Stable Isotope Biogeochemistry***
Project Investigators:	***Marilyn Fogel , Andrew Steele***

Project Progress

Stable isotope biogeochemistry was studied in four projects during this year. 1) Isotopic composition of fossil food webs in the Enspel formation. This 25 million year old deposit has recognizable fossils that have retained their original isotopic signatures. 2) Oxygen isotopes in oceanic phosphates. Oxygen isotopes in phosphate record bacterial turnover and could be used as biosignatures. 3) Carbon isotopes in the Apex cherts. These 3.5 billion year old samples are controversial as to whether the carbon in these rocks is biologically or non−biologically derived. 4) Fe oxidizing bacteria and autotrophic growth. These microorganisms are thought to be important CO_2 fixing bacteria at hydrothermal vents. The role in early life and on Mars is debated.

Highlights

- Isotopic biosignatures in fossils from millions of years old rocks preserve ecological relationships.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

I have collaborated with Andrew Steele, CIW, and John Lindsay (JSC) on the carbon isotopic record of Precambrian cherts. Robin Sutka and her advisor Dave Emerson are part of the CIW team. Kevin Boyce, an NAI fellow at

Harvard, has also done some isotopic investigations on fossil plant taxa that are enigmatic.

Fellowships: Jet Propulsion Laboratory

There are no Postdoctoral Fellowships for this team.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

EPO: Jet Propulsion Laboratory

These are the Education and Public Outreach activities for the Jet Propulsion Laboratory.

Signs of Life

Mark Andrews, a student in the Science and Nature Filmmaking program at Montana State University, is making a 15− to 25−minute film tentatively titled "Signs of Life". This film will be targeted for use in museum displays, with possible later expansion to a format suitable for broadcast use. Members of the JPL Astrobiology group were filmed in interviews and at field sites (Death Valley and Mono Lake) for this film. The JPL1 NAI team also provided financial support from its EPO budget.

Astrobiology Museum Community Survey

The Science Museum of Minnesota was contracted to circulate a survey of science museums on their interest, knowledge, and current involvement in astrobiology. The results from this survey are currently being compiled and evaluated.

Publications: Jet Propulsion Laboratory

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Members: Jet Propulsion Laboratory

Team Members sorted by current team.

Name:	Thomas Ahrens
Email:	tja@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Name:	G. Arnold
Email:	gail@earth.rochester.edu
Institution:	University of Rochester
Name:	Jill Banfield
Email:	jill@seismo.berkeley.edu
Institution:	University of California, Berkeley
Name:	William Barker
Email:	barker@ls.admin.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Jane Barling
Email:	barling@earth.rochester.edu
Institution:	University of Rochester
Name:	Brian Beard
Email:	beardb@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Geoffrey Blake

Email:	gab@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Susan Brantley
Email:	brantley@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Paul Braterman
Email:	psb@unt.edu
Institution:	University of North Texas
Name:	Clara Chan
Email:	chan@seismo.berkeley.edu
Institution:	University of California, Berkeley
Name:	George Cody
Email:	g.cody@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Albert Colman
Email:	a.colman@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	David Des Marais
Email:	ddesmarais@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	Marilyn Fogel
Email:	fogel@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Donna Galuszka
Email:	dgaluszka@usgs.gov
Institution:	USGS Flagstaff
Name:	Isaac Hilburn

Email:	dyth@its.caltech.edu
Institution:	California Institute of Technology
Name:	Heinrich Holland
Email:	holland@eps.harvard.edu
Institution:	Harvard University
Name:	A. Jarzecki
Email:	jarzecki@Princeton.EDU
Institution:	Princeton University
Name:	Clark Johnson
Email:	clarkj@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Jeff Johnson
Email:	jrjohnson@usgs.gov
Institution:	USGS Flagstaff
Name:	Joseph Kirschvink
Email:	kirschvink@caltech.edu
Institution:	California Institute of Technology
Name:	K. Klochko
Email:	katya@earth.rochester.edu
Institution:	University of Rochester
Name:	Andrew Knoll
Email:	aknoll@oeb.harvard.edu
Institution:	Harvard University
Name:	Robert Kopp
Email:	rkopp@caltech.edu
Institution:	California Institute of Technology
Name:	Keliann LaConte

Email:	keliann@caltech.edu
Institution:	California Institute of Technology
Name:	Laurie Leshin
Email:	laurie.leshin@asu.edu
Institution:	Arizona State University
Name:	Mao−Chang Liang
Email:	mcl@gps.caltech.edu
Institution:	California Institute of Technology
Name:	John Lindsay
Email:	John.f.lindsay1@jsc.nasa.gov
Institution:	Johnson Space Center
Name:	Timothy Lyons
Email:	LyonsT@missouri.edu
Institution:	University of Missouri, Columbia
Name:	Francis Macdonald
Email:	francis@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Gene McDonald
Email:	Gene.D.McDonald@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Michelle Minitti
Email:	Michelle.Minitti@asu.edu
Institution:	Arizona State University
Name:	John Moreau
Email:	moreau@seismo.berkeley.edu
Institution:	University of California, Berkeley

Name:	Michael Morton
Email:	morton@its.caltech.edu
Institution:	California Institute of Technology
Name:	Cody Nash
Email:	nascz@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Kenneth Nealson
Email:	knealson@jpl.nasa.gov
Institution:	University of Southern California
Name:	Dianne Newman
Email:	dkn@gps.caltech.edu
Institution:	California Institute of Technology
Name:	John O'Keefe
Email:	dinosr@aol.com
Institution:	California Institute of Technology
Name:	Hiroshi Ohmoto
Email:	ohmoto@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Beverly Pierson
Email:	Bpierson@ups.edu
Institution:	University of Puget Sound
Name:	Jeffrey Plescia
Email:	jplescia@usgs.gov
Institution:	USGS Flagstaff
Name:	Rebecca Poulson
Email:	poulson@geology.wisc.edu
Institution:	University of Wisconsin, Madison

Name:	Eric Roden
Email:	eroden@bsc.as.ua.edu
Institution:	University of Alabama
Name:	J. Roe
Email:	jroe@mail.rochester.edu
Institution:	University of Rochester
Name:	Robert Rye
Email:	rye@usc.edu
Institution:	University of Southern California
Name:	Rachel Schelble
Email:	rachels@usc.edu
Institution:	University of Southern California
Name:	Maia Schweizer
Email:	m.schweizer@gl.ciw.edu
Institution:	Princeton University
Name:	Silke Severmann
Email:	silkes@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Andy Shen
Email:	ahshen@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Mahadeva Sinha
Email:	mahadeva.p.sinha@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	T. Spiro
Email:	spiro@Princeton.EDU
Institution:	Princeton University

Name:	Andrew Steele
Email:	a.steele@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Michael Storrie−Lombardi
Email:	mike@kinohi.org
Institution:	Kinohi Institute
Name:	Henry Sun
Email:	hjsun@mail1.jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Robin Sutka
Email:	rsutka@atcc.org
Institution:	George Mason University
Name:	A. Taunton
Email:	taun6868@uidaho.edu
Institution:	University of Wisconsin, Madison
Name:	Alexandre Tsapin
Email:	tsapin@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Benjamin Weiss
Email:	bweiss@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Susan Welch
Email:	swelch@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	S. Weyer
Email:	stefan.weyer@em.uni−frankfurt.de
Institution:	University of Frankfurt

Name:	Rene Wielsi
Email:	renew@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Michael Willis
Email:	mjwillis@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Kosei Yamaguchi
Email:	kosei@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Yuk Yung
Email:	yly@gps.caltech.edu
Institution:	California Institute of Technology

Johnson Space Center
Executive Summary
Principal Investigator: David McKay

The JSC Astrobiology Center is very diverse team that has about as many non−JSC members as it does JSC members. Since we are unable to add new civil servants, only 3 civil servants participate significantly in any of the projects or the education and outreach activities, and only two of them can spend significant time on the science projects. Most of the JSC team consists of contractor scientists, two of which are also graduate students while working at JSC, summer student interns, a NAI post−doctoral fellow, and scientists from nearby institutions. Our team represents a variety of disciplines, including geology, mineralogy, microbial extremophiles, geochemistry, and planetology.

The uniting theme for the JSC team is sample and material analysis to provide characterization data on terrestrial samples, astromaterials, and experimental samples. The types of data sought are usually features related to microbial life and the byproduct of microbial activities. Such features include morphology of living microbes and their surroundings, including biofilms on geologic substrates, as well as the morphology of fossilized forms of this living biota. In addition to morphology, chemistry and mineralogy of microbial produced features and fossilized microbes are of great interest to us. We typically use probe instruments (scanning electron micrograph (SEM), transmission electron microscopy (TEM), electron microprobes, TOF−SIMs, double laser beam mass spectrometers, and Confocal and epi−fluorescence microscopy to acquire information on living or dead microbial life. The overall goal is to relate chemistry, mineralogy, atomic structure, morphology, spectral interactions, and other properties for specific types of features so that multiple data can be used to characterize or fingerprint life in all its forms (including ancient fossils and bioassisted mineral precipitates). But we also strive to understand the processes that create the characteristics of life, the processes that alter or fossilize life, and the processes that produce and preserve interaction between life forms and rocks or minerals. Fingerprints of life are valuable for themselves, but they may also contain the history of that life and its environment over time.

The ability to confidently identify the presence of life or the former presence of life has been taken for granted in many types of terrestrial samples. However, as we are looking more and more at astromaterials from beyond Earth and taking a fresh look at terrestrial Archean samples, many in the scientific community have realized that it is not always obvious or easy to determine whether life was or is present in the rocks, minerals, soils, and fluids of Earth

or another planet.

Consequently, our overall goal is to develop better techniques for detecting and understanding life and develop a biosignature classification system that assigns biosignature potential ranked by probability. It will be absolutely necessary to do this for returned Mars samples, but these techniques should first be well tested on terrestrial samples, and should also be applied to other types of samples as well: meteorites, cosmic dust, cometary dust, and samples from various satellites and small bodies. Because of the extreme interest in the possibility of life elsewhere, we must develop strong criteria for detecting it and certifying it. That is the current overreaching goal of the JSC team. That may also become the core objective for all of NASA in the coming decade or two.

Projects

During the past year we have made progress on some ongoing projects and have started several new ones. A brief description of each project and a few highlights of our progress is given below:

Publications:

During the past 12 months, our JSC Astrobiology Institute team has published more than 100 scientific papers and abstracts:

Peer−reviewed publications: 73
Published abstracts: 87
−−−
Total 160

The peer−reviewed publications include book chapters. Most of the abstracts are extended abstracts. Most of the published abstracts were also presented at meetings as talks or sometimes posters. In addition to talks associated with published abstracts, we gave at least 25 more scientific talks to various meetings and technical groups, amounting to about 90 scientific talks and posters total.

Science Projects

We have subdivided our several small projects into five main work projects listed below:
(1) New Technique Development and Application

- Continued development of using antibodies and state−of−the−art array approach may be used to search for life on Mars on robotic missions.
- Hopanes, a reliable established class of chemical biosignature, has been successfully detected in ELISA tests during Mars microgravity experiments performed for NASA's KC−135 flight program.
- *Limulus Amebocyte Lysate (LAL) and Prophenoloxidase system (PPO)* −− We have developed very sensitive methods to detect microbial contamination based on the *Limulus Amebocyte Lysate (LAL)*

and Prophenoloxidase system (PPO). These methods are to detect LPS, glucan and peptidoglycan down to sub−picogram level in pharmaceutical applications that have adapted them to rock, soil and metallic surfaces.
- Use of multiple fluorescent probes gives a visual representation of disseminated organic material in geologic materials such as interplanetary dust particles (IDPs) and rock varnish.
- New analyses of Nakhla, Mars meteorite, by double laser spectrometry shows presence of complex organics.

(2) Organic Biosignatures

- We have used antibodies to detect category 1 and other biomarkers in rock samples. Extraction takes a few minutes and analysis a few hours.
- We have presented use of new antibodies to detect hopanes and have shown proof of operation during Martian gravity.
- The analysis of the carbon in AHL84001 carbonate globules is organic carbon. The C−ring analyzed is consistent with the detection of polycyclic aromatic hydrocarbons (PAHs) associated with the carbonate globules. We found that carbon was approximately uniformly distributed throughout the carbonate, although the C−ring and C=O to total carbon (which is mainly in carbonate) is highest in the rim carbonate.

(3) Terrestrial Analogs and Martian Meteorites

- We discovered novel strains related to the bacterial genera *Coprothermobacter, Geobacillus, Clostridium, Anaerobaculum*, and also a previously uncultivated spirochete in ultradeep gold mines in South Africa.
- Microbial communities in hypersaline environments suggest that mineralization is controlled through biofilm production, and extreme desiccation of those films contributes to evaporate mineral deposits on a micrometer scale.
- Atacama Desert bacteria isolates suggest variation of species through elevation changes.
- Mn carbonates with complex textures were found in Nakhla.
- Rock varnish preserves C disseminated throughout the varnish microlayers, but is generally a poor morphological preserve for bacteria in older varnish samples. Hematite in the banded iron formation has a better preservation of microorganisms than seen in older ferricrete or hematite in rock varnish.
- A variety of microbes and viruses thrive in permanently ice−covered Antarctic lakes, even though the ice filters out more than 98% of the light.
- "Hot" (2°C) springs emerging from the upper surface of some Canadian Arctic glaciers contain microbial life.
- Carbonate globules in igneous rocks are extremely complex and are often associated with secondary silica−rich phases −− preliminary evidence suggests that this silica phase forms at relatively low temperatures and is not a melt glass.

(4) Mineral Biomarkers

- Tiny magnetite in ALH84001 was confirmed as indistinguishable from magnetite made by bacteria.
- Magnetite in ALH84001 continues to strongly support the early life on Mars hypothesis.
- Manganese minerals formed in caves and on rock varnish with the help of bacteria may provide possible biomarkers for use on Mars.
- Transmission Electron Microscopy tomography has confirmed the original geometry MV−1 and ALH84001.
- Nanobacteria may have ribonucleic acid (RNA) and nucleate calcium phosphate precipitation.
- Recent experiments show that Dolomite has demonstrated that sulfate reducing bacteria may initiate the formation of this mineral.

(5) Archean Biosignatures

- Hydrothermal systems preserved in the Archean Pilbara succession suggest that abiotic hydrothermal processes dominate sedimentation, making it very difficult to isolate biotic signatures.
- In the search for signs of microbial mats in zones of quieter sedimentation away from vents, promising results have come from fine−grained clastic sediments in the Paddy Market Formation. The formation consists of thinly laminated shales and sandstone −− probably turbiditic in origin.

Education and Public Outreach

Our Education and Public Outreach (EPO) program is one of the most active in the NAI. Their work his past year includes workshops, classroom activity product development, display events, CD authoring, public presentations, and the support of many undergraduate interns. We helped design and build the major museum exhibit called *Microbes!*, which is continuing its tour of major U. S. science museums. Members of the JSC Astrobiology Institute Team held more than 50 press interviews, TV and radio appearances, and other media events during the past 12 months. In addition, we made dozens of general public presentations and classroom presentations around the world. All of these Education and Public Outreach projects are documented in the detailed report. We believe we have an exemplary program in this area and we intend to continue its rapid pace.

Collaboration

We have put together two teams from Historically Black and Hispanic Universities and have helped them get independent funding through proposals. We now have an Astrobiology group at Highlands University in New Mexico, which is a subunit of the JSC Astrobiology Institute. In addition, a member of our local team (Penny Morris−Smith) has been awarded a significant grant to incorporate minority students and from Texas Southern University, the University of Houston (downtown campus) into some of our projects as interns, visiting faculty, and graduate students. We will also work

with the Houston Museum of Natural History on this project. In summary, we have added three universities to our active group, all specifically in astrobiology. We have raised more than half a million dollars from other sources to support these efforts.

We currently also have a Memorandum of Understanding in negotiation between NASA Headquarters to work with a group at the Geological Survey of Canada specifically on Astrobiology topics, generally focused on biosignatures. This MOU was signed this past calendar year.

As indicated in our science project reports, we are now actively working with a number of universities as documented also in previous progress reports. These collaborations have proven to be valuable and have provided our team with considerable expertise, which we originally lacked, specifically in microbiology, genomics, microbial ecology, and field and laboratory procedures for sampling, culturing, preserving, and working with microbes. However, we now have two new astrobiology labs at JSC to continue nanobacteria and Microarray Assay for Solar System Exploration (MASSE) hopane research, the MASSE extraction test bed prototype development and a lab for clean and sterile preparation of geologic samples and astromaterials. These new laboratories opened May 2003 to better serve our research collaboration with Carnegie, Montana State and the University of Arizona. We are now capable of interacting better with other NAI teams on a scale that we have not had before.

We also have an established a working relationship with the Madrid Center for Astrobiology for work on the MASSE project. They are helping develop the array technology and we are working on the antibody−antigen reactions. We will both participate in final design and in the test program, and they will start field tests at the Rio Tinto in September of this year. They will be partners on any flight hardware that we are successful in getting onto a mission.

In addition to the Centro de Astrobiologia (CAB), we also have an established and strong partnership with Carnegie Institute through MASSE PI, Andrew Steele. His project engineer and PostDoc are housed at JSC, utilizing our new laboratory space.

Overall, we believe we have made considerable progress this year and we look forward to more collaboration with other NAI members in the coming year.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Archean Biosignatures

Lead Team:	***Johnson Space Center***
Project Title:	***Archean Biosignatures***
Project Investigator:	***John Lindsay***

Project Progress

The Archean Biosignatures project is not so new to the JSC team. We have done work on the Waroonga formation and now we have extended that work in to the Pilbara of Western Australia. We can apply what we learn from Earth's history to other worlds in our solar system. We can do this comparison through astromaterials, such as Martian meteorites. Astromaterials come to us largely devoid of context, making their interpretation both difficult and complex. To develop effective biospheric models we need to understand the context, at a stratigraphic and planetary level, in which life evolved and was preserved. Given our knowledge of the terrestrial planets, it is reasonable to assume that regardless of size their early histories will have many parallels. In this context Archean Earth should provide us with a reasonable analogue for early Mars and other terrestrial planets. To this end we have an ongoing program at the JSC Astrobiology Institute analysing rocks from the Achean and Early Paleoproterozoic succession from the Pilbara of Western Australia. The Pilbara Craton is unique in that it includes part of an Archaean protocontinent consisting of granitoid complexes that were emplaced into and overlain by a 3.51−2.94 Ga volcanigenic carapace, the Pilbara Supergroup (Van Kranendonk, 2000). The craton is in turn overlain by a series of younger basins that form a time series recording Earth history from c.2.8 Ga to c.1.9 Ga. In spite of their age the rocks of the Pilbara are only gently deformed and metamorphosed, for the most part, to lower greenschist facies.

Our work to date on the hydrothermal systems preserved in the Archean Pilbara succession suggests that abiotic hydrothermal processes dominate sedimentation, making it very difficult to isolate biotic signatures. The zones around hydrothermal vents in particular are swamped by silica and carbonate sedimentation, which is frequently disrupted by later hydrothermal events forcing their way, sometimes explosively, to the sea floor. During our 2002 field season to the Pilbara we initiated a reconnaissance program to search for signs of microbial mats in zones of quieter sedimentation away from vents. Promising results have come from fine−grained clastic sediments in the Paddy Market Formation. The formation consists of thinly laminated shales and sandstone −− probably turbiditic in origin (Van Kranendonk, 2000). We have been able to identify structures comparable with wrinkle mats and also

concretionary structures suggesting activity of sulfur reducing life forms. We will now expand this program both in outcrop, where the mat structures are more obvious because of weather, and also in core samples, where the primary geochemistry is more likely to have been preserved. We have access to large numbers of deep cores through local mineral exploration companies (Sipa Resources and Newexco, both in Perth) and will carry out fieldwork in a joint program with the Geological Survey of Western Australia.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars SMART lander	Background research to test instrumentation for MASSE

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The samples brought back from the Pilbara so far are currently being used to test for Hopanes using MASSE techniques for antibody extraction development.

Field Expeditions

Field Trip Name: Pilbara Field Expedition 2003	
Start Date: June 2003	***End Date:*** Aug 2003
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Perth
Latitude:	***Longitude:***

Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Work was cut short before the field expedition actually began when news of NAI CAN Cycle 3 was not awarded to JSC. The original intent was to continue the stratigrahic mapping of the hydrothermal vents. This field season will not resume until new funding has been aquired.	
Members Involved: John Lindsay	

Field Trip Name: Pilbara Expedition 2002	
Start Date: June 2002	***End Date:*** Aug 2002
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Perth
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Pilbara	***Keywords:***
Description of Work: Worked with Newexco to study drill cores and used the core info to construct 3−D map of the subsurface of the Archean hydrothermal vents. Successfully mapped main stratigraphic sections of the Archean sedimentary basin units.	
Members Involved: John Lindsay	

Cross Team Collaborations

We have initiated a detailed field mapping and sampling program of the Apex chert as a basis for understanding the geochemical environment in which they formed. Chert samples collected from throughout the hydrothermal system will be analysed in thin section and by scanning electron microscope ay JSC and Oxford University and the morphology of the contained carbon−rich structures evaluated against our isotope and geochemical data as described above. Further fieldwork in cooperation with the Geological Survey of Western Australia is planned.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Immunoassay life detection test

Lead Team:	***Johnson Space Center***
Project Title:	***Immunoassay life detection test***
NAI−NRC Postdoctoral Fellow :	***David Warmflash***

Project Progress

This project centers on the use of immunological tests such as Enzyme−linked Immunosorbant Assay (ELISA) to easily distinguish between samples containing life markers and samples free of life markers. I have used various antibodies so biomarkers such as deoxyribonucleic acid (DNA), ribonucleic acid (RNA), porphyrins, and bacterial membranes to demonstrate the concept that more automated antibody tests that work in a way similar to that of ELISA can be used for *in situ* instrumentation during robotic exploration of Mars, Europa, or other bodies.

Highlights

- I have found the selectivity of a newly developed antibody for the porphyrin class of molecules to be moderate and thus possibly useful for an automated biomarker detection instrument.

- I have shown the ELISA technique reported last year with regard to soil and Mars regolith simulant to produce similar results when used on extracts of permafrost samples from Devon Island, Canada.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Any one of future Mars landers for which instruments have not yet been chosen.	Not officially connected with any active mission

3	Any future Europa mission which performs in situ analysis of samples.	Member of Science definition team for Jupiter Icy Moons Orbiter Mission

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

I collaborated with Andrew Steele of Carnegie for long−term planning for in situ instrument concepts.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Mineral Biosignatures

Lead Team:	***Johnson Space Center***
Project Title:	***Mineral Biosignatures***
Project Investigator:	***Kathie Thomas−Keprta***

Project Progress

We define mineral biosignatures to be those minerals that exhibit properties that are characteristic of, produced by, or influenced by biological activity. Furthermore, these properties must be such that they could not reasonably occur through random, stochastic interactions in the natural environment . One example is magnetite (Fe_3O_4), which is an abundant mineral on Earth and is typically formed through inorganic processes. When magnetite is formed intracellularly by prokaryotic organisms called magnetotactic bacteria, the crystals display a morphology, size distribution, and chemical purity that have never been observed in the absence of biogenic activity. These properties are controlled by the cell and are a product of evolution. Unlike organic biomarkers, which represent the molecular components of an organism, mineral biosignatures represent the interaction of an organism with its environment. Hence mineral biosignatures make no assumption as to the molecular makeup of the organism and so are inherently less Earth−centric. Analysis of the Martian meteorite Allan Hills 84001 (ALH84001) revealed several lines of evidence that have led some investigators to suggest that microbial life existed on Mars approximately four Ga (billion annum) ago. One of the strongest lines of evidence is the presence of tens−of−nanometer sized magnetite [Fe_3O_4] crystals found within carbonate globules and their associated rims in the meteorite.

We continue to confirm our original geometry for _ of the magnetite population in the ALH84001 carbonate globules to be of identical geometry to a magnetotactic bacteria strain known as MV−1 through transmission electron microscope tomography. This technique has confirmed the original geometry of MV−1 and ALH84001 magnetite to be indistinguishable.

We are continuing progress of producing chemically simplistic analogs to the ALH84001 carbonates. Experimental work by Chris Romanek and colleagues at the Savannah River Ecology Laboratory shows that both magnetite and siderite can be produced at relatively low temperatures from aqueous solutions under CO_2 partial pressure equal to that on Mars. These carbonates have been heated to produce magnetite that can be compared with those observed

in ALH84001.

We have also begun a research collaboration with Neva Ciftcioglu and her study of "nanobacteria" mineralization of a unique morphological calcium phosphate shells that grow around the nanoforms. The genetic makeup and the nature of the nanobacteria and associated mineralization process is still being categorized at present. Preliminary results indicate the presence of ribonucleic acid (RNA). Current collaboration with the MAYO Institute will conform these results within the year.

Working with Lisa Robbins and her graduate student Van Cleave, we have developed the foundation and protocols to test the hypothesis that ancient microbes can be utilized to produce suites of minerals similar to those found in ALH84001. Using the chemolithotrophic thermophile *Archeaoglobus fulgidus*, a variety of carbonate minerals were produced in laboratory experiments, including iron, magnesium and calcium carbonates. We propose to continue producing carbonates for examination of biomarkers within these microbially induced minerals. These mineral suites can be analyzed through a variety of methods, including scanning electron micrography (SEM), transmission electron microscopy (TEM), and fluorescent microscopy.

Highlights

- Transmission Electron Microscopy tomography has confirmed the original geometry MV−1 and ALH8400
- Nanobacteria may have RNA and nucleate calcium phosphate precipitation.
- Dolomite is one of the more enigmatic minerals that are found in the rock record because it rarely is found forming at Earth surface temperatures. However, recent experiments have demonstrated that sulfate reducing bacteria may be the initiate the formation of this mineral. It has not been previously demonstrated that bacteria in higher temperatures can also form this mineral. Therefore this experiment could provide insight into how this very abundant mineral has been produced.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Cross Team Collaborations

Atomic Force Microscopy, Ion probe, Raman Spectroscopy (Carnegie)

Squid magnetometer (California Institute of Technology)

Savannah River Ecological Laboratories mixed carbonate experiments

USGS St Petersburg, Florida carbonate precipitation experiments
Iowa State TEM tomography of MV−1

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: New Technique Development and Application

Lead Team:	***Johnson Space Center***
Project Title:	***New Technique Development and Application***
Project Investigator:	***Simon Clemett***

Project Progress

Limulus Amebocyte Lysate (LAL) and Prophenoloxidase system (PPO) −− The goal of LAL is to develop very sensitive methods to detect microbial contamination based on the Limulus Amebocyte Lysate (LAL) and Prophenoloxidase system (PPO). These methods have been documented to be able to detect lipopolysaccharide (LPS), glucan and peptidoglycan down to sub−picogram level in pharmaceutical applications. We have adapted them to rock, soil and metallic surfaces. We project application of these methods to known contemporary samples of Earth origin and then to fossilized Earth samples, with the ultimate goal of using these methods to examine Mars meteorites and samples returned from future Mars missions. It is anticipated that methods will continue to be developed that will enable visualization of microbial structures in rock or mineral by "staining" such samples with chromogenic or electron dense substrates for LAL and PPO.

Fluorescent Molecular Probe Derivatization −− Our approach is to target specific organic monofunctional groups on a sample and tag them with a fluorescent molecular probe. Once a sample surface has been tagged the spatial distribution of those monofunctional groups can be determined by fluorescence microscopy. This same surface can then subsequently be analyzed by two−step laser microprobe mass spectrometry (mL^{2}MS) to determine the specific molecular species tagged (see below). Since a single fluorphor molecule is typically capable of being consecutively cycled through the fluorescence "excitation−emission" sequence many times, that is it has a low−photobleaching quantum yield, single molecule detection can routinely be achieved by fluorescence microscopy. The spatial resolution limit is determined by the wavelength of the light emission from the fluorphor and is typically sub−micron. Four molecular probes have been determined to be suitable for geological samples, fluorescein−5−isothiocyanate (FITC), o−phthaldialdehyde (OPA), naphthalenedicarboxaldehyde (NDA), and 4−phenylspiro[furan−2(3H),1'−phthalan]3,3'−dione (Fluorescamine). To date we have successfully demonstrated the detection of primary amines and amino acids on individual microtomed thin−sections of carbonaceous meteorites and interplanetary dust particles (Clemett, S. J.; Messenger, S;

Thomas−Keprta, K.L.; Wentworth, S.J.; Robinson, G−A; McKay, D.S.; "Spatially Resolved Analysis of Amines Using a Fluorescent Molecular Probe: Molecular Analysis of IDPs," LPSC XXXIII Clemett, S.J.; Messenger,, S.; Keller, L.P.; Thomas−Keprta, K.L., McKay, D.S.; "Spatially Resolved Analysis of Amines in Interplanetary Dust Particles Using Fluorescent Molecular Probes," MetSoc 2002). Because most fluorphors are conjugated and/or aromatic species they are also ideally suited to subsequent analysis by mL^2MS (see below).

Microprobe Two−Step Laser Desorption / Laser Ionization Mass Spectrometer (mL^2MS) −− We are at present testing our new instrument at NASA Johnson Space Center (JSC), and anticipate full operational status by the end of September 2003. The mL^2MS is a powerful technique for spatially resolved analysis of sub−attomole concentrations of complex aromatic molecules. By using fluorescent molecular probes to selectively tag particular organic molecules, species ordinarily not amenable to mL^2MS analysis (i.e. non−aromatic species such as amino acids) become readily detectable. Moreover, since it is the fluorphor of the molecular probe that undergoes multiphoton resonant ionization, the photoionization cross sections for tagged molecules are approximately constant, allowing for direct quantitation of the results from mL^2MS analysis.

Another part of this project is the development and testing of new combinations of fluorescent probes as applied to live or nonfossilized cells and biofilms. When properly used in the appropriate combinations, such probes can provide the following information on single cells, cell colonies, and complex biofilms: (1) physiological status, (2) specific metabolic activities, (3) gene expression, and (4) total cell densities. We have just begun these studies in our new laboratory at JSC to pursue these techniques. We have been able to test this technique and observe microbial activity within desert varnish layers and organic components in Murchison meteorite. The current work is to try this technique on Martian meteorites.

Antibody development techniques and mission applications −− Working with NAI at Carnegie Institute, Mars simulated microgravity experiments testing the ELISA and LAL techniques using hopane antibodies were performed on KC−135 flights. Results show microgravity is not an issue in prohibiting antibody reactions using ELISA and LAL. This has applications to spacecraft instrument development using antibody technology for organic and biosignatures.

Highlights

- Amine functional groups were identified and preserved throughout desert varnish layers and within the Murchison meteorite.
- Mars simulated microgravity experiments using KC−135 demonstrates ELISA and LAL techniques are viable applications for spacecraft instrument development.
- Fluorescent probes are a unique technique to provide information

about organic functional groups in and on astromaterials and provide another technique to life detection that may be adapted to spaceflight instruments as opposed to standard culturing techniques.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement****
2	2009 Mars SMART Lander	Organic detection instrument using antibody technology.
3	Mars Sample Return	Using fluorescent molecular probes and Microprobe Two−Step Laser Desorption / Laser

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Microgravity ELISA and LAL techniques have a direct application to ISS and any mission that requires bacterial detection methods. The LAL technique has already been used to identify microbial contamination on spacecraft parts as well as in the Lunar Lab and Valut at NASA Johnson Space Center.

Field Expeditions

Field Trip Name: Microgravity Experiments	
Start Date: May 2002	***End Date:*** May 2003
Continent: North America	***Country:*** USA

State/Province: TX FL	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Microgravity experiments using ELISA and LAL techniques.	
Members Involved: Jake Maule	

Cross Team Collaborations

Team collaboration between NAI institutions at JSC, Carnegie and the Marine Biology Lab (MBL) have been crucial in success of the microgravity experiments and the development of the LAL for spacelight applications and hopane antibody development.

Project Report: Organic Biosignatures

Lead Team:	***Johnson Space Center***
Project Title:	***Organic Biosignatures***
Project Investigator:	***Everett Gibson***

Project Progress

We have divided our MASSE Development Project and our organic analysis of Martian meteorites projects and combined the sciences into 2 categories: Organic Biosignatures and New Technique Development and Applications.

The acronym for MASSE comes from Microarray Assay for Solar System Exploration. The NASA Fundamental Biology Program has supported early development, but the project has transitioned over to an Astrobiology Institute project. Other acronyms used by us for the same general concept include MIDI (Mars Immunoassay Detection Instrument), PASO, Protein Array Sensor for Organics, and one or two others. We work extensively with Carnegie and Montana State to develop reliable and robust biosignatures. The goal for MASSE research is to develop a flight worthy instrument. Much of the instrumentation aspects will be the focus of the New Techniques project report. We have now proven the instrument concept and have been busy working on the background science to test the MASSE instrument prototypes.

Antibody selection is critical to the success of MASSE instrument. Jake Maule from Carnegie conducts the study of the antibody to hopane at NASA JSC. Hopane is an organic molecule only found in bacterial walls and is extremely stable over geologic time. Hopane antibody development and testing has progressed to rock samples and low gravity experiments. Hopane antibodies reacted with 3−hydroxyhopane, hopane and sediments from the Enspel formation, Germany − known to contain high levels of hopane. (Jan Toporski, personal communication). Little cross−reactivity was observed between hopane antibodies and BAP−13 (BAP−13 is a commercially available anti−polycyclic aromatic hydrocarbon (PAH) antibody).

We will use many other different techniques to analyze samples and use a variety of common materials the astrobiology community uses in biosignature research. The types of test samples are interplanetary dust particles (IDPs), lunar samples, meteorites such as Murchison and Tagish Lake and Martian meteorites, and terrestrial samples such as rock varnish and Archean samples from the Pilbara in Western Australia. The goal of this wide range in samples is to better understand terrestrial organics versus indigenous organic material

inherent in every rock and provide a more clear understanding of what constitutes an organic biosignature.

Work by Dr. Flynn, Dr. Clemett and Dr. Keller have used infrared spectroscopy as a well−established technique for the identification of organic functional groups. We examine ALH84001 samples (as well as other meteorites and IDPs) using much more sensitive Fourier Transform InfraRed (FTIR) instruments, consisting of conventional Spectra−Tech IRms and Nicollet Continuum FTIR microscopes coupled to a synchrotron−generated infrared beam that achieves ~1,000 times the intensity of a conventional global infrared source. We have also employed the STXM to search for organic matter in an ultramicrotome section of an ALH84001 carbonate globule consisting of three different types of carbonate: an inner core of Fe−rich carbonate and an outer rim of Mg−rich carbonate separated by a band of porous carbonate. We also performed C−XANES spectroscopy on each of the three regions, and found two large pre−edge absorptions, one at ~285 eV, characteristic of the C−ring functional group, and a second at ~288.5 eV, characteristic of carbonyl (C=O). The presence of carbonyl demonstrates that this carbon is organic, while the C−ring is consistent with the detection of PAHs associated with the carbonate globules. We found that carbon was approximately uniformly distributed throughout the carbonate, although the C−ring and C=O to total carbon (which is mainly in carbonate) is highest in the rim carbonate (Flynn et al., 1988; Flynn et al., 1989).

Other organic analysis work from Dr. Flynn includes the preservation of organic matter in fossils. The presence of organic carbon in the likely position of cell walls in a population of spheres having a small range of radii might well serve as a biosignature. Although the traditional view is that organic carbon is easily destroyed in the fossilization process, we have recently demonstrated that carbon is still present in detectable concentrations in the walls of certain Eocene and early−Devonian fossils that they examined using the STXM, and that C−XANES spectra of that carbon demonstrate indicate that it is organic. The C−XANES spectra of organic matter in the cell walls of terrestrial bacteria are quite distinct from the spectrum of the abiotic organic matter in interplanetary dust particles and meteorites. We expect that bacterial protein will degrade with time. The focus of this effort is to determine how long after the onset of fossilization the C−XANES spectrum remains distinct from abiotic organic matter. Initially we will examine samples of recent desert varnish, Bahamian stromatolite, and the Warawoona formation (~3.5 Ga old) to determine if any carbon remains. If so, we will measure its C−XANES spectrum, and determine how long it takes for the signature of proteins to disappear.

Highlights

- We have used antibodies to detect category 1 and other biomarkers in rock samples. Extraction takes a few minutes and analysis a few hours.

- We have presented use of new antibodies to detect hopanes and have shown proof of operation during Martian gravity.

- The analysis of the carbon in AHL84001 carbonate globules is organic carbon. The C−ring analyzed is consistent with the detection of PAHs associated with the carbonate globules. We found that carbon was approximately uniformly distributed throughout the carbonate, although the C−ring and C=O to total carbon (which is mainly in carbonate) is highest in the rim carbonate.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	SMART Lander	Background research and analysis techniques.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This research is vital to testing organic material on other worlds, whether we go there or bring samples back or analyze the samples we already have (i.e. Martian meteorites).

Cross Team Collaborations

Andrew Steele, the PI for the MASSE project, is at Carnegie Institute. We intend to continue working closely with him, Jake Maule and Jan Toporski and others who may contribute to this project. The current plan is for Carnegie to rigorously test the hopane antibody for false positives. The objective would be to develop and refine techniques and apply them to terrestrial rocks, minerals, and fossils as well as to astromaterials. We will continue to work with our Montana State collaborators in robust biosignature identification. We have built and installed a double laser system at JSC, but will continue to work with our

collaborators at Stanford University. We also welcome other NAI teams to participate in both the instrument development and the actual analysis of terrestrial rocks, minerals, biology features, and fossil. The more labs and the more eyes, the more we can discover.

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Project Report: Terrestrial Analogs and Martian Meteorites

Lead Team:	***Johnson Space Center***
Project Title:	***Terrestrial Analogs and Martian Meteorites***
Project Investigator:	***David McKay***

Project Progress

Terrestrial analogs provide testing environments to better understand processes of life that may occur on other worlds, such as Mars. The Johnson Space Center (JSC) is dedicated to studying the mineralogy associated with microorganisms in Mars analog environments. One current mineralization study under Dr. Henry Chafetz is Mn− and Fe−rich hot spring deposits, which provided strong evidence that these were bacterially induced precipitates (Chafetz et al., 1998). Our desire is to now conduct a study of an active Mn− and Fe−precipitating system in order to acquire a better understanding of the conditions under which these types of deposits originate, that is, the physical, chemical, and biotic attributes of the system, and to establish criteria by which biotically induced Mn− and Fe−rich deposits can be recognized in the rock record. More research to note is by Dr. Kieft on microbial processes, which are: (1) characterization of dwarf microorganisms in an extreme environment, specifically desert surface soil; and (2) culture−dependent and culture−independent characterization of microorganisms in deep, hot subsurface environments, accessed via ultra deep gold mines in South Africa. Sampling in the gold mines has been primarily of flowing fracture waters. The water samples were filter to concentrate cells from which deoxyribonucleic acid (DNA) can then be extracted for characterization by 16S ribosomal DNA (rDNA)−based approaches. Our efforts have thus far yielded a multitude of novel sequences and cultures. Many of the cultures are thermophiles growing at 55−60°C. These include novel strains related to the bacterial genera *Coprothermobacter, Geobacillus*, *Clostridium, Anaerobaculum*, and also a previously uncultivated spirochete. Other mineralogical studies focus on hypersaline environments that would preserve biotic material through fossilization. Sites of this study include hypersaline tolerant biota from Storr's Lake, San Salvador Island (Bahamas), Mono Lake (California), and the Dead Sea (Israel); they represent marine and nonmarine sites for comparative studies of potential analogs for interpreting some Mars meteorites and Mars sample return.

Defining locations where conditions may have been favorable for life is a key objective for the exploration of Mars. Of prime importance are sites where

conditions may have been favorable for the preservation of evidence of pre−biotic or biotic processes. Areas displaying significant concentrations of the mineral hematite ($-Fe_2O_3$) have been identified from orbit by thermal emission spectrometry. Therefore we are investigating morphology and mineralogy associated with terrestrial life found in rock varnish, banded iron formations and ferricrete. We have also begun collaboration support with the U.S. Geological Service (USGS) and the University of Arizona to investigate microbial ecology and preservation mechanisms in the Atacama Desert. The Atacama Desert in Northern Chile is the coldest, driest and highest desert on Earth. The high altitude and dry conditions the Atacama make it the best terrestrial analog for Mars studies. The primary force controlling mineralization in these systems are the microbes because of their ability to attract both actively and passively metallic ions on their surfaces, and to alter the chemistry of the immediate environment through secretion of biofilms.

The best Mars analog is an actual piece of Mars. JSC continues to study Martian meteorites, looking at terrestrial contaminants as well as indigenous organics and mineral biosignatures. The range of these studies is reported in the Organics Biosignatures and Mineral Biosignatures project reports. Other mineralogical studies of Martian Meteorites include carbonate and weathering products preserved in the Martian Meteorites. These results yield that ALH84001, Nakhla and Shergotty all contain indigenous evaporates from subsurface water circulating through fractures in the rock. Martian meteorite EETA79001 has also preserved remnants of the Martian regolith. The regolith contains part of the weathering record of Mars. Dr. Rao continues his studies to better understand the late weathering nature of this shergottite and what it implies to the weathering history of Mars.

Highlights

- We have discovered novel strains related to the bacterial genera Coprothermobacter, Geobacillus, Clostridium, Anaerobaculum, and also a previously uncultivated spirochete in ultradeep gold mines in South Africa.

- Microbial communities in hypersaline environments suggest that mineralization is controlled through biofilm production, and extreme desiccation of those films contributes to evaporation of mineral deposits on a micrometer scale.

- Atacama Desert bacteria isolates suggest variation of species through elevation changes.

- Mn carbonates with complex textures were found in Nakhla.

- Rock varnish preserves C disseminated throughout the varnish microlayers, but is generally a poor morphological preserve for bacteria in older varnish samples. Hematite in the banded iron formation has a better preservation of microorganisms than seen in older ferricrete or hematite in rock varnish.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

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Fellowships: Johnson Space Center

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: David Warmflash
Project Title: Immunoassay life detection test
Advisor: David McKay, Advisor
NAI Lead Team: Johnson Space Center
Fellowship Began In: January 30, 2001

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EPO: Johnson Space Center

These are the Education and Public Outreach activities for the Johnson Space Center.

Fingerprints of Life? Web site and CD−ROM

Fingerprints of Life?, a JSC education Website, is the product of the partnership of scientists from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials and educators. The classroom activities reflect the biomarker research that is being conducted in our laboratories. The Website includes classroom activities, inquiry−style standards−based lessons, annotated PowerPoint presentations with many images, links to national mathematics and science standards, and a comprehensive resource guide. Over the 2002−2003 school year, the classroom activities have been tested and are currently in review. The developed materials are available on the NASA Johnson Space Center Website at http://ares.jsc.nasa.gov/Education/Websites/AstrobiologyEducation/index.html.

Public Presentations/Media Interviews/Lab Tours

The scientists of the NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials actively participate in public presentations, media interviews, and laboratory tours. Over the past year the science team of David McKay, Everett Gibson, Simon Clemet, Kathie Thomas−Keprta, Carlton Allen and others have conducted over 40 presentations or interviews for a variety of media personnel, including radio, television, newspapers, and magazines. Over the past year the science team conducted public presentations for the University of Texas, Stanford University Club, Australian Mars Society, Houston Community College, and other groups. The team conducted over 20 tours of the NASA Johnson Space Center research laboratories for groups, including Texas Aerospace Scholars, International Aerospace Scholars, NASA Education Workshops, American University at Monterey, University of Houston, Texas Southern University, Stanford University, Urban and Rural Community Enrichment Program, Undergraduate Minority Students, and Minority Outreach Student Ambassadors.

Astromateials Curriculum Development Workshop

The education team from NASA Johnson Space Center Astromaterials Research and Exploration Science Office and the Institute for the Study of Biomarkers in Astromaterials conducted a curriculum workshop June 9−21, 2003. The educators and scientists tested and enhanced some of the team's

hands−on activities about Mars meteorite research.

Educator Workshops

The education team from NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials presented educator workshops entitled "It's Out There − Extreme Life!" The workshops include hands−on activities and PowerPoint presentations from the Fingerprints of Life! CD−ROM/Website. Participants received the CD−ROM as well as the NASA Astrobiology Educator Guide, Destination: Mars Activity Packet, and other materials.

− Extreme Life workshop, National Science Teachers Association Regional Convention, Albuquerque, NM (12−02)
− Extreme Life workshop, Space Center Houston, Houston, TX (6−03)
− Astrobiology Short Course, National Science Teachers Association National Conference, Philadelphia, PA (6−27−03)

Minority and Underrepresented Education and Public Outreach

The education team of NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials conducts a number of workshops and career events focused on minority or underrepresented students and the adults who lead or teach them. We share hands−on Astrobiology activities, reading materials, and career guidance about becoming an astrobiologist. Some of the events are part of larger space science related workshops.

The events and workshops include the following:

*Houston Community College Career Day, NASA Astrobiology Keynote speaker and student workshop conducted JSC Astrobiology scientist.

*Exploring the Solar System workshops for Girl Scouts in Michigan, Louisiana, Colorado. (total of 60 trainers) conducted by JSC Astrobiology scientists and education team.

*Space Science Student Ambassadors Mars and Astrobiology presentations (June 2002−January 2003)−− sponsored by Office of Space Science Minority University Initiative − University of Houston Downtown.

*Science, It's a Girl Thing 2003, a hands−on, three−day course for 10 middle school girls held at Texas Tech University, Lubbock, TX (June 23 −26, 2003).

*Bright Futures Fair: Demonstrations, hands−on activities, and career discussions with hundreds of urban Houston students and their sponsors.

Formal and Informal Education Workshops with an Astrobiology Component

The education team of NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials conducts workshops for formal and informal educators where Astrobiology activities are a component of the longer space science−focused workshop. We share activities and resources from the NAI Educator Guide and from Johnson Space Center's Fingerprints of Life? Educator Website. All presentations for formal educators address National Science Education Standards. Workshops are listed below:

− Exploring the Solar System workshops for Girl Scout trainers and leaders − Michigan (10−02), Louisiana (10−02), California (11−02)
− Mars Curriculum Development Workshop, Johnson Space Center, Houston TX, (7−02)
− Exploring the Solar System and the Search for Life − 2 workshops, Houston Museum of Natural Science, Houston, TX (9−02)
− Exploring the Solar System; CAST, Texas science teacher conference, El Paso, Texas (10−02)
− Astromaterials workshops CAST, El Paso, Texas (10−02)
− Space Rocks Tell Their Secrets Workshop at NSTA, Philadelphia, PA (March−03)
− Space Science Student Ambassadors training sessions (2−03 −− 5−03) Houston, TX. This program is a part of a NASA Minority University Initiative project to share space science with the public.
− Exploring Solar System Workshop; University of Houston Downtown, Houston, Texas (June 3−4, 2003. This program is a part of a NASA Minority University Initiative project to share space science with the public.
− Exploring the Solar System and Astrobiology, Our Lady of the Lake University Short Course, San Antonio, TX (June 4−6. 2003)
− The University of Arizona Alumni Association Advanced Teen Astronomy Camp, Tucson, AZ (June 2003)
− Bioastronautics and Astrobiology workshop; Space Center Houston, Houston TX (6−03)

Astrobiology Science Conference Education Posters

Four education team members from the NASA Johnson Space Center's Institute for the Study of Biomarkers in Astromaterials attended the NAI Science Conference 2003, Feb. 9−12, 2002, at Arizona State University. Marilyn Lindstrom, Jaclyn Allen, Kay Tobola, and Penny Morris attended the conference and presented posters.

Bioastronomy/Fulbright Symposium

Kay Tobola and Karen Stocco attended the Bioastronomy/Fulbright Symposium conference on Hamilton Island, Australia. They participated in conference and education seminars and presented workshop sessions. They received scholarships to assist with the travel expenses.

Publications: Johnson Space Center

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Allen, C.C., Wainwright, N.R., Grasby, S.E. Harvey, R.P. (2003). Life in the ice [Abstract]. *Sixth International Conference on Mars, 20−25 July 2003, Pasadena, CA*. Abstract #3138.

Allen, C.C., Westall, F., Longazo, T.G., Schelble, R.T., Probst, L.W. Flood, B.E. (2003). Mars hematite: Potential for preservation of microfossils [Abstract]. *34th Lunar and Planetary Science Conference, Houston, TX*. Abstract #1005.

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NASA ASTROBIOLOGY INSTITUTE
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Members: Johnson Space Center

Team Members sorted by current team.

Name:	Carlton Allen
Email:	Carlton.c.allen@nasa.gov
Institution:	Johnson Space Center
Name:	Ricep Avec
Institution:	Montana State University
Name:	Jake Bailey
Institution:	University of Arizona
Name:	Dennis Bazylinski
Email:	dbazylin@iastate.edu
Institution:	Iowa State University
Name:	Martin Brazier
Institution:	Oxford
Name:	Henry Chafetz
Email:	hchafetz@uh.edu
Institution:	University of Houston
Name:	Neva Ciftcioglu
Institution:	Universities Space Research Association (USRA)
Name:	Simon Clemett
Email:	simon.j.clemett@jsc.nasa.gov
Institution:	Johnson Space Center
Name:	Beverly Flood
Email:	Bflood@ems.jsc.nasa.gov

Institution:	University of Texas, Galveston
Name:	George Flynn
Email:	george.flynn@plattsburgh.edu
Institution:	SUNY, Plattsburgh
Name:	George Fox
Email:	Fox@uh.edu
Institution:	University of Houston
Name:	Everett Gibson
Email:	everett.k.gibson1@nasa.gov
Institution:	Johnson Space Center
Name:	Sean Guidry
Institution:	University of Houston
Name:	Larry Hersman
Email:	hersman@lanl.gov
Institution:	Los Alamos National Laboratory
Name:	Lindsay Keller
Email:	lindsay.p.keller1@nasa.gov
Institution:	Johnson Space Center
Name:	Thomas Kieft
Email:	tkieft@nmt.edu
Institution:	New Mexico Institute of Mining and Technology
Name:	John Lindsay
Email:	John.f.lindsay1@jsc.nasa.gov
Institution:	Johnson Space Center
Name:	Teresa Longazo
Email:	teresa.g.longazo1@jsc.nasa.gov
Institution:	Hernandez Engineering

Name:	Kennda Lynch
Email:	Kennda.l.lynch1@jsc.nasa.gov
Institution:	Lockheed Martin
Name:	Jake Maule
Email:	Jake.g.maule1@jsc.nasa.gov
Institution:	Carnegie Institution of Washington
Name:	David McKay
Email:	David.s.mckay@nasa.gov
Institution:	Johnson Space Center
Name:	Scott Messenger
Email:	dbunny@wuphys.wustl.edu
Institution:	Johnson Space Center
Name:	Penny Morris−Smith
Email:	penny.a.morris−smith1@jsc.nasa.gov
Institution:	University of Houston
Name:	Dorothy Oehler
Email:	Dorothy.a.oehler@jsc.nasa.gov
Institution:	Lockheed Martin
Name:	Charlie Ott
Email:	charlie.m.ott1@jsc.nasa.gov
Institution:	Johnson Space Center
Name:	James Papike
Email:	jpapike@unm.edu
Institution:	University of New Mexico
Name:	M. Rao
Institution:	LZ Technology
Name:	Lisa Robbins

Email:	lrobbins@usgs.gov
Institution:	USGS St. Petersburg
Name:	Chris Romanek
Email:	romanek@srel.edu
Institution:	University of Georgia/SREL
Name:	Rick Socki
Email:	Richard.a.socki@jsc.nasa.gov
Institution:	Lockheed Martin
Name:	M. Spilde
Institution:	University of New Mexico
Name:	Andrew Steele
Email:	a.steele@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Kathie Thomas−Keprta
Email:	kthomas@ems.jsc.nasa.gov
Institution:	Lockheed Martin
Name:	Jan Toporski
Email:	j.toporski@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	H. Vali
Institution:	McGill University
Name:	Norman Wainwright
Email:	nwainwri@mbl.edu
Institution:	Marine Biological Laboratory
Name:	David Warmflash
Email:	david.m.warmflash1@jsc.nasa.gov
Institution:	Johnson Space Center

Name:	Susan Wentworth
Email:	susan.j.wentworth1@jsc.nasa.gov
Institution:	Lockheed Martin

Marine Biological Laboratory
Executive Summary
Principal Investigator: Mitchell Sogin

Environmental Genomes and the Evolution of Complex Systems in Simple Organisms

Biology imposes an overwhelming force on planetary change through biogeochemical processes that originated in ~3.5 billion year old microbial communities. Through metabolic activities, microorganisms orchestrate key processes in carbon fixation, geochemical cycling, biodegradation and atmospheric change. For at least 80 percent of our evolutionary history, microbes were the only forms of life. By comparison, the multicellular world of plants, animals and fungi are derived forms whose continued existence is completely dependent upon a microbial world of uncharted diversity. Whether biological systems similar to those on Earth ever occurred or continue to function on other planets or large satellites is unresolved but if life occurs elsewhere in our solar system, it will be microbial in form.

The primary objectives of the Astrobiology Team at the Marine Biological Laboratory are rooted in delineating the evolutionary history of microbial life, exploring the nature of early metabolic processes, and defining the limits of the "habitable zone". We seek to understand patterns and mechanisms of genome evolution and metabolic variation that allowed diverse microorganisms to adapt to new environments, to generate novel phenotypes, and to evolve processes that cause environmental changes on a global scale. Key questions include: When and where did life originate? How did biological complexity develop from emergent properties of living organisms? Which metabolic processes were significant drivers in modifying early Earth? What are the limits of extreme environments compatible with life? Answers to these questions will have a direct impact on how to organize and target exploration in search of living organisms beyond our own biosphere.

Our general strategy capitalizes on advanced molecular biological techniques and ranges from analyses of genomes to holistic studies of individual organisms within microbial communities. The physiological and microbial diversity studies focus on the hydrothermally altered sediments of Guaymas basin in the Gulf of California, the acidic, heavy metal laden Río Tinto of southwestern Spain, and photosynthetic cyanobacteria from microbial mats.

Evolution of Proteins: a genomic approach. The study of complete genome information from even a single organism can provide important insights about

how metabolic diversity evolved from a relatively small number of catalytic centers that must have been present in early proteins. For example, fatty acid biosynthesis is an important pathway for every organism. It is a multi−step process and one of the key enzymes in the biosynthesis of lipids is fadB.

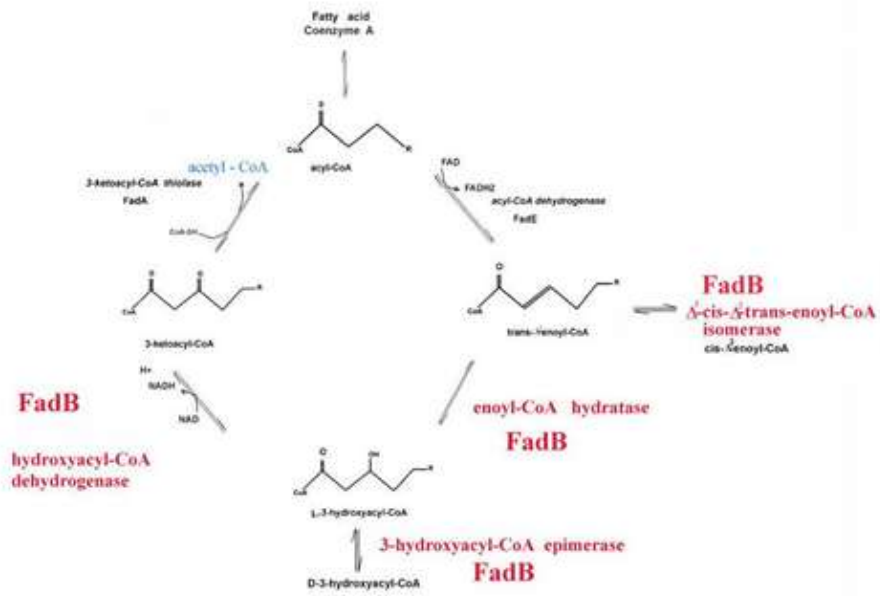

Figure 1. *The Pathway (² oxidation of Fatty acids)*

Using the N terminus as a probe for in silico studies, Dr. Riley and her colleagues mapped domains of the fadB sequence onto known structures of enzymes that catalyze reactions as diverse as epimerase,isomerase, hydratase and protease. They demonstrated that the C terminal part of the fadB protein has a dehydrogenase activity, whereas a single catalytic site is structurally related to epimerase, isomerase and hydratase.

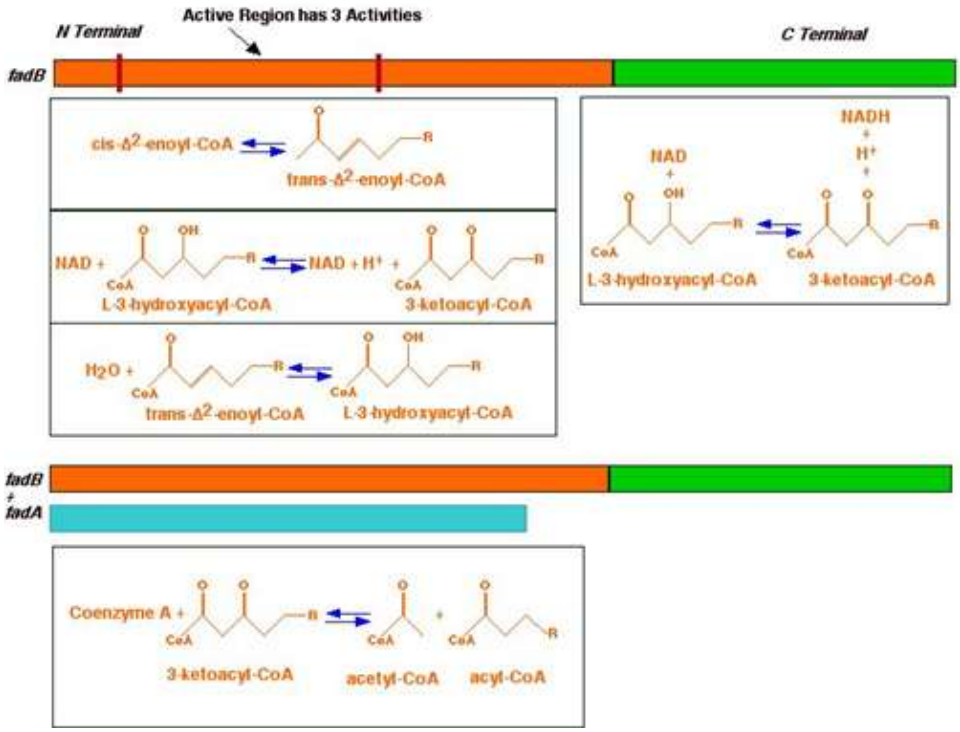

Figure 2. *The Reaction Mechanism*

The proteins of the hydratase/isomerase superfamily catalyze a very diverse range of reaction types using a structurally conserved active site fold. This reinforces the idea that a relatively small number of catalytic domains in early proteins gave rise to metabolic complexity found in contemporary cells. The basic signatures of these seminal domains could provide the basis for design of life detection strategies.

Diversity and Evolution of MicroOrganisms.

Woese's seminal work funded through NASA's original Exobiology program unveiled a Universal Tree of Life that included three primary lines of descent; the Archaea, Bacteria and Eukarya. The MBL Astrobiology team continues to use and develop new molecular methodologies that can more efficiently describe microbial evolution, microbial diversity and how these organisms function in extreme environments. This information will expand our definition of habitable conditions and may suggest new targets for developing life detection capabilities. We now seek greater resolution in studies of microbial population structures as well as information about their association with specific metabolic functions. For example, we have explored the phylogenetic and functional diversity of sulfate−reducing bacteria in the sediments of Guaymas Basin (Gulf of California). In this hydrothermal vent site, thermal alteration of deposited planktonic and terrestrial organic matter forms petroliferous material. These hydrocarbons are a significant carbon source to the vent microbial communities, which includes diverse sulfate reducing bacteria.

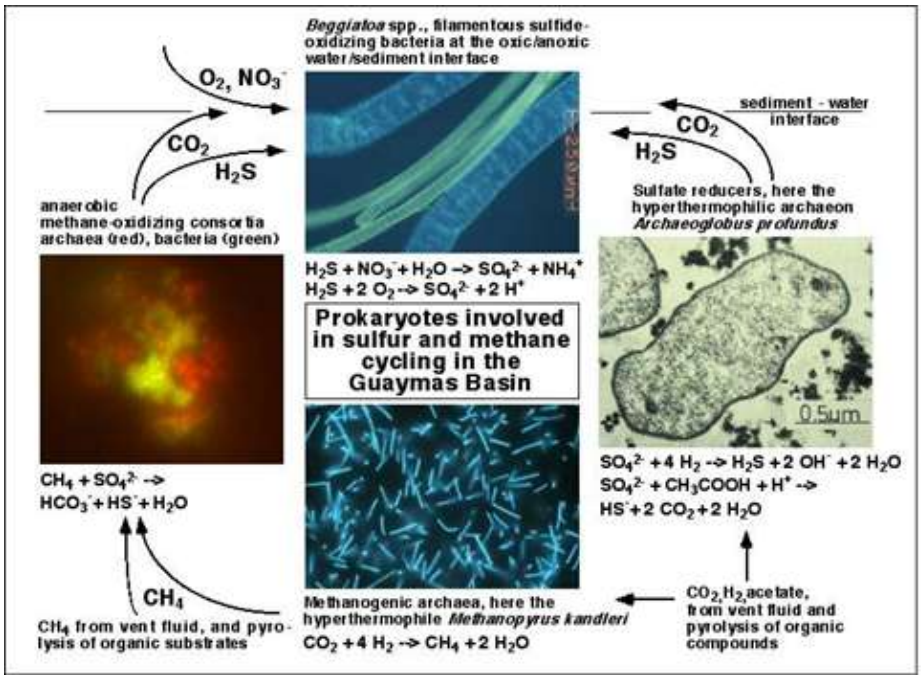

Figure 3. *Microorganisms and their reactions (sulfate reduction, methanogenesis, methane oxidation, sulfide oxidation) in the methane and sulfur cyles in the Guaymas Basin hydrothermal vents.*

Using conserved primers, we polymerase chain reaction (PCR) amplified dissimilatory sulfate reductase genes, the key gene for sulfate reduction (dsrAB), and 16S ribosomal ribonucleic acid (rRNA) genes from the upper 4 cm of Guaymas sediment. Figure 3 is a phylogenetic analysis of the nearly full length dsr sequences. In this analysis the dsrAB sequences revealed a major clade that branched with dsr sequences of the genus *Desulfobacter*, acetate oxidizers of the family *Desulfobacteriaceae* within the delta Proteobacteria, and a clade of novel, deeply branching dsr sequences related to environmental dsr sequences from marine sediments in Aarhus Bay and Kysing Fjord (Denmark). Two other clones showed similarity to dsr genes of gram−positive thermophilic sulfate reducers (genus *Desulfotomaculum*) and the toluene degrader *Desulfobacula toluolica*, while one was related to *Desulforhabdus amnigena* and *Thermodesulforhabdus norvegica*.

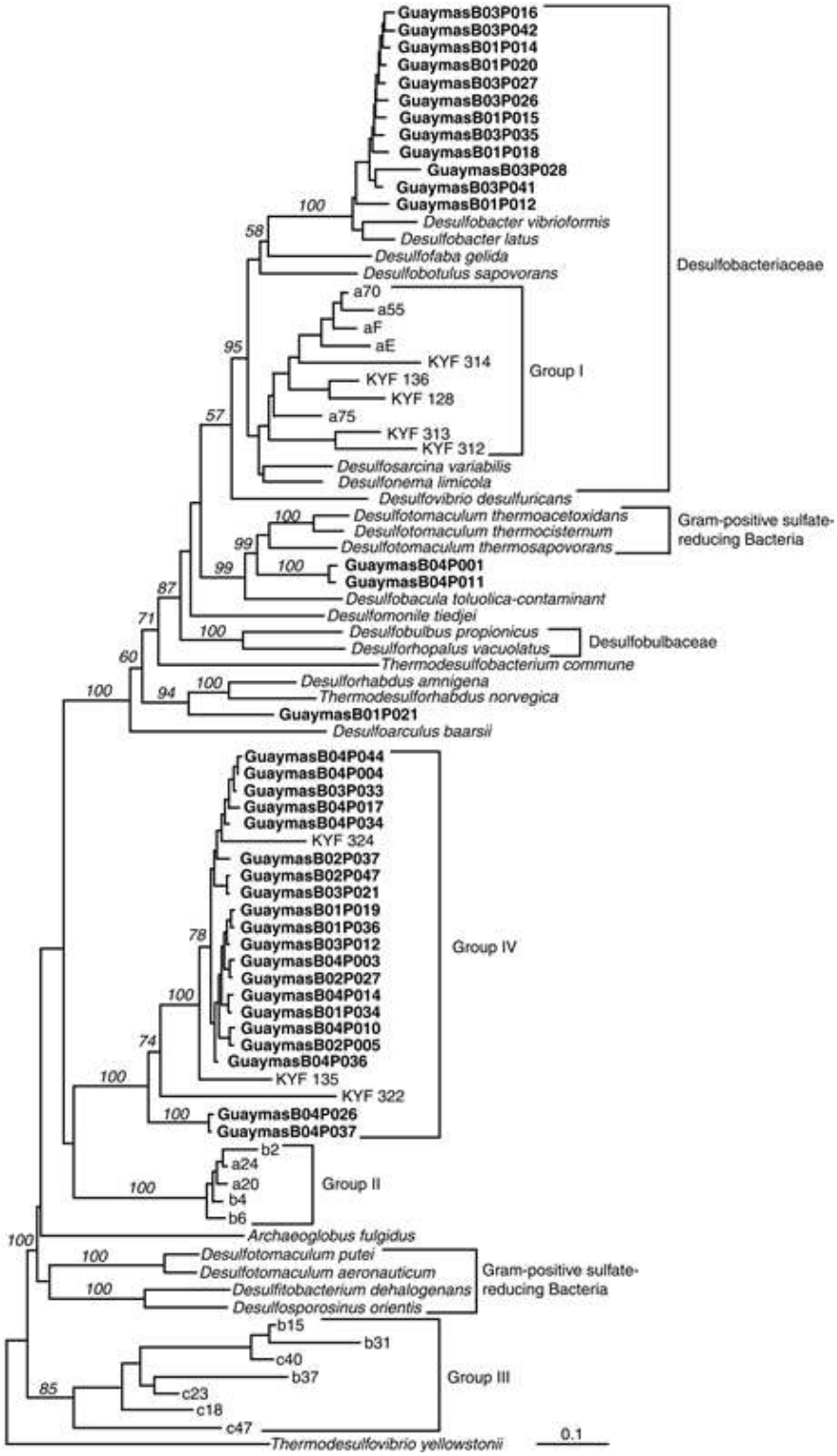

Figure 4. *Phylogenetic tree based on the translated amino acid sequences of PCR−amplified dsr AB genes from sulfate reducing prokaryotes.*

The two−pronged approach of using 16S rRNA and dsr clone library sequencing has resulted in a more detailed picture of the sulfate−reducing bacterial community at Guaymasthan each of these approaches alone. At

Guaymas, the 16S rRNA and the dsrAB datasets indicate the significance of members of the Desulfobacteriaceae, most likely the genus Desulfobacterium, in the Guaymas sediment. The dsrAB dataset also demonstrated the presence of uncultured and unknown major clades of sulfate reducing prokaryotes in the Guaymas sediments that could not be identified by 16S rRNA sequencing.

We also seek to establish linkages between patterns of gene expression that underlie metabolic activity and the formation of biogeochemical gradients. To meet this objective, we must obtain information about global gene expression patterns and detailed information about microbial population structures. We have constructed a custom microarray to examine how the cyanobacterium *Microcoleus chthonoplastes* responds to changes in environmental conditions. The array contains 1090 unique sequences and it has provided information about changing gene expression patterns in response to diel cycling and salinity changes of Microcoleus cultures. High and low salt shocks induced quite distinct expression signatures; genes involved in metabolism, signal transduction, transportation of compounds across membranes, and other cellular processes appear to change their expression levels in response to this environmental stimulus. With knowledge about coordinate gene expression patterns associated with changing metabolic patterns, we will be able to faithfully model fluxes in microbial ecosystems and identify biomarkers for detecting and monitoring biological activity.

Figure 5. *Coordinate gene expression during high and low shock treatments of 1 to 3 hours.*

In order to interpret the gene expression data it is necessary to identify the diversity and relative numbers of different kinds of taxa in a microbial setting. Analyses of PCR products from ribosomal RNA (rRNA) coding regions provides a window on the microbial world that has revealed new levels of largely unexplored microbial diversity not represented in laboratory cultures. Unfortunately this low throughput methodology is expensive (typically $1−2/sequenced template) and sometimes inefficient when a limited number of organisms dominate a microbial population. Deoxyribonucleic acid (DNA) fingerprinting techniques such as denaturing gradient gel electrophoresis (DGGE) and terminal restriction fragment length polymorphism (T−RFLP) offer higher throughput but little or no taxonomic information, and many fingerprinting studies ultimately rely on DNA sequencing to characterize phylotypes.

We have developed a new, high−throughput method Serial Analysis of Gene

Tags (SAGT) that provides estimates of relative frequencies and sufficient phylogenetic information to identify the phylotype of most taxa in an environmental sample. SAGT ligates together the PCR products from orthologous hypervariable regions in rRNA genes to form large concatemers. A single DNA sequencing reaction of a cloned concatemer can include as many as 20−30 orthologous hypervariable regions represented in a population of nucleic acid molecules. In this way, samples loaded onto a 96−channel capillary sequencing machine can provide information about thousands of microorganisms in an analyzed sample. Comparison against a comprehensive rRNA gene database identifies the taxonomic assignment of individual amplicons in the concatemers. SAGT analyses of bacterial community composition in hydrothermal marine sediments from Guaymas Basin (Gulf of California) are comparable to results of cloning and sequencing of single, full−length PCR products from ribosomal RNA genes of the same microbial community. Both methods identify the same major bacterial groups. The application of this technology will allow us to deeply sample the diversity and relative abundance of microbial populations in any environmental setting.

Education and Outreach.

Our EPO program includes a rich mixture of workshops and courses in disciplines that are relevant to NASA's Astrobiology initiative. Our workshop series includes "Living in the Microbial World", a one−week intensive summer workshop for middle and high school students, focusing on microbial diversity and evolution. "Life and Living in Space", a four−day workshop for high school and community college teachers, convenes in the fall and is offered in conjunction with the Center for Advanced Studies of Space Life Sciences (CASSLS) at the MBL. This workshop combines NASA Life Science topics and areas of Astrobiology content including planetary protection and life detection. We also offered two advanced workshops that target investigators who work in astrobiology related disciplines. The first is the Workshop on Molecular Evolution at the Marine Biological Laboratory directed by Michael Cummings. The Workshop includes a series of lectures, demonstrations and computer labs that span the field of molecular evolution. A distinguishing feature of the course is a state−of−the−art computer laboratory furnished with Linux and Unix servers and workstations for comparative analysis of molecular data. Topics covered in the course include: databases and sequence matching, phylogenetic analysis including Bayesian analysis and maximum likelihood theory, molecular evolution at organismal and higher levels, molecular evolution and development, gene duplication and divergence, gene family organization, evolution of large multigene families, molecular evolution in bioinformatics and comparative genomics.

Our new course Advances in Genome Technology and Bioinformatics, directed by Mitchell L. Sogin and Claire Fraser (President of The Institute for Genomic Research (TIGR)), is a comprehensive, four−week course in genome science that integrates bioinformatics with the latest laboratory techniques for genome sequencing, genome analysis, and high throughput gene expression (DNA microarrays). With a distinguished faculty from major universities and bioinformatics centers, TIGR and the MBL provide instruction that integrates lectures with laboratory exercises both at the computer and in a high

technology, high throughput facility.

Figure 6. *The computational biology laboratory for Advances in Genome Sciences and Bioinformatics.*

The major laboratory modules include 1) Genome Sequencing (vector development, library construction, high throughput sequencing technologies, principles of automation using advanced robotic liquid handlers, genome assembly algorithms and closure strategies); 2) Bioinformatics (Gene prediction algorithms, annotation, database construction and searching, phylogenetics and molecular evolution); and 3) Functional Genomics (DNA microarrays, data analysis). Symposia focusing on Environmental and Evolutionary Genomics, Eukaryotic Microbial Genome Projects, Organelle Evolution and other topics are also part of the program.

In addition to our MBL Astrobiology web site (which is under total revision) we have expanded micro*scope to include a broader range of microbial habitats, more images, more text, enhanced functionality in the form of outlinks and input fields for user contributions. The micro*scope web site (http://www.mbl.edu/microscope) is an image−rich resource providing descriptions and pictures of all categories of microorganisms, currently containing thousands of downloadable high−resolution images. The images and accompanying information can be accessed by a number of methods, including by habitat, cell shape, alphabetically by genus name and by hierarchical taxonomic classification. We are developing micro*scope into a central educational repository for students and teachers interested in astrobiology and microbial diversity. The micro*scope website fills the gap in available resources and provides students, teachers and researchers with easy access to high quality digital micrographs and information about diverse microbes, both prokaryotic and eukaryotic. Micro*scope is designed to bring

together information distributed at other authoritative sites. It uses software to track the taxonomic location of the user and to initiate searches into remotely located databases or other sites generally available on the web, based on the genus being examined. The list of databases and remote sites to be searched can be customized to return results from only certain selected databases. Our goal is to maintain micro*scope as a resource to assist those interested in gathering information about microbial taxa and in understanding better the diversity, complexity and evolution of the microbial world.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Diversity and physiology of prokaryotes in selected thermophilic and mesophilic environments that might resemble early Earth's biosphere

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Diversity and physiology of prokaryotes in selected thermophilic and mesophilic environments that might resemble early Earth's biosphere***
Project Investigators:	***Andreas Teske , Virginia Edgcomb , Mitchell Sogin***

Project Progress

We concluded our analysis of dissimilatory sulfite reductase genes, a key gene of sulfate reduction, in the Guaymas Basin hydrothermal vents. We have investigated the Guaymas Basin hydrothermal vents as a model system to study anaerobic microbial communities (methane oxidizers, and sulfate reducers) that catalyze a sulfate−and methane−driven anaerobic carbon cycle that is compatible with stable carbon and sulfur isotope evidence for early Earth ecosystems (Teske et al. 2003). A new phylotype of dissimilatory sulfite reductase from the Guaymas vents formed one of the deepest branches in the DSRtree, implying the existence of ancestral sulfate−reducing prokaryotes in the Guaymas Basin. These sulfate reducers have not been cultured, and would have remained undetected by 16S ribosomal ribonucleic acid (rRNA) sequencing (Dhillon et al. 2003). A comprehensive phylogenetic analysis of the dissimilatory sulfite reductase gene family (with assimilatory as well as dissimilatory enzymes, and the new Guaymas phylotypes) and a study of reaction center conservation of these enzymes is in progress, to gain insight into the evolution of sulfate− and sulfite assimilation and respiration (Dhillon, Riley et al., in preparation).

In collaboration with Kai−Uwe Hinrichs and Helen Sturt (WHOI), a lipid biomarker catalogue for sulfate−reducing bacteria and archaea is in development. We intend to complement ribosomal and functional genes with a similarly detailed database of biomarker molecules, for detection and identification of the full phylogenetic range of sulfate−reducing microorganisms in different environments (Sturt et al. 2003).

We also completed an analysis of 16S rDNA genes in the Forearc Basin of the Nankai Trough. The prokaryotic community of the deep subsurface sediments in the Forearc Basin of the Nankai Trough southeast of Japan (ODP site 1176A) was analyzed by 16S rDNA sequencing. Sediment samples from 1.15, 51.05, 98.50 and 193.96 meters below sea floor (mbsf) harbored highly

diverse bacterial communities. The most frequently retrieved clones included members of the Green−non sulfur bacteria whose closest relatives come from deep subsurface environments, a new epsilon−Proteobacterial phylotype, and representatives of a cluster of closely related bacterial sequences from hydrocarbon− and methane−rich sediments around the world. Archaeal clones were limited to members of the genus Thermococcus, and were only obtained from the two deepest samples.

Highlights

- Deeply branching dsr sequences reveal a new, phylum−level lineage of sulfate reducing prokaryotes in Guaymas Basin Hydrothermal vent sediments. Deep phylum−level divergence of sulfate−reducing prokaryotes is consistent with their early emergence and diversification during Earth's evolution.

- The Nankai subsurface sediments harbor many bacterial species that lack cultured relatives.

- Archaebacterial populations in the Nankai subsurface sediments are unlikely to be active and were probably introduced by lateral subsurface flow.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Microbial ecosystem analogs for Europa	Background research on potential microbial communities in anoxic, deep ocean ecosystems

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission

Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project informs NASA missions on life forms that are possible on planets with anaerobic subsurface or hydrothermal habitats (Europa). An anaerobic C1 carbon cycle can be sustained, as long as sulfate is available as oxidant. The deep, phylum−level phylogenetic divergences found among sulfate−reducing key genes in the methane−oxidizing sediments at Guaymas and elsewhere suggest that sulfate−reducing communities have emerged early in microbial evolution on Earth, and should be included in a future ?microbiology check list? for early microbial life on other planets. The lipid biomarker catalogue for sulfate reducers is being developed as a detection tool for biogeochemical signatures of early life.

Field Expeditions

Field Trip Name: none	
Start Date:	***End Date:***
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: The samples for this project were collected during a diving expedition to the Guaymas vents (Gulf of California, Mexico) in April and May 1998, with RV ATLANTIS and Research Submersible ALVIN of the Woods Hole Oceanographic Institution.	
Members Involved: Andreas Teske	

Cross Team Collaborations

The DSR genes were characterized in collaboration with David Stahl's research group, which is part of the Astrobiology Team at the University of Washington at Seattle.

The collaboration with the University of Rhode Island Astrobiology team (P.I. Steve D'Hondt) started with a 16S rRNA sequencing survey of deeply buried marine sediments in the Nankai trough, a subduction zone southeast of Japan. The samples were obtained by URI team member David Smith on ODP leg 190, May/June 2000, with Deep−sea drill ship JOIDES Resolution. The microbiology of deeply buried sediments is an important research target of the

NAI Astrobiology program, to explore analogs for potential deep subsurface microbiota on planets without hospitable surface environments. The sediment samples were sequenced by Konstantinos Kormas, a postdoc on the URI−NAI team from the University of Athens (Greece) in the laboratory of Andreas Teske, using the sequencing facilities of the MBL group. Bacteria and archaea showed distinct depth distributions. A novel branch of epsilon proteobacteria, and members of the thermophilic archaeal genera Thermococcus and Pyrococcus were found only in the deepest sediment samples, at 100 and 200 m below the sediment surface, indicating a source of thermophilic, heterotrophic microbial populations in deep, geothermally active sediments of the subduction zone. (Kormas et al. 2003).

The planned ODP cruise to the Equatorial Pacific and the Peru Margin has taken place in February/March 2002; initial results from this deep subsurface biosphere cruise are collected in the Initial Cruise Report, available on the web, and were presented at the 2003 NAI general Meeting (D'Hondt et al 2003).

To assess the environmental tolerance of hyperthermophilic archaea in the deep subsurface, we studied growth and survival of selected vent hyperthermophiles (Thermococcus fumicolans; Pyrococcus strain GB−D, Methanococcus jannaschii) under specific environmental stress conditions that characterize their habitat (low pH, high pressure, high sulfide concentrations, high temperature). Actively growing cells tolerated these stresses better than cells that were surviving during depletion of electron and carbon sources. Survival tolerances decreased when high pressures were combined with the stresses of high acidity, temperature, and sulfide concentrations (Lloyd et al. 2003).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Ecological genomics

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Ecological genomics***
Project Investigators:	***Mitchell Sogin , Michael Cummings , Andreas Teske***

Project Progress

In most ecosystems, consortia of microorganisms orchestrate key processes in geochemical cycling, but little is known about ecological and evolutionary responses of these communities to cyclic and transient environmental shifts. The goal of this project is to employ advanced molecular techniques that will allow us to efficiently describe microbial population structures and to build deoxyribonucleic acid (DNA) microarrays for monitoring gene expression patterns both in laboratory cultures and in naturally occurring microbial mats.

We have developed high throughput technology for analyzing complex microbial populations and have applied it to studies of microbial communities in Guaymas Basin and the Rio Tinto. Serial Analysis of Gene Tags (SAGT) ligates together the polymerase chain reaction (PCR) products from orthologous hypervariable regions in ribosomal ribonucleic acid (rRNA) genes to form large concatemers. A single DNA sequencing reaction of a cloned concatemer can include as many as 20−30 orthologous hypervariable regions represented in a population of nucleic acid molecules. In this way, samples loaded onto a 96−channel capillary sequencing machine can provide information about thousands of microorganisms in an analyzed sample. The first step in the SAGT technique involves PCR amplification of small subunit rRNA genes from genomic DNA extracted from an environmental sample using conserved primers that contain a type II restriction site and flank a hypervariable region (20−100 bp) of the rRNA gene. The primer sequences are removed from the amplicons by digestion with this type II enzyme, leaving a short base pair extension. Digested fragments are ligated to form concatemers that are then cloned and sequenced. The primer pairs can be designed to amplify any of the rapidly evolving regions in rRNA genes. Alternatively, we can design primers to amplify regions that are not rapidly evolving and hence restrict the granularity of the analysis, but at the same time identify population members that are more distantly related. We have a manuscript ready for submission that shows the comparison of the SAGT technique with more expensive full length rRNA analyses from microbial populations in sediments of Guaymas Basin. We are now applying this technique to analysis of microbial populations in the Rio Tinto and have been

able to fully describe microbial populations at several sites in this river system.

The complementary component of our ecogenomics project is the use of DNA microarrays to characterize gene expression patterns throughout the diel cycle for organisms isolated from microbial mats. We have constructed a genomic library of the mat−forming cyanobacterium Microcoleus chthonoplastes using DNA extracted from a culture of a strain collected from the Sippewissett salt marsh, in West Falmouth, Massachusetts. We have sequenced 10,241 clones with insert sizes of 650 − 1150 bp, and used this information to select the sequences to array. Selection criteria for including a gene was based on a BLASTX hit to a known cyanobacterial sequence with an e value −4 and a Pfam score >= 25. This filter ensured that clones on the array were from Microcoleus and that they contained a gene coding region. After removing redundant clones, we selected 1090 sequences to array. These sequences were PCR amplified from the vector, and the DNAs printed onto glass slides for expression profiling studies.

Preliminary experiments have used the array to examine differences in gene expression during the day and night. We took laboratory cultures of Microcoleus, placed them into a 14 hr light / 10 hr dark cycle for 3 days, and then collected cells after two hours of light exposure and after two hours of darkness. As expected, a number of genes directly involved in photosynthesis were expressed at higher levels in the day samples as compared to the night samples. A large number of other genes involved in growth, replication, and many other processes were also upregulated during the day. At night, we found "light repressed proteins" showing increased expression, as well as a number of regulatory proteins. These data have also shown us a number of unexpected putative results, such as an increase in expression of an iron transporter at night.

To help better understand and verify these results, we are currently in the process of assembling a time course of expression data across an entire diel cycle. This information should provide us with valuable information about the precise timing and daily expression patterns of many of these genes. Once we have collected these data on diel variations, we plan to take environmental samples directly from the Sippewissett marsh and see how closely our laboratory manipulations can match what is actually happening in the environment.

Highlights

- A new technology, serial analysis of gene tags (SAGT) provides a sequence based technology for characterizing tens of thousands of micro organisms in a natural population at a fraction of the cost of conventional DNA cloning and sequencing technologies

- We have exhaustively sampled microbial populations at several sites in the Rio Tinto river system.

- Using DNA microarrays we have identified specific gene expression patterns associated with different phases of diel cycles for the

cyanobacterial isolate *Microcoleus chthonoplastes*.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement****
3	Future missions that will require life detection based upon biomarkers.	Design of life detection experiments based upon biology induced changes in planetary environments.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Although this work is not directly related to a specific NASA mission, it does provide information that will be important in the search for extraterrestrial life. . We seek to understand how microbial ecosystems affected the early atmosphere and the biological processes that left traces of early life in ancient sedimentary rocks. It is clear that the discovery of life on other solar system bodies would most likely be microbial. These studies allow us to design life detection experiments and to interpret geological studies of samples returned to earth.

Cross Team Collaborations

Norman Pace, University of Colorado

Project Report: Eukaryotic origins and the evolution of cellular complexity − Eukaryotic rRNA evolution: early diverging eukaryotes

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic origins and the evolution of cellular complexity − Eukaryotic rRNA evolution: early diverging eukaryotes***
Project Investigators:	***Mitchell Sogin , Virginia Edgcomb***

Project Progress

A common feature of early diverging eukaryotic lineages is the absence of mitochondria and their ability to thrive in anoxic environments. We have characterized ribosomal RNAs (rRNAs) from several amitochondriate species, including *Carpediemonas*, which contains double membrane−bounded structures physically resembling hydrogenosomes. In some protists, hydrogenosomes appear to be derived from mitochondria, and molecular analyses of heat shock proteins argue that mitochondria were once present in all protists, including those that live in anoxic environments. Whether or not the first eukaryotes had mitochondria is a key issue that will require extensive molecular analyses of several amitochondriate protists. We already know that Entamoebae and microsporidial genomes contain several coding regions that define proteins that likely came from the ancestral symbiont of mitochondria. We have recently characterized two new amitochondriate protists isolated from anoxic environments. Analyses of ribosomal RNAs from *Monopylocystis visvesvarai* and *Sawyeria marylandensis* demonstrate their affinity with heterolobosean amoebae. Both species lack mitochondria but they have organelles provisionally interpreted as hydrogenosomes. Neither tolerate aerobic conditions; however, they do tolerate very low levels of oxygen. These heteroloboseans have unusual nuclear morphologies, and *Monopylocystis visvesvarai* is the first example of an amitochondriate heterolobosean protist for which a cyst is known. Future studies will focus upon questions that explore the possible occurrence of nuclear genes that were once targeted to mitochondria. If the amitochondriate state of heteroloboseans reflects loss of mitochondrial function, it should be possible to identify nuclear genes that were derived from the alpha proteobacterial symbionts that were ancestral to mitochondria. We have taken a similar but more comprehensive approach to search for mitochondrial targeted proteins in the amitochondrial parasite *Giardia lamblia*. Using full genome characterizations of the diplomonad *G. lamblia*, we have only discovered a single gene, cpn60, which is clearly related to cpn60 genes of alpha proteobacteria. The absence of other

mitochondrial−like coding regions in the Giardia genome suggests that it never harbored a mitochondrial−like organelle. Finally, we continue to explore phylogenetic relationships for parabasalids,which are deep branching eukaryotes and lack mitochondria. We have developed a rather extensive phylogeny for this group of protists with the addition of *Snyderella tabogae*, *Calonymha grassii* and *Metacoronympha senta*.

Highlights

- Phylogenetic analysis of ribosomal RNAs for several new amoebae isolates from anoxic environments show them to be related to heterolobosean amoebae, which can switch between flagellated and amoeboid morphologies.

- These are the first examples of heteroloboseans that are capable of forming cysts and therefore capable of long term survival in extreme environments such as anoxic sediments.

- Although all early diverging eukaryotes lack mitochondria but contain nuclear encoded cpn60 coding regions similar to those targeted to the mitochondria, there is no evidence of other mitochondrial targeted proteins in the Giardia genome. This suggests that Giardia is primitively without mitochondria.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Microbial ecosystem analogs for anoxic environments.	Background research on eukaryotic diversity that may be encountered in extreme environments beyond Earth.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

For 80−90% of Earth's history, micro organisms were the only life forms and they continue to dominate biologically mediated planetary processes. All multicellular forms including the full diversity of fungi, plants and animals are completely dependent upon the activities of and interactions with microbial forms. If life exists beyond Earth, it most likely will be microbial. Single cell eukaryotes or protists must have played a key role in the transition from a microbial world to one of complex fungi, plants and animals. Understanding the evolutionary history as well as the diversity of protists will provide important information about how life evolved on Earth as well as how to detect biological systems beyond earth. to search for it must have had its origins within a microbial world. Life detection experiments for in situ and sample return missions may take advantage of bio−signatures that are characteristic of early diverging eukaryotes. This will provide a greater range of complex signatures that might be capable of detecting extraterrestrial organisms.

Project Report: Eukaryotic Biodiversity and Physiology at Acidic Extremes: Spain's Tinto River

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic Biodiversity and Physiology at Acidic Extremes: Spain's Tinto River***
Project Investigators:	***Mitchell Sogin , Linda Amaral Zettler , Ricardo Amils***

Project Progress

One of the goals of the Astrobiology Roadmap is to explore the limits of life on Earth as analogues for environments on Mars, Europa and other planets that might support life. Our current research centers on such an analog: the Rio Tinto, a 100 km long river in southwestern Spain, has a pH range of 1.7−2.5, high concentrations of heavy metals, and an iron content that is thought to resemble conditions that may exist on Mars. Our recent small−subunit ribosomal ribonucleic acid (rRNA)−based studies reveal unexpectedly high eukaryotic phylogenetic diversity in the river. These studies identify organisms that live under acid/high metal extremes but tell us little about how these organisms have adapted to such environments. We are currently focusing on exploring the alterations in physiological mechanisms that might allow for growth of eukaryotic microbes at acid extremes. To this end we have isolated divergent protists from the Rio Tinto such as *Chlamydomonas sp.*, *Euglena cf. Mutabilis, Chlorella sp.*, and a lobose amoeba, assigned to the genus *Vannella*. − We are currently isolating and characterizing ion−transporting ATPases in the chlamydomonad, euglenid and vannellid amoeba and comparing these genes with those from neutrophilic counterparts obtained from culture collections. We have conducted polymerase chain reaction (PCR) experiments with primers designed to target the phosphorylation and ATP−binding sites found in members of the P−type ATPase superfamily. After cloning and sequencing these PCR products, we have determined that some of our clones fall into the heavy−metal P−type class but others may represent different ion transporters. We predict that special properties of these ion transporters allow protists to survive in the Rio Tinto's extreme conditions.

Highlights

- Protists can thrive and dominate extremely acidic, heavy metal laden environments.
- The Rio Tinto contains the major eukaryotic microbial lineages.

- Acidophiles closely related to cultured neutrophiles also thrive in the Rio Tinto.
- The transition from neutral to acidic environments occurs relatively rapidly over geological time scales.
- Eukaryotic extremophiles are more widely distributed and phylogenetically diverse than previously thought.
- Our acidophilic Chlamydomonas sp. RT1no2009 does not branch closely with C. acidophila UTCC 121, indicating that it may be a novel acidophilic species of Chlamydomonas.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

Field Expeditions

Field Trip Name: Rio Tinto Sampling	
Start Date: October 26, 2003	***End Date:*** November 7, 2003
Continent: Europe	***Country:*** Spain
State/Province: Andalucia	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Rio Tinto	***Keywords:*** acidic, high metal, microbial diversity
Description of Work: Sampling for targeted culturing with the aid of field microscope; some samples for DNA collected; physical and chemical measurements taken	
Members Involved: Ricardo Amils	

Cross Team Collaborations

We have been collaborating with the Spanish Centro de Astrobiologi-a for over 4 years. Our collaboration was one of the first international cooperations at the NAI and serves to further international and interdisciplinary research in extreme environments. This past year we carried out our third collection expedition to the Tinto River. One collaborative manuscript is in press and another review article is planned. Dr. Amils plans to return to Woods Hole to continue collaboration efforts and prepare additional manuscripts to summarize the data obtained thus far.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Eukaryotic rRNA evolution: origins of "Crown Group taxa"

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Eukaryotic rRNA evolution: origins of "Crown Group taxa"***
Project Investigators:	***Mitchell Sogin , Linda Amaral Zettler , Virginia Edgcomb***

Project Progress

Major shifts in Earth's environment including the increase of oxygen set the stage for evolution of increased biological complexity in the form of multicellular organisms. Analyses of ribosomal ribonucleic acid (rRNA) genes, and more recently other protein families, demonstrate a massive radiation in the eukaryotic line of descent that gave rise to plants, animals, fungi, numerous other independent protist lineages and several complex protist assemblages including Alveolates, (ciliates, dinoflagellates and sporozoans), and Stramenopiles (diverse heterotrophic and phototrophic protists, e.g. diatoms, various chromophytes, slime nets, small flagellates etc.). This sudden radiation obscures the identification of protists that gave rise to animals and the potential common evolutionary history of chlorophytes and other photosynthetic groups such as red algae. We seek to understand relative branching orders for major groups that emerged from this massive radiation and to infer what kind of environmental changes on a planetary scale might have stimulated this massive diversification. To address this issue we have focused our attention on the analyses of both small and large rRNA genes from key taxa. Earlier studies from our laboratory demonstrated that the animals share a common and unique evolutionary history with fungi. Together with a several other protist groups, the animals and fungi now comprise a new complex assemblage that we describe as opisthokont protists.

The origins of multi−cellularity require evolutionary transitions towards increased levels of complexity. We have generated new sequence data from the nuclear large subunit ribosomal deoxyribonucleic acid (DNA) gene (LSU rDNA) and the small subunit (SSU) rDNA gene of several unicellular opisthokont protists − a nucleariid amoeba (*Nuclearia simplex*), and four choanoflagellates (*Codosiga gracilis*, *Choanoeca perplexa*, *Proterospongia choanojuncta* and *Stephanoeca diplocostata*). These data provided a basis for re−examining relationships among several unicellular lineages and their multicellular relatives (animals and fungi). Our data indicate that 1) choanoflagellates are monophyletic rather than a paraphyletic assemblage that independently gave rise to animals and fungi as suggested by some

authors, and 2) the nucleariid filose amoebae are the likely sister group to Fungi.

We have also been exploring evolutionary relationships within two other crown−groups. The first is a complex assemblage called the Gymnamoebia. Some investigators have suggested that amoeboid protists within the Gymnamoebia are candidates for early diverging lineages. Our phylogenetic analysis clearly demonstrates they are not monophyletic but instead represent distinct clades within a complex assemblage of amoeboid protists that diverged nearly concurrently with plants, animals, fungi, alveolates and stramenopiles.

Highlights

- Choanoflagellates, which share structure similarities with choanocytes of sponges, are a monophyletic group that shared the most recent common ancestry with metazoans.
- The addition of nucleariid filose amoebae to the rDNA trees positions these protists as a sister group to fungi and together these taxa form a complex lineage that shared a common ancestry with the animals.
- The Gymnamoebia are not monophyletic but they are members of a complex evolutionary assemblage of amoeboid protists.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Search for complex life beyond earth.	The development of a detailed history for eukaryotic evolution provides a basis for designing life detection experiments through the selection of appropriate biomarkers.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

A goal of Astrobiology is to understand the origins of multicellular species and to determine what kind of planetary processes may have contributed to their emergence. If we determine how and when the immediate ancestors to animals and other complex life forms emerged, it may be possible to correlate these key evolutionary events with major shifts in planetary environments. Knowing the potential impact of such shifts on evolutionary projectories will influence the kinds of biomarkers targeted for life detection experiments.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Evolution of Proteins

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Evolution of Proteins***
Project Investigator:	***Monica Riley***

Project Progress

We have concentrated on evolution of proteins during this period from the point of view of distantly related families of proteins that share mechanism of reaction.

In some cases, families of proteins related transitively by sequence similarity are closely related in the actual reaction performed, such as aminotransferases, and in the organic biochemistry of the reaction mechanisms. Members of such a family are closely related to each other, differing only in specificity for the substrates.

In other cases, families of proteins related transitively have a loose structure so that all members are not related to all others. The same reaction mechanisms are employed, but are used to carry out different reactions. Another example of a family of similar sequences includes reactions with different Enzyme Commission numbers and different names such as oxidase, synthase, carboligase. Yet they are all FAD−utilizing, thiamine diphosphate−requiring decarboxylases. Protein names can fool us. Sequence similarities point out relationships.

By understanding such mechanistically similar families, we can picture an ancestral protein giving rise to each family. The diversity in evolutionary paths followed from the ancestor to the present is evident in the fact that protein families are not identical in membership in different organisms. The above−mentioned thiamine diphosphate−requiring decarboxylase families are not identical in *E. coli* and *B. subtilis*. Some members are close orthologs, but others have no instance in the other bacterium. For instance, the *B. subtilis* enzyme malonic semialdehyde oxidative decarboxylase is involved in utilization of myo−inositol as a carbon source. *B. subtilis* encounters quantities of myo−inositol in its soil environment, but *E. coli* does not encounter it in its various environments, thus evidently has no need for this enzyme.

Thus by examining families of proteins in different organisms, we gain an appreciation for common ancestry and for the ways that evolutionary divergence of proteins met diverse biological needs. The families in different

organisms may have descended from a common ancestor but the end products of evolution that exist today in contemporary organisms have been tuned to fulfill the individual needs of that organism.

Highlights

- Families of distantly related proteins use the same biochemical mechanism of reaction to carry out reactions that are closely related for some families, more distantly related for others.
- Common ancestors can be predicated for each such protein family.
- Not all members of a protein family are the same in different organisms.
- The different evolutionary paths from the common ancestor to the protein families in each organism represent the responsiveness of the evolutionary path to the diverse needs of each organism.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

Cross Team Collaborations

The work on protein families at MBL relates directly to our work for the EvoGenomics Team at Penn on the shared component parts of proteins as examples of preprotein elements used in many combinations in proteins as they evolved.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Genes that Regulate Photosymbiotic Interactions

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Genes that Regulate Photosymbiotic Interactions***
Project Investigator:	***Rebecca Gast***

Project Progress

Isolation of Differentially Expressed cDNA by rapid amplification of cDNA ends (RACE).

We are interested in identifying genes that may impart symbiotic competence to the dinoflagellate symbionts of planktonic protists (foraminifera and radiolaria). Our work has focused on the symbiotic and free−living states of the dinoflagellate symbiont (*Scrippsiella nutricula*) from the radiolarian *Thalassicolla nucleata*. Clones of gene fragments expressed in one messenger ribonucleic acid (mRNA) population (symbiotic state) but not in another population (free−living state) were identified using a method called cDNA Suppression Subtractive Hybridization. Sequence analysis and comparison of these clones suggested that most, if not all, of these genes were previously unknown.

Over the past year, we have attempted to isolate the complete gene sequence of several of these target clones using 5'− and 3'−rapid amplification of cDNA ends (RACE). Clone−specific primers have been designed for 3 different clones (E7, B8, C4) originating from 2 separate experiments. Typical RACE amplifications result in fragments ranging from approximately 200−400 nucleotides in length with a short overlapping region of close similarity to the target clone. To date, at least 1 additional fragment has been amplified from each of the 3 clones mentioned above. We intend to continue designing clone−specific primers as needed for RACE analysis until the longest possible ORF is identified for each target gene.

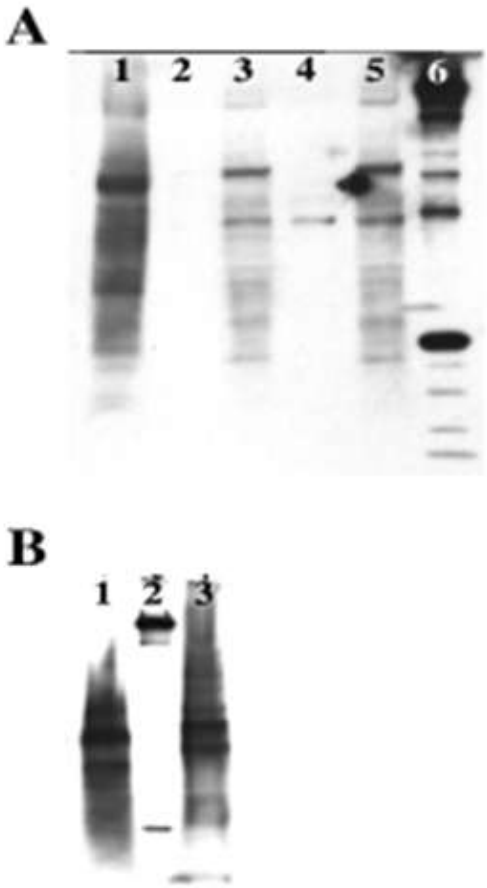

Figure 1. *Summary of RACE analysis for the E7 subtraction clone.*

Symbiont Surface Protein Analysis.

It is unknown what traits impart symbiotic competence to certain organisms and not others. Presumably, a potential symbiont must have certain identifying features by which a prospective host may distinguish it from other similar non−symbiosis forming organisms. It is possible that proteins expressed on the surface of symbiotic cells play an important role in identifying and retaining likely symbionts.

Using cell surface protein labeling reagents, we investigated surface protein expression in 3 dinoflagellates. Two of these, *Scrippsiella nutricula*, and *Gymnodinium beii*, are known to form symbiotic associations with *radiolaria* and *foraminifera* respectively. The third, *Gymnodinium simplex*, is a strictly free−living organism. We hypothesized that proteins might be expressed by both symbiosis−capable dinoflagellates, but not G. simplex, might be important for the successful recognition/initiation of the symbiotic state.

The surface proteins of live cells were biotinylated with either amine−reactive or sulfhydryl−reactive reagents. Total protein was then separated by SDS−PAGE. Labeled proteins were visualized on Western Blots by chemiluminescent detection and the protein patterns of all 3 dinoflagellates were compared.

Although many surface proteins from each organism were successfully labeled, we were unable to identify any that were specifically shared by the symbiotically competent algae. In fact, even the two symbiosis competent dinoflagellates showed few, if any, proteins in common. It is possible that not all of the surface exposed proteins were labeled in our experiments. We chose labeling reagents that differentiate between amine containing and sulfhydryl containing protein residues. It is possible that continued experimentation with additional reagents such as glycoprotein or tyrosine targeting reagents would yield different results.

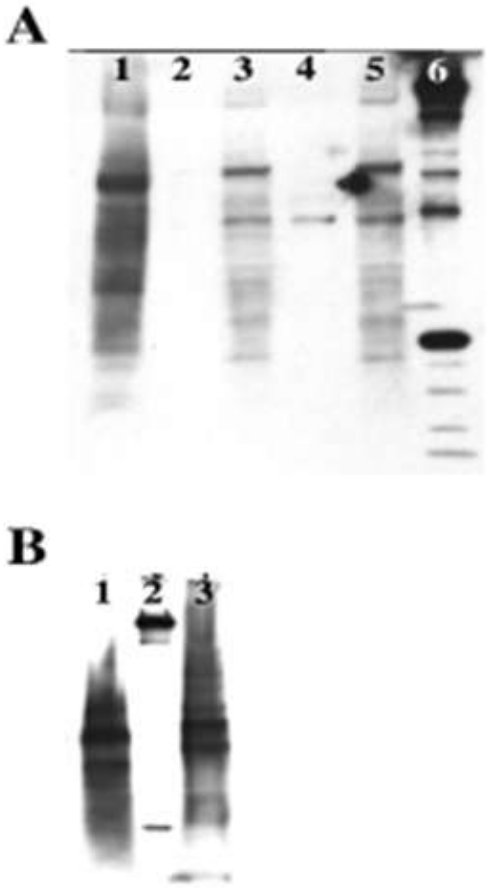

Figure 2. *Gel images of biotinylated surface proteins. A) Comparison of symbiotic and non−symbiotic dinoflagellates using amine reactive biotinyllation reagent. Lane 1,* Gymnodinium simplex*; lane 2 rainbow marker for gel; lane 3* Gymnodinium beii *(symbiont); lane 4,* G. beii*, no biotinyllation; lane 5* G. beii*;*

lane 6, marker. B) Comparison of symbiotic dinoflagellates using sulfhydryl reactive biotinyllation reagent. Lane 1, Scrippsiella nutricula*; lane 2, marker;* Gymnodinium beii*.*

***Gymnodinium beii* / *Gymnodinium simplex* Subtraction Results.**

A second suppression subtraction experiment was accomplished to examine the differences between free−living states of a symbiotically competent alga and one that is never symbiotic (but genetically very similar). Analysis of the SSH products from a known foraminifera symbiont *Gymnodinium beii*, and the closely related but strictly free−living dinoflagellate *Gymnodinium simplex* is under way. Our motivation for this work is similar to that of the surface protein analysis. We hypothesize that genes expressed by *G. beii*, but not *G. simplex*, may play an important role in recognition of the symbiont by the host.

Nine clones (A2, A7, A12, B12, C3, C7, D2, F12, and G8) have been identified as potential differentially expressed gene fragments that are present in *G. beii*, but not *G. simplex*. Expression levels of these clones are currently being confirmed by Dot Blot analysis of the cDNA libraries. DNA sequencing has been completed on some of the clones, and results of BLAST searches on these clone fragments indicate that they are likely new genes. Clones C7 and A2 do have short regions of high similarity to Symbiodinium photosystem 11 and alpha tubulin genes respectively. Following sequencing, we will attempt to retrieve full−length gene sequences by RACE as was done previously.

***Scrippsiella nutricula* cDNA Library Construction.**

Probes targeting the differentially expressed clones isolated from our suppression subtraction experiments will be made and used to screen a symbiont cDNA library. Recently, Scrippsiella symbionts were collected from Velella velella, an oceanic chondrophore. Gast and Caron (1996) previously showed that these dinoflagellate symbionts are the same as those from the radiolarian (Thalassicolla) that were used in the initial SSH. Full−length cDNAs were generated from Scrippsiella mRNA by Long−Distance polymerase chain reaction (PCR), and these cDNAs were then inserted into a donor vector that will enable us to perform functional analysis of individual genes at a later date.

Gast, R. J., and Caron, D. A. 1996. Molecular Phylogeny of Symbiotic Dinoflagellates from Planktonic Foraminifers and Radiolaria. *Mol. Biol. Evol* 13(9):1192−1197.

Highlights

- We have constructed the first cDNA library for the symbiotic state of a dinoflagellate involved in photosymbiotic relationships. This is also one of very few cDNA libraries for dinoflagellate algae in general.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in

microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities

Field Expeditions

Field Trip Name: none	
Start Date: April 7, 2003	***End Date:*** April 10, 2003
Continent: North America	***Country:*** USA
State/Province: CA	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Samples of the planktonic radiolarian, Thalassicolla nucleata, were collected by net tows. These individuals were preserved for isolation of the symbiotic algae, and the extraction of RNA for cDNA and RACE analyses. Symbionts were also collected from the pelagic chondrophore, Velella velella. RNA was isolated from these cells and used to construct a symbiotic expression cDNA library.	
Members Involved: Rebecca Gast	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Genomic determinants of parasitism and mutualism in bacterial endosymbionts

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Genomic determinants of parasitism and mutualism in bacterial endosymbionts***
NAI−NRC Postdoctoral Fellow :	***Seth Bordenstein***

Project Progress

Symbiotic interactions involving intracellular bacteria have been the foundation for several major evolutionary transitions in the history of Life, including the origin of organelles, the expansion of acceptable habitats for Life, and increases in cellular complexity and species diversity. These kinds of bacteria are known as endosymbiotic bacteria and are formidable players in evolution even today. One such group of bacteria is Wolbachia−−a genus of alpha−Proteobacteria that are the most abundant endosymbiotic bacteria on the planet, occurring in up to 75% of all insect species, as well as other arthropods and all filarial nematodes. These bacteria are influential passengers in their animal hosts, affecting key evolutionary processes such as sex determination, sexual selection, and speciation. And unlike many endosymbiotic bacteria that typically elicit long−term mutualisms within a limited host range, Wolbachia notably show more labile interactions with their eukaryotic hosts by spanning the spectrum of symbiotic associations (mutualism to parasitism) and transmission patterns (vertical to horizontal transfer).

By studying this natural plasticity with molecular evolution and comparative genomic approaches at the Bay Paul Center, we are determining how lateral transfer, gene acquisition, gene loss, and mobile genetic elements associate with symbiont−host interactions and genome−genome interactions. Objective 1 is to determine the direction of evolution of Wolbachia parasitism and mutualism, i.e., which arose first during the diversification of this prokaryotic−eukaryotic interaction. To accomplish this objective we are sequencing four key genes that span the major parasitic and mutualistic lineages of Wolbachia and constructing phylogenies to resolve when these lineages with different symbiotic associations arose. Objective 2 is to examine the evolution of a bacteriophage that infects the parasitic Wolbachia lineages. In contrast to mutualistic endosymbionts that traditionally lack selfish genetic elements, we have shown that this bacteriophage is common to the parasitic Wolbachia and has the ability to 'jump' into new Wolbachia genomes that are

distantly related. Such lateral phage transfer can potentially move novel genes into recipient genomes and perhaps even the eukaryotic host genome, and, therefore, may be a unique source of evolutionary innovation. Finally, objective 3 is to profile genome size variability across parasitic and mutualistic lineages to quantify the extent of gene acquisition and loss that has occurred during this endosymbiosis. Preliminary data confirm the prediction that the mutualists have undergone significantly greater reductions in genome size than the parasites.

Highlights

- Bacteriophage laterally transfer between distantly related, parasitic, Wolbachia that co−infect host cells.
- Multiple variants of bacteriophage can infect the same Wolbachia strain.
- The mutualistic Wolbachia of nematodes are strictly confined to the filariid group of nematodes.
- The parasitic Wolbachia genomes are consistently larger than the mutualistic genomes.

Roadmap Objectives

- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Hyperthermophiles of the hydrothermal vent subsurface: limits of life and extraterrestrial analogs

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Hyperthermophiles of the hydrothermal vent subsurface: limits of life and extraterrestrial analogs***
NAI−NRC Postdoctoral Fellow :	***Virginia Edgcomb***

Project Progress

Hyperthermophilic archaea, isolated from deep−sea hydrothermal vents, survive and grow under extreme heat, pressure, and chemical toxicity. Although it has been assumed that their environmental tolerance range sets the extreme limits for life, particularly in deep, hot subsurface environments, many critical factors and components of this tolerance have not been systematically tested. Defining the critical chemical and physical environmental extremes that limit growth and survival of hydrothermal vent archaea allows us to determine the likelihood of a deep subsurface biosphere −− a possible analog to extraterrestrial habitats. This has implications for understanding the ecology and evolution of prokaryotic life on Earth, and for searching for comparable life on other planets. We have tested growth (all nutrients available) and survival (minimal media without heterotrophic substrates) of two heterotrophic archaea under relevant (simulated *in situ*) environmental conditions.

The tolerance to sulfide, acidic pH, heavy metals, high pressure and temperature was examined under both survival and physiological conditions for two heterotrophic archaea (*Pyrococcus sp.* strain GB−D and *Thermococcus fumicolans*) and two autotrophic archaea (*Methanocaldococcus jannaschii* and *Archaeoglobus fulgidus*), all originally isolated from hydrothermal vent sites. The chemical and physical extremes that limit growth and survival of these organisms indicate the range of conditions that can be tolerated by hyperthermophilic archaea in the deep subsurface biosphere. In the last 5 months of this project, several experiments were repeated to confirm earlier results.

Highlights

- Alleviation of metal toxicity by complexation with sulfide, as dissolved metal−sulfide complexes or precipitates, is of considerable importance

for the survival of these archaea in the hydrothermal vent environment. In situ sulfide concentrations of seafloor hydrothermal solutions are in the range of 3−12 mM, providing ample sulfide to complex free metal ions at in situ concentration.

- Naturally occurring endmember concentrations of Cu (10−40 µM) exceed the range that can be tolerated without soluble sulfide complex formation. Zn concentrations (40−780 µM) reach the range where sulfide amelioration is required for survival. Co−concentrations in endmember fluids (10−220 nM) remain below the range where sulfide amelioration is required (Methanocaldococcus jannaschii, Archeoglobus fulgidus, Thermococcus fumicolans, and Pyrococcus strain GB−D)

- As long as the molarity of the sulfide equals or exceeds the molarity of the free metal ion, cell viability is not affected over 48 hours. But when metal ion concentration exceeds sulfide concentration, survival is usually significantly impaired.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
3	Life detection	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

By defining the limits of tolerance of selected archaea from hydrothermal environments to conditions of acidic pH, sulfide, heavy metals, temperature

and pressure, better proposals can be made for where (under what potential sets of environmental conditions) to look for similar organisms on Mars or Europa.

Cross Team Collaborations

There was no collaborative research during this period of time with other NAI teams; however, there was collaboration with Mak Saito from Princeton University, who provided guidance on metals experiments.

Project Report: Microbial symbionts: Agents for reorganizing genome architectures.

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Microbial symbionts: Agents for reorganizing genome architectures.***
Project Investigator:	***Jennifer Wernegreen***

Project Progress

The evolution of multicellular complexity required close interactions among a myriad of microbial symbionts, ranging from transient associations within populations to genome integration of endosymbionts and organelles. Today, bacterial endosymbionts allow numerous animal, plant, and protist lineages to occupy niches that are otherwise inhospitable. Stable associations between bacteria and insects provide model systems to study host−symbiont coevolution and the specialization of bacterial genomes to long−term intracellular associations. We integrate molecular evolution, population genetics, and comparative genomics to decipher the evolutionary forces operating in three such symbiotic systems: Blochmannia of ants, Wigglesworthia of tsetse flies, and Buchnera of aphids. Our lab also hosts Seth R. Bordenstein, an NAI/NRC Postdoctoral Fellow whose project is described in a separate progress report.

During the reporting period, we made significant progress toward identifying the effects of mutational pressure and genetic drift on protein evolution in obligate endosymbionts. We obtained a broad phylogenetic sample of protein−coding loci from Blochmannia, Buchnera, and their free−living relative *E. coli*, totaling more than 450 kb across isolates. Our sample of Blochmannia provided the first protein−coding genes of this ant endosymbiont (~7.34 kb for each of 16 taxa associated with diverse Camponotus host species). Using maximum likelihood and Bayesian methods of phylogenetic inference, we demonstrated congruence of host and symbiont phylogenies that indicates strict host−symbiont cospeciation throughout tens of millions of years (Degnan et al. 2003). Similarly, congruence among bacterial loci implies severe constraints on lateral gene transfer in obligate endosymbionts. This genome stasis may limit the evolutionary potential of these intracellular bacteria and accelerate the accumulation of deleterious changes through genetic drift.

Population genetic analyses provided insights into the specific forces that shape deoxyribonucleic acid (DNA) sequence evolution, and further supported effects of mutational pressure and drift. We identified signatures of genetic drift

at groEL, a highly expressed chaperonin that is considered critical in the bacterial−aphid symbiosis (Herbeck et al., submitted). Thus, even these functionally important endosymbiont genes are not immune from genome degradation. Our population genetic analysis of synonymous base changes in Buchnera also provided the first robust estimates of their AT mutational bias (Wernegreen and Funk, submitted). We found that a remarkable 90% of the mutational changes within Buchnera species were GC−>AT.

Genome analyses included a comparison of gene contents of Buchnera and Wigglesworthia, which we linked to the distinct nutritional physiologies of their insect hosts (Wernegreen 2003). As an expansion of a previous study in Buchnera, we explored codon and amino acid usage in the fully sequenced genome of Wigglesworthia (Herbeck et al., in press). This bacterium has a similar lifestyle as Buchnera, but is phylogenetically distinct and thus provides an independent "natural experiment" to identify forces shaping endosymbiont genome evolution. Our correspondence analysis demonstrated a strong impact of AT mutational bias on amino acid usage across this small (698 kb) genome, yet a reduced impact of AT pressure at high expression genes. This pattern parallels that observed in Buchnera and might provide a computational tool to identify candidate high expression genes in uncultivable bacteria that are difficult to study experimentally.

Highlights

- Bacterial endosymbionts of diverse insects show similar patterns of genome reduction, strong AT mutational bias, and effects of genetic drift on protein evolution. However, certain distinct features of these endosymbiont genomes (e.g. the specific biosynthetic genes they retain) can be linked to the nutritional physiology of their specific hosts.

- Endosymbiont genomes show distinct amino acid profiles at high expression genes, reflecting greater effects of selection against mutation−driven amino acid changes. This profile may provide a computational tool to identify candidates for highly expressed, functionally important genes in uncultivable, intracellular bacteria.

- Population genetic analysis provided further insight into the specific evolutionary forces shaping endosymbiont genomes. We found strong effects of genetic drift at even the most conserved endosymbiont loci, suggesting that no genes are immune from this degradative process. Intraspecific analyses also offer robust calculations of AT mutational pressure in endosymbionts, which we estimated to be a remarkable 90% GC−>AT in Buchnera.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
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Project Report: micro*scope (http://www.mbl.edu/microscope) − a web−based tool for microbial diversity research

Lead Team:	***Marine Biological Laboratory***
Project Title:	***micro*scope (http://www.mbl.edu/microscope) − a web−based tool for microbial diversity research***
Project Investigators:	***Mitchell Sogin , David Patterson***

Project Progress

micro*scope (http://www.mbl.edu/microscope) is an innovative biodiversity bioinformatics web site that greatly improves access to information about microbes. It makes use of uBio software (http://www.ubio.org), developed at the MBL/WHOI Library, to reconcile alternative names for an organism within a flexible multi−classification system and overcome problems in using organism names to retrieve information from remote sites. This project was begun in Year 3 and has continued into Year 4 and Year 5. micro*scope now contains a complete list of all bacterial and protist genera organized into a hierarchical classification. It currently provides descriptions and pictures of all categories of microorganisms and contains approximately 5000 freely downloadable high−resolution images organized in over 40 different collections, along with descriptions of 3500 protists. Habitats that have been surveyed include marine, saltwater marshes, fresh water ponds, and other environments, including Yellowstone National Park, Rio Tinto (Spain), Ross Sea (Antarctica) and Lake Toolik in Arctic Alaska. Laboratory culture collections (e.g. American Type Culture Collection) have also been surveyed.

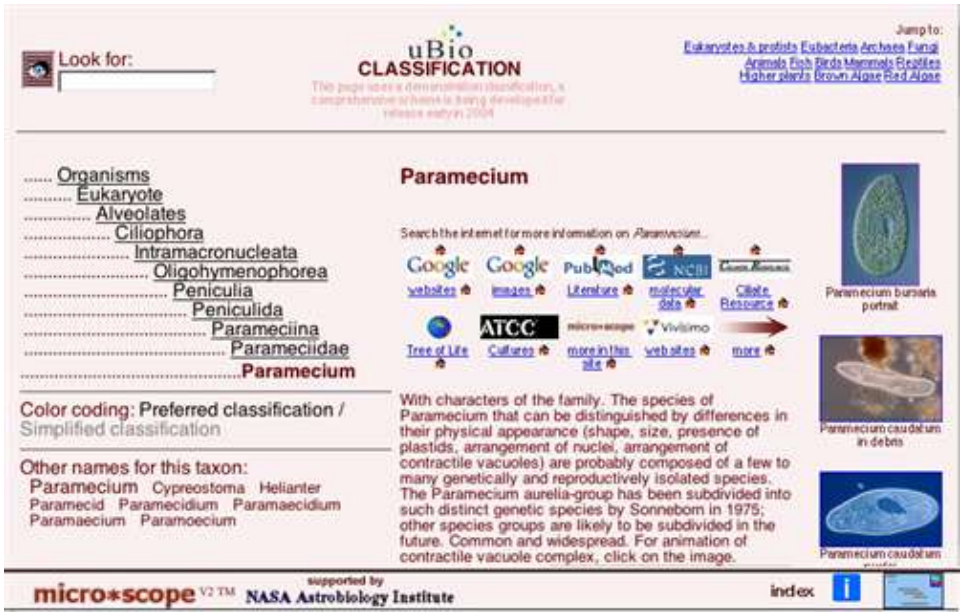

Figure 1. *micro*scope classification page with dynamic outlinks (top center)*

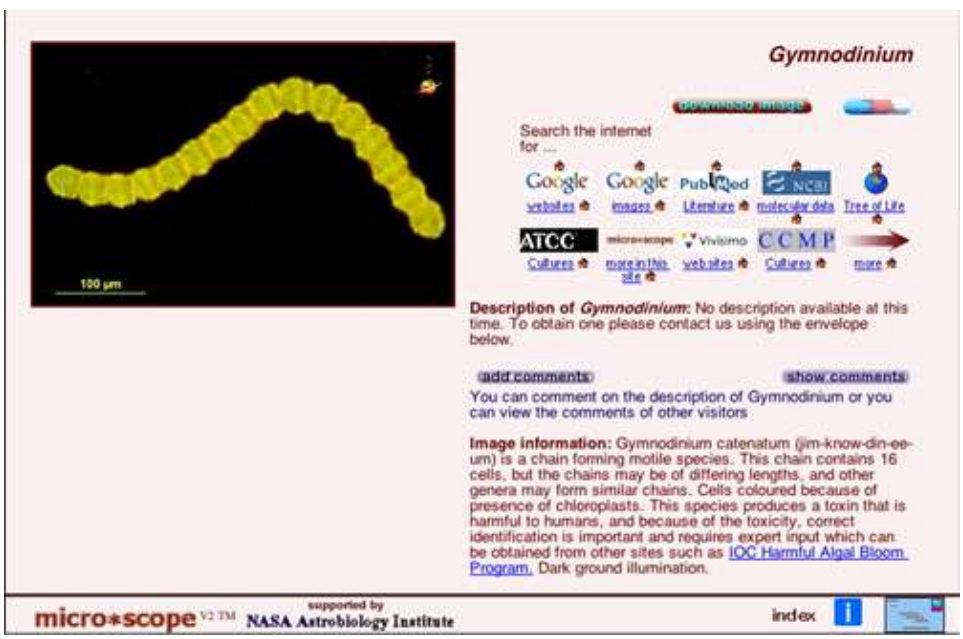

Figure 2. *micro*scope organism page*

micro*scope makes use of a number of generic and custom software tools. It has expanded to include a novel system of dynamic, customizable outlinks which link locally held data to information on a specific taxon held at remote sites. We have developed 'Link−in' software that reads html and text documents and attaches hyperlinks for information held in micro*scope to the names of organisms in the document. This allows extremely rapid integration of information held within micro*scope into any document.

micro*scope is a flexible, continuously expanding resource and development is on−going. In addition to containing expert information about microbes, the

generic structure of micro*scope can be adapted to the needs of both researchers and educators to organize any type of information in a hierarchical classification.

We are actively seeking continuing funding for the further growth of micro*scope.

Highlights

- micro*scope is an unparalleled web resource that contains image−rich information on eukaryotic and prokarotic microbes and uses unique software tools to link to expert information available on the internet for specific taxa.

- micro*scope has been expanded to include a complete taxonomy of protists and prokaryotes, 5000 images of microbes, descriptions of 3500 protists and dynamic linkouts for accessing taxon specific information from other sites.

- taxon specific outlinks have been created from Genbank and the National Center for Culture of Marine Phytoplankton (CCMP) culture web site to access the information held within micro*scope.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

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Project Report: Physiological Regulation of Cytosolic pH in Eukaryotic Acidophiles

Lead Team:	***Marine Biological Laboratory***
Project Title:	***Physiological Regulation of Cytosolic pH in Eukaryotic Acidophiles***
NAI−NRC Postdoctoral Fellow :	***Mark Messerli***

Project Progress

The overlying goal of our work is to characterize the physiological and molecular basis for survival in acidic environments. A component of this work is to design new methodologies for studying these organisms, as most common methods do not work at acidic pH. We first determined that the cytosolic pH levels in three acidophiles, *Euglena*, *Chlamydomonas*, and a *Vanelli* amoeba, cultured at pH 2 were in the neutral range, 6.2−7.8, indicating that all 3 species maintain nearly a 40,000−fold H+ concentration gradient across the plasma membrane. We also found that *Chlamydomonas* maintains an inside positive membrane potential that slightly decreases the total electrochemical H+ gradient. We proposed that maintenance of such a steep H+ gradient would depend on enhanced energy−dependent H+ efflux at low pH compared to neutral pH. By monitoring the rate of ATP consumption directly, after inhibiting ATP production we found that *Chlamydomonas* is working 7% harder at pH 2 than at pH 7 and that this increased rate of ATP consumption could account for maintenance of the near 40,000−fold H+ gradient without imposition of cell surface H+ diffusion barriers.

In order to fully explore the positive membrane potential of *Chlamydomonas* we have started studying Cl− transport, the primary anion involved with maintaining charge balance across the plasma membrane. We have also been investigating non−invasive, electrochemical detection of physiologically important ions and molecules as a means to study the physiology of acidophiles without having to be able to grow the cells in mass quantities. One such discovery is that we can characterize ion channels from single cells without disturbing the cells, a technical feat that was explored due to the fact that many acidophiles are difficult to culture in the lab. This method will enable us to study the physiology of a population of cells that cannot be grown up under lab conditions, by studying just a few individuals from that population.

Highlights

- We have collected partial sequences of heavy metal transporters from 3 different acidophiles. While looking for the H+−transporter sequence we came across heavy metal transporters of the same superfamily. We are building cDNA libraries to fully sequence these transporters in order to compare them to heavy metal transporters found in neutral growing organisms.

- Non−invasive electrochemical detection of ionic concentrations is useful for characterizing mean open time and mean conductance of ion channels in single cells. Some acidophiles are easy to culture in the lab while others are not. We hope to be able to study the physiology of cells without sacrificing or even disturbing them. This will enable us to study the physiology of different organisms by studying a few individuals without having to culture a massive population.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	origins of life, extreme environments	background research, analytical techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The search for life in the universe is based around what we know from life here on Earth. However, that knowledge base is lacking on the microorganism level, particularly regarding organisms living in extreme environments. It had

been thought that organisms couldn't survive in extreme environments. However, now we understand that certain organisms thrive in them. Since most other planetary bodies consist of what we would term extreme environments, it is essential that we characterize extreme life on Earth in order to get an understanding of where and how other organisms might be surviving outside our world.

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Fellowships: Marine Biological Laboratory

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Seth Bordenstein
Project Title: Genomic determinants of parasitism and mutualism in bacterial endosymbionts
Advisor: Jennifer Wernegreen, Co−Investigator
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: July 2002

Recipient: Virginia Edgcomb
Project Title: Hyperthermophiles of the hydrothermal vent subsurface: limits of life and extraterrestrial analogs
Advisor: Andreas Teske, Advisor
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: July 2002

Recipient: Mark Messerli
Project Title: Physiological Regulation of Cytosolic pH in Eukaryotic Acidophiles
Advisor: Peter Smith, Advisor
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: January 2002

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EPO: Marine Biological Laboratory

These are the Education and Public Outreach activities for the Marine Biological Laboratory.

Living in the Microbial World teacher workshop

Living in the Microbial World is a one−week intensive hands−on workshop for middle and high school teachers, grades 6−12. Our objective is to prepare middle and high school teachers to teach students and other teachers about the importance of the microbial world by incorporating hands−on microbiology activities into existing curricula. During the workshop, resident and visiting scientists from within the Woods Hole community present teachers with background information and current research developments on topics related to the importance of diversity of microbes in natural environments and microbial processes in the biosphere. In addition to presentations, teachers spend most of the time in a teaching laboratory, engaging in easy and inexpensive hands−on activities that exemplify basic principles of microbiology. During the workshop, teachers hear six lectures from research scientists highlighting the role of microbes in maintaining the biosphere, the origin of ecosystems, biomineralization and chemolithoautotrophy, extremophiles, protist diversity and fungal biology, and symbiosis. Teachers took field trips to the MBL's Marine Resources Center and the Great Sippiwissett Marsh in Falmouth to see microbial mats. Days were structured to include one lecture per day, and the balance of the time was spent doing hands−on activities in the lab. Evening sessions highlighting available Internet and video resources and a tour of the Josephine Bay Paul DNA sequencing facility also took place. Activities included: a demonstration of capturing magnetotactic bacteria; an investigation of fungal biology using an inquiry approach; culturing of basidiomycetes using sawdust culture techniques; making simple agar media; soil sample dilutions; making Winogradsky columns; construction of plankton nets, Uhlig extractors, and coverslip traps for collecting microorganisms; observation of termite hindgut microbes; and demonstration of the effects of naturally produced antibiotics on microbial growth. Three lab options involving culture and isolation of bacteria were offered simultaneously: culture and isolation of luminescent bacteria, culture and isolation of lactic acid bacteria, and culture and isolation of antibiotic−resistant bacteria from alfalfa sprouts. Astrobiology teaching materials were highlighted in a one−hour demonstration of the Website microscope and in an exploration of other Astrobiology URLs. Teachers received Life on Earth and Elsewhere? Educator Resource Guide, micro*scope and Astrobiology bookmarks, and planet cards. This workshop is offered yearly. Two sessions have been offered during the reporting time:

August 11−17, 2002, and August 10−16, 2003. Between both sessions, 41 middle and high school teachers attended.

Life and Living in Space teacher workshop

This three and one−half day workshop for teachers focused on various current topics in planetary protection and space life sciences, including microbe detection on equipment destined for spaceflight, growing plants in space, the gravitropic response in plants, and effects of spaceflight and microgravity on the human body. Norm Wainwright (Marine Biological Lab and Johnson Space Center) described his work on developing a rapid detection system for bacteria using the enzyme cascades found in the blood of the horseshoe crab Limulus and the rock crab. He also demonstrated extracting blood from Limulus and showed the clotting response of the blood in the presence of bacterial lipopolysaccharide. Robert Phillips (Colorado State University and NASA Life Sciences Outreach) gave a lecture on trends in food and nutrition in space and the effect of spaceflight on the physiology, anatomy, and life cycles of a variety of organisms. Mary Musgrave (University of Massachusetts Amherst) presented an overview of her research into the problems of growing multiple generations of plants in space, in particular the fertilization of plants and production of viable seeds. Lab activities included testing the effectiveness of different cleaning methods on equipment surfaces and assessing the results using enzyme cascade reactions. We also explored the effect of induced gravitational effect on plant growth (Which Way to Grow? activity), and observed the response of the human vestibular system to spinning motion. Participants were 25 middle and high school teachers. Materials distributed included the Life on Earth and Elsewhere? Educator Resource Guide, planet cards, and Astrobiology bookmarks.

Forams Through Time and Space: Astrobiology Teacher Workshop

This one−and−a−half day workshop focused on the biology of forams and their use in reconstructing past environments and as biostratigraphic markers. Twenty−five middle and high school teachers attended. Feedback solicited by written evaluation was positive, although teachers asked for more time to devote to the topic.

Online Article for Fathom.com

Rebecca Gast authored an article for a general audience entitled "Life in the Antarctic: Protistan Biodiversity," which appears as part of the Fathom.com Website for online learning.

National Science Teachers Association Astrobiology short course

Lorraine Olendzenski participated in the NSTA Astrobiology Short Course organized by Lisa Brown and Angela Phelps by leading a questioning circle involving microbial mats from Guerrero Negro and Rio Tinto water samples, and presenting the micro*scope Website. The program consisted of a mix of hands−on activities presented by EPO personnel and content presentations by scientists. Other presenters included Catherine Tsairides (Ames), Jackie Allen, Kay Tabola and Marilyn Lindstrom (JSC), Krisstina Wilmoth, Darlene Gadd and Daniella Scalice (NAI Central), Jim Kasting (Penn State), Andrew Steele (Carnegie) and Pamela Harmon (Voyages Through Time). 50 middle and high school teachers participated and received micro*scope bookmarks, instructions for the questioning circle activity, and flyers describing this year's Living in the Microbial World course at the MBL.

Development of Microscope Web site

The Microscope Website, developed through the Astrobiology Institute at the MBL (Woods Hole), is an innovative biodiversity bioinformatics Web site that greatly improves access to information about microbes; it is the single best resource for high−quality, downloadable, digital light micrographs of microbes. Presently, the site contains software to manage names and classification; a classification of protists and bacteria; dynamic outlinks for internet searching; original data about microbes; a comprehensive classification of all protist genera and prokaryotes, including 4500 images of microbes with explanatory text; and a variety of educational resources, including Lucid taxonomic guides. Information in the site can be accessed by habitat, cell shape, alphabetic list of genus name, and formal classification. We are continuing to expand and improve the site for larger public promotion by ensuring that all aspects work properly. We are adding educational material, including hands−on classroom activities already developed by NAI at MBL, glossary terms, and a tutorial for using Lucid guides. We will be adding a database of available K−12 hands−on activities in microbiology that details which aspects of the National Science Standards are met by each activity.

Presentation to University of Southern Connecticut Teachers

Lorraine Olenzendski met with 16 middle and high school teachers from all disciplines enrolled in the Southern Connecticut State University Institute for Science Instruction and Study (ISIS) Master's Degree Program. An overview of MBL Astrobiology research and education activities as well as an introduction to the Roadmap of the NAI was given during the one and one−half hour session. Classroom teaching materials were distributed.

Classroom presentations on Microbial Mats

Lorraine Olendzenski met with three 7th grade classrooms (45 students total) for 40 minutes each at Falmouth Academy to discuss the importance of microbial mat communities to the study of astrobiology. Students were asked "What do you know about microbial mats?", engaged in a questioning circle

with microbial mat samples, viewed a video on microbial communities (From Bacteria to Biosphere), and discussed slides showing modern microbial mats, stromatolites and the early fossil record.

American Society for Microbiology Teacher Science Day

Lorraine Olendzenski presented a 1.5 hour workshop as part of the American Society for Microbiology Teacher Science Day in College Park, MD. Hands on activities included a questioning circle using microbial mat samples, and the "What is Life?" activity from the Educator Resource Guide. An overview of the NAI, MBL Astrobiology research and education activities, and the micro*scope Web resource in microbial diversity was also presented.

National Association of Biology Teachers

Lorraine Olendzenski demonstrated the micro*scope Website at the National Association of Biology Teachers Annual Convention. Demonstrations were held continuously in the exhibit hall, at the Astrobiology section of the NASA Education booth.

Teacher Course: Current Topics in Ocean Research

Astrobiology Team members participated in a course for local Cape Cod High School teachers entitled "Current Topics in Ocean Research". We participated in a three hour module that focused on MBL Astrobiology Research, NAI educational resources and a tour of our high throughput DNA sequencing facility. Lorraine Olendzenski gave an overview of NAI and presented NAI educational resources, including micro*scope. Ashita Dhillon presented "Molecular Characterization of Sulfate Reducers from Guaymas Basin". Virginia Edgcomb gave a talk entitled "The Invisible Majority − Eukaryotic Microbes of the Deep Sea". Teachers toured the DNA sequencing facility and learned about the equipment and steps involved in template purification and DNA sequencing.

NSTA Astrobiology Short Course

Lorraine Olendzenski participated in the NSTA Astrobiology Short Course organized by Lisa Brown and Angela Phelps by leading a questioning circle involving microbial mats from Guerrero Negro and Rio Tinto water samples, and presenting the micro*scope website. The program consisted of a mix of hands−on activities presented by EPO personnel and content presentations by scientists. Other presenters included Catherine Tsairides (Ames), Jackie Allen, Kay Tabola and Marilyn Lindstrom (JSC), Krisstina Wilmoth, Darlene Gadd and Daniella Scalice (NAI Central), Jim Kasting (PennState), Andrew Steele (Carnegie) and Pamela Harmon (Voyages Through Time). 50 middle and high school teachers participated and received micro*scope bookmarks, instructions for the questioning circle activity, and flyers describing this year's

Living in the Microbial World course at the MBL.

Science Fair Judging: Falmouth Academy

MBL Astrobiology Team Members Linda Amaral Zettler, Lorraine Olendzenski, Hilary Morrison and Ashita Dhillon participated as judges for the middle school science fair at Falmouth Academy. Each judged three projects and interacted with student researchers individually by discussing the completed projects.

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Publications: Marine Biological Laboratory

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Members: Marine Biological Laboratory

Team Members sorted by current team.

Name:	Maria Aguilera
Email:	aaguilera@cbm.uam.es
Institution:	Centro de Astrobiologia
Name:	Linda Amaral Zettler
Email:	amaral@evol5.mbl.edu
Institution:	Marine Biological Laboratory
Name:	Ricardo Amils
Email:	ricardo.amils@uam.es
Institution:	Centro de Astrobiologia
Name:	Claudio Bandi
Email:	claudio.bandi@unimi.it
Institution:	University of Milan
Name:	David Beaudoin
Email:	beaudoin@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Steven Biller
Email:	sbiller@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Seth Bordenstein
Email:	sbordenstein@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Maurizio Casiraghi

Email:	maurizio.casiraghi@unimi.it
Institution:	University of Milan
Name:	Allen Collins
Email:	acollins@biomail.ucsd.edu
Institution:	University of California, San Diego
Name:	Amy Crump
Institution:	Marine Biological Laboratory
Name:	Michael Cummings
Email:	mike@bluefish.mbl.edu
Institution:	Marine Biological Laboratory
Name:	Patrick Degnan
Email:	pdegnan@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Ashita Dhillon
Email:	dhillon@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Jesse Dillon
Email:	jdillon@u.Washington.edu
Institution:	University of Washington
Name:	Virginia Edgcomb
Email:	vedgcomb@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Davida Fitch
Email:	david.fitch@nyu.edu
Institution:	New York University
Name:	Richard Fox
Email:	rfox@mbl.edu

Institution:	Marine Biological Laboratory
Name:	Rebecca Gast
Email:	rgast@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Felipe Gomez
Email:	fgomez@cbm.uam.es
Institution:	Centro de Astrobiologia
Name:	Sulip Goswami
Email:	sgoswami@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Katherine Hammar
Email:	khammar@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Joshua Herbeck
Email:	jherbeck@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Pamela Hinkle
Email:	pclapp@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Kai−Uwe Hinrichs
Email:	khinrichs@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Jennifer Hsieh
Email:	jhsieh@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Brendan Keenan
Email:	bgk00002@uconnvm.uconn.edu

Institution:	University of Connecticut
Name:	Abby Laatsch
Email:	alaatsch@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Adam Lazarus
Email:	alazarus@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Pauline Lim
Email:	lim@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Monica Medina
Email:	M_Medina@imap4.lbl.gov
Institution:	Lawrence Livermore National Laboratory
Name:	Mark Messerli
Email:	mmesserli@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Stephen Molyneaux
Email:	smolyneaux@whoi.edu
Institution:	University of Western Australia
Name:	Richard Mullen
Email:	rmullen@mbl.edu
Institution:	Marine Biological Laboratory
Name:	John Mustard
Email:	John_Mustard@postoffice.brown.edu
Institution:	Brown University
Name:	Thomas Nerad
Email:	nerad@atcc.org

Institution:	American Type Culture Collection
Name:	Tara Nihill
Email:	tnihill@mbl.edu
Institution:	Marine Biological Laboratory
Name:	C. O'Kelly
Email:	cokelly@bigelow.org
Institution:	Bigelow Laboratory for Ocean Sciences
Name:	Lorraine Olendzenski
Email:	lolendzenski@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Bertil Olsson
Email:	olsson@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Carmen Palacios
Email:	palacios@mbl.edu
Institution:	Marine Biological Laboratory
Name:	David Patterson
Email:	paddy@mail.usyd.edu.au
Institution:	Marine Biological Laboratory
Name:	Monica Riley
Email:	mriley@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Laura Shulman
Email:	shulman@evol5.mbl.edu
Institution:	Marine Biological Laboratory
Name:	Jeffrey Silberman
Email:	silberman@hades.biochem.dal.ca

Institution:	University of California, Los Angeles
Name:	Alastair Simpson
Email:	simpson@hades.biochem.dal.ca
Institution:	Marine Biological Laboratory
Name:	Peter Smith
Email:	psmith@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Mitchell Sogin
Email:	sogin@mbl.edu
Institution:	Marine Biological Laboratory
Name:	David Stahl
Email:	dastahl@u.washington.edu
Institution:	University of Washington
Name:	Helen Sturt
Email:	hsturt@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Sean Sylva
Email:	ssylva@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Andreas Teske
Email:	teske@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Jillian Ward
Email:	jward@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Jennifer Wernegreen
Email:	jwernegreen@mbl.edu

Institution:	Marine Biological Laboratory
Name:	John Werren
Email:	werr@mail.rochester.edu
Institution:	University of Rochester

Michigan State University
Executive Summary
Principal Investigator: Michael Thomashow

Low temperature is a predominant environmental characteristic of interstellar space, asteroids, meteors and of course, our solar system, including most of the planets and their satellites. An understanding of the impacts that low temperature has on the responses and evolution of biological organisms is, therefore, integral to our knowledge of Astrobiology. Toward this end, we are exploring multiple aspects of microbial adaptation to low temperature. One line of investigation −− Genomic and Proteomic Analysis of Permafrost Bacteria −− is to conduct genomic and proteomic analyses of bacteria that have been isolated from the Arctic and Antarctic permafrost. Our basic objectives include identifying genes and proteins that enable permafrost bacteria to inhabit subfreezing environments and determining how genome expression in the permafrost bacteria is affected by low temperature and other environmental conditions associated with the permafrost. We are also interested in conditions that "hitchhiker" bacteria might encounter during travel through space on natural objects or spacecraft. In a second line of investigation −− Bacterial Adaptation to Low Temperature −− we are directly examining, through "test−tube evolution" experiments, how bacteria genetically adapt to low temperatures. The fundamental objective here is to better understand how an organism, with a given complement of genes, can cross niche barriers that are defined by decreasing temperatures. Finally, in a series of "Field Truth" investigations −− Indigenous Bacteria of Arctic and Antarctic Permafrost −− we are exploring the microbial ecology of the permafrost environment and the physiological state of the resident microbial community. This is being accomplished by determining the phylogenetic diversity of the bacterial permafrost population and the metabolic activities present in permafrost soils.

An exciting advance in the Genomic and Proteomic Analysis project is the completion of the genome sequence for Psychrobacter 273−4, a bacterial strain that we isolated from 20−40 thousand year old permafrost soil. Completion of this bacterial genome sequence, which is being done in collaboration with the Department of Energy (DOE) Joint Genome Institute (JGI), will represent a milestone in bacterial genome sequencing as no complete genome sequence has been obtained for any psychoactive bacterium. Preliminary analysis of the Psychrobacter genome, in collaboration with JGI and the bioinformatics group at Oak Ridge National Laboratory, indicates that the isolate encodes approximately 2,140 predicted open reading frames (ORFs), with 11% of the ORFs being unique to Psychrobacter. Furthermore, 42% of the ORFs had a "hypothetical protein" as the best "hit" in

the GenBank database, indicating that the function of a major portion of the Psychrobacter genome is yet unknown. A search of the Psychrobacter ORFs indicated the presence of potential orthologs for proteins previously shown to be involved in cold adaptation including four Csp cold shock proteins, but a number of genes known to be involved in growth of mesophilic bacteria at low temperature were not found in Psychrobacter 273−4 suggesting that it encodes novel cold adaptation genes. Interestingly, 40 transposases from other microorganisms were identified in the Psychrobacter isolate suggesting that horizontal gene transfer may have played a significant role in the evolution of its genome.

A fundamental component of the genomics/proteomics project is to determine how expression of the genomes of permafrost bacteria is affected by low temperature and other conditions associated with the permafrost environment. This work is currently focused on Psychrobacter 273−4 and Exiguobacterium 255−15, a bacterial strain that we isolated from 2−3 million year old permafrost soils. Work to date with the Psychrobacter isolate has directly demonstrated that the proteome responds to changes in temperature. In particular, using two dimensional polyacrylamide gel electrophoresis, we found that certain proteins were only present at either cold (4°C) or warm (24°C) temperature. Analysis of the low temperature specific proteins using mass spectrometry indicated that one was novel and that the other three were orthologs of the *Escherichia coli* Csp cold shock proteins. In addition, two of the high temperature specific proteins were found to be novel while a third belonged to the diene lactone hydrolase protein family. To obtain high resolution proteome information for the Psychrobacter and Exiguobacterium isolates, we have been developing a novel 2−dimensional liquid fractionation method that uses a pH column−based separation in the first dimension followed by separation of the proteins in each pH fraction using nonporous silica (NPS) reversed phase high−performance chromatography (HPLC). The result is a 2−dimensional image of the proteins in the cell as a function of pH versus hydrophobicity. After developing effective cell lysis conditions and appropriate temperatures for protein fractionation, we now have a powerful set of procedures and methods to produce high resolution protein "maps" for the permafrost isolates.

Significant insights have also emerged from the Bacterial Adaptation to Low Temperature project. In studying adaptation of the mesophilic bacterium *E. coli* to low temperature (20°C), it has been found that the rate of adaptation is independent of previous thermal adaptive history; that is, change in relative fitness or fitness after 2000 generations is no different if the bacteria were previously adapted to 32, 37, or 42°C or an alternation of 32 42°C. We have further found that adaptation to 20°C is associated with a significant decrease in fitness at high (40°C) temperature. Genomic analysis of the 20°C adapted lineages has revealed the existence of several small deletions of the chromosome. The deletions appear to have occurred independently in many of the lineages. Most remarkably, genes at approximately 1.85Mb on the circular chromosome were independently deleted in 6 of the 30 lines examined. Thus, one mechanism of evolutionary adaptation to low temperature appears to involve gene deletion. Moreover, with *E. coli*, the occurrence of deletions in the same region of the genome suggests a functional significance for elimination of a few particular genes. We are in the process of mapping exactly which

genes were involved in each lineage and will determine the genes in common that were deleted.

A fundamental objective of the "Field Truth" investigations is to increase our understanding of the phylogenetic diversity of the bacteria that inhabit the Arctic and Antarctic permafrost. In the past, we have examined permafrost under typical subarctic tundra, near the East Siberian Sea, Russia and permafrost of the Beacon Dry Valley, Antarctica. This year we extended our work to the slopes of the active volcano Ploskii Tolbachik (Fig. 1), situated on Kamchatka peninsula in the far−east of Russia. It is one of the largest modern volcanic regions with widespread glaciers and permafrost at high altitudes. This site was chosen because one possibility for liquid water on Mars at shallow depths would be in proximity to subglacial volcanism. Such volcano−ice interfaces could occur beneath the polar caps of Mars today, or even within the adjacent permafrost around the margins of the ice caps.

To examine the microbial communities in this niche, we drilled a series of boreholes at different landscapes and altitudes between 800 and 2600 m a.s.l. (Fig. 2). Frozen (−1 to −2°C) samples extracted from a borehole at 1100m, representing young volcanic interstratified ash, sand and scoria 12 to 16 m thick (from the eruption of 1975−76), contained viable microorganisms and methane up to 1100−1900 µlCH4/kg soil. We found both psychrophilic and thermophilic microbes in the samples, with the psychrophilic heterotrophs the most numerous followed by psychrophilic methanogens and sulfate reducers. We have obtained enrichment cultures of psychrophilic, mesophilic and thermophilic bacteria of different metabolic types, including acetogens, methanogens, sulfate reducers, ferroreducers and spore−formers. The scoria texture of these sites is presumably close to Martian regolith. Such terrestrial volcanic microbial communities in permafrost potentially serve as good exobiological models for testing hypotheses on existing ancient microbial communities.

Last year we reported initial results of determining the diversity of Arctic and Antarctic permafrost bacteria using high throughput 16S ribosomal deoxyribonucleic acid (rDNA) gene sequencing. During the past year, we continued this analysis and determined whether new phylotypes could be isolated after incubating permafrost samples at low temperature (4°C) under both aerobic and anaerobic conditions. The analysis indicated that Arctic surface soils had considerably more phylotype diversity than did Antarctic surface soils and that incubating soil samples at 4°C resulted in significant changes in the microbial profile in all soil samples tested, indicating that less numerous microbes were alive and could be recovered.

Finally, we have sought to isolate bacterial strains that are related to permafrost bacteria from tropical sites in Puerto Rico. In particular, soil samples obtained from the El Yunque National Forest (hot and moist ecosystem), the Las Cabezas de San Juan Reserve (hot, dry and salty ecosystem) the Guánica State Forest (hot and dry ecosystem) and the Las Carmelitas Cave System were processed for the isolation of Psychrobacter, Exiguobacterium and Arthrobacter strains (we previously isolated Arthrobacter strains from ancient permafrost). Preliminary results indicate that we

potentially have isolated relatives of Exiguobacterium and Arthrobacter. The isolation of such strains will provide powerful tools for comparative genomic studies to help identify cold adaptive genes in the permafrost microbes.

Figure 1. *View of volcano Ploskii Tolbachik which has surrounding permafrost*

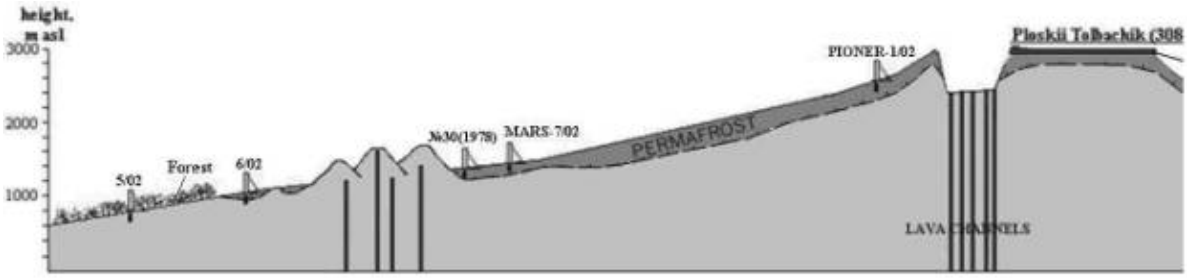

Figure 2. *A schematic cross−section of the volcano Ploskii Tolbachik with the drilled boreholes*

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Bacterial Adaptation to Low Temperatures

Lead Team:	***Michigan State University***
Project Title:	***Bacterial Adaptation to Low Temperatures***
Project Investigators:	***Richard Lenski , Albert Bennett***

Project Progress

This project analyzes the adaptation of experimental lineages of the bacterium *Escherichia coli* to low temperatures. We have established thirty replicate lineages of diverse thermal history that have now been adapted to 20°C for 2000 generations. We are in the process of analyzing both the adaptive consequences of that evolution and its genetic basis. We are also preparing further selection experiments at even colder temperatures to determine the limits of cold tolerance and its consequences.

We have demonstrated that the rate of adaptation to low temperature (20°C) is independent of previous thermal adaptive history; that is, change in relative fitness or fitness after 2000 generations is no different if the bacteria were previously adapted to 32, 37, or 42°C or an alternation of 32 42°C. We have further found that adaptation to 20°C is associated with a significant decrease in fitness at high (40°C) temperature. Not only is this general effect significant, it was also demonstrated in 15 of 24 replicate lineages of diverse thermal history.

Genomic analysis of the 20°C adapted lineages has found that several deletions of small portions of the chromosome have occurred independently in many of the lineages. Most remarkably, genes at approximately 1.85Mb on the circular chromosome were independently deleted in 6 of the 30 lines examined. We are in the process of mapping exactly which genes were involved in each lineage and will determine the genes in common that were deleted.

We previously demonstrated significant mortality of bacteria during repeated freeze−thaw cycles, and that populations that had grown and evolved for 20,000 generations at 37°C were more sensitive to this mortality than their ancestors. Based on these findings, we began an experiment to investigate the potential for evolutionary adaptation to cycles consisting of freeze, thaw, and growth at 37°C.

Highlights

- The rate and extent of adaptation to 20°C is independent of previous evolutionary thermal adaptive history.

- Adaptation to low temperature entails a tradeoff in loss of performance at high temperature.

- One mechanism of evolutionary adaptation to low temperature apparently involves gene deletion. In addition, the same deletion may occur repeatedly in independent lines, suggesting a functional significance for elimination of a few particular genes.

- Mortality of *E. coli* at −80°C is low, even in the absence of added cryo−protectant, but it is greatly increased by alternating freeze−thaw treatments.

- *E. coli* strains vary in mortality rates during freeze−thaw cycles, with strains that evolved for long periods at constant 37°C becoming more sensitive than was their ancestor.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Genomic and Proteomic Analysis of Permafrost Bacteria

Lead Team:	***Michigan State University***
Project Title:	***Genomic and Proteomic Analysis of Permafrost Bacteria***
Project Investigators:	***Michael Thomashow , James Tiedje***

Project Progress

The overall objective of this project is to identify genes and proteins that enable bacteria to inhabit the permafrost environment. An initial goal is to determine the complete genome sequence −− the "informational content" −− of two bacterial permafrost isolates. Exciting progress has been made. In collaboration with the DOE Joint Genome Institute (JGI), we have obtained nearly the complete genome sequence of Psychrobacter 273−4, a bacterial strain that we previously isolated from 20−40 thousand year old Siberian permafrost soil. In addition, progress is being made on determining the genome sequence of Exiguobacterium 255−15, a bacterial strain that we isolated from 2−3 million year old permafrost soils in Siberia. Preliminary analysis of the Psychrobacter genome, in collaboration with JGI and the bioinformatics group at Oak Ridge National Laboratory, indicates that the isolate encodes approximately 2,140 predicted open reading frames (ORFs), with 11% of the ORFs being unique to Psychrobacter. Furthermore, 42 % of the ORFs had a "hypothetical protein" as the best "hit" in the GenBank database, indicating that the function of a major portion of the Psychrobacter genome is yet unknown. A search of the Psychrobacter ORFs indicated the presence of potential orthologs for proteins previously shown to be involved in cold adaptation, including four Csp cold shock proteins, six proteins with known cold−induced expression and 12 stress−associated proteins. However, a number of genes known to be involved in bacterial growth at low temperature, including polynucleotide phosphorylase and CsdA, were not found, suggesting that novel cold adaptation genes remain to be discovered in the Psychrobacter genome. Interestingly, 40 transposases from other microorganisms were identified in the Psychrobacter isolate, suggesting that horizontal gene transfer may have played a significant role in the evolution of its genome.

An integral component of this project is to determine how expression of the Psychrobacter and Exiguobacterium genomes is affected by low temperature and other conditions associated with the permafrost environment. Work to date with the Psychrobacter isolate has demonstrated that the proteome responds to changes in temperature. In particular, using two−dimensional

polyacrylamide gel electrophoresis, we found that certain proteins were only present at either cold (4°C) or warm (24°C) temperature. Analysis of these polypeptides by trypsin digestion followed by liquid chromatography and tandem elecrospray mass spectrometry indicated that three of the low temperature specific proteins were orthologs of the *Escherichia coli* Csp cold shock proteins and that another was novel. In addition, one high temperature specific protein was found to belong to the diene lactone hydrolase protein family while two others have not been previously described. To obtain higher resolution of the Psychrobacter proteome, we have been developing a novel 2−dimensional liquid fractionation method that uses a pH column−based separation in the first dimension followed by separation of the proteins in each pH fraction using nonporous silica (NPS) reversed phase high−performance liquid chromatography (HPLC). The result is a 2−dimensional image of the proteins in the cell as a function of pH versus hydrophobicity. After considerable effort to develop effective cell lysis conditions and appropriate temperatures for protein fractionation, we now have a powerful set of procedures and methods to produce a high resolution protein "map" for the Psychrobacter isolate.

Highlights

- Near−complete genome sequence was found for a Psychrobacter isolate from the Siberian permafrost. Currently, there is no complete genome sequence for a psychrophilic or psychrotolerant bacterium.
- We found indications that a large portion of the Psychrobacter genome encodes novel proteins.
- We identified novel proteins in Psychrobacter that are present specifically at either cold or warm temperatures
- We developed a novel liquid protein fractionation procedure to produce high resolution protein maps of Psychrobacter.
- We developed new methods for lysing gram positive bacteria and bacteria with cell membranes that are difficult to disrupt.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Indigenous Bacteria of Arctic and Antarctic Permafrost

Lead Team:	***Michigan State University***
Project Title:	***Indigenous Bacteria of Arctic and Antarctic Permafrost***
Project Investigators:	***David Gilichinsky , James Tiedje , Lycely Sepúlveda***

Project Progress

The overall goal of this project is to provide "Field Truth" about microbial biology in permafrost, and once genomic information suggests genes of importance to the cryo−environment, to test the importance of those genes or markers *in situ*. We have examined permafrost under typical subarctic tundra, near the East Siberian Sea, Russia and permafrost of the Beacon Dry Valley, Antarctica. This year we extended our work to the slopes of the active volcano Ploskii Tolbachik, situated on Kamchatka peninsula in the far−east of Russia. It is one of the largest modern volcanic regions with widespread glaciers and permafrost at high altitudes. This site was studied because one way to have liquid water on Mars at shallow depths would be through subglacial volcanism. Such volcano−ice interactions could be going on beneath the polar caps of Mars today, or even within the adjacent permafrost around the margins of the ice caps. We addressed the question of whether such econiches contain recently developed microbial communities. A series of boreholes, ranging from 5 to 15m depths, were drilled at different landscapes and altitudes between 800 and 2600m a.s.l. Frozen (−1 to −2°C) samples extracted from a borehole at 1100m and representing young volcanic interstratified ash, sand and scoria 12 to 16 m thick from the eruption of 1975−76 contain viable microorganisms and methane (up to 1100−1900 µlCH_4/kg soil). We found both psychrophilic and thermophilic microbes in the samples, with the psychrophilic heterotrophs the most numerous followed by psychrophilic methanogens and sulfate reducers. We have obtained enrichment cultures of psychrophilic, mesophilic and thermophilic bacteria of different metabolic types, including acetogens, methanogens, sulfate reducers, ferroreducers and spore−formers. The scoria texture of these sites is presumably close to Martian regolith. Such terrestrial volcanic microbial communities in permafrost serve as good exobiological models for testing hypotheses on existing ancient microbiocenoses.

Main phylotypes of permafrost bacteria. Last year we reported initial results from our new high throughput rrn sequencing and analysis of Arctic and Antarctic permafrost bacteria. Here we report on the further analysis of this >2000 clone data set. We addressed the question of which phylotypes are common in permafrost, whether new phylotypes could be detected after

incubation of the soil aerobically and anaerobically at 4°C, and which phylotypes were present under all conditions. The most and least phylotype diversity was observed in Arctic and Antarctic surface soils, respectively. After incubation at 4°C, significant changes in microbial composition was observed for all samples. Both the aerobic and anaerobic low temperature incubation yielded microbes not detected in the original samples, verifying that less numerous members are viable.

High percent similarity between 16S rDNA of bacterial phylotypes that appeared in the original sample and the low temperature incubated indicates that those bacteria are not contaminants. Genera such as Arthrobacter , Desulfitobacterium, Kitasatospora, Chloroflexus, Nocardioides, Comamonas, Thermaerobacter, Brevibacterium, Pseudomonas, Rubrobacter, Rhodoferax, Flexibacter, Geobacter, Leptothrix represented the most common phylotypes. The results demonstrate that long−time impact of both age and subzero temperature are not a limiting factor for life preservation within permafrost and that we need to reconsider the understanding of possible limits of life in the Earth's biosphere and possibly on Mars.

Are there tropical variants of common permafrost isolates? To help identify cold adaptive traits in the permafrost microbes, we have sought to isolate the same genera from tropical sites (in Puerto Rico). Ten soils were processed for the isolation of possible Arthrobacter, Exigiobacterium and Psychrobacter: 3 samples from the El Yunque National Forest −− hot and moist ecosystem, 2 samples from Las Cabezas de San Juan Reserve −− hot, dry and salty ecosystem, 2 samples from Guánica State Forest −− hot and dry ecosystem, 3 samples from Las Carmelitas Cave System −− tested because some references mention the presence of Arthrobacter−like bacteria in such ecosystems. We are also attempting to isolate Psychrobacter and Exiguobacterium−like microbes from seawater and fish captured from the Caribbean Sea. The former genus, which is both cold and salt tolerant, has been isolated from sea fish products. We have isolated bacteria related to Arthrobacter and Psychrobacter based on 16S ribosomal deoxyribonucleic acid (rDNA) sequence. We have also isolated at least two bacteria that show the rod−coccus cycle observed in Arthrobacter and Exiguobacterium.

Highlights

- We identified and sampled a volcanic−permafrost interface in Kamchatka. Such interface zones would be likely zones of liquid water, and they offer strong potential for active Martian microbial life.

- We detected both psychrophiles and thermophiles of several physiological groups in the volcanic−permafrost interfacial zone.

- We identified common Bacteria genera in Arctic and Antarctic permafrost.

- áæ¡¦We found Bacterial genera previously undetected after permafrost soil was incubated at 4áæÛ¤.

- We found a few relatives of dominate permafrost species in tropical soils, which may be useful comparisons for finding cold adaptive genes.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Beringiya02	
Start Date: 01.08.2002	***End Date:*** 04.09.2002
Continent: Asia	***Country:*** Russia
State/Province: Kamchatka	***Nearest City/Town:***
Latitude: 57N	***Longitude:*** 160E
Name of site(cave, mine, e.g.): Tolbachik volcano	***Keywords:*** Mountain permafrost, thermophile microorganismus, anaerobic microrganismus, biogenic gases, frozen ground
Description of Work: Several boreholes on the different sites of Tolbachik volcano were drilled. Sites characterized by the different landscape, geological and permafrost condition. Sampling of frozen piroclastic material (dross, ashes e.t.c.) for detail microbiological, lithological and geochemical analyses were carried out. Also temperarure of permafrost in different landscapes were measured.	
Members Involved: A. Kholodov	

Fellowships: Michigan State University

There are no Postdoctoral Fellowships for this team.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

EPO: Michigan State University

These are the Education and Public Outreach activities for the Michigan State University.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Publications: Michigan State University

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Members: Michigan State University

Team Members sorted by current team.

Name:	Nancy Aguilar
Email:	nmaguila@uci.edu
Institution:	University of California, Irvine
Name:	Corien Bakermans
Email:	bakerman@usc.edu
Institution:	Michigan State University
Name:	Albert Bennett
Email:	abennett@uci.edu
Institution:	University of California, Irvine
Name:	Peter Bergholz
Email:	bergholz@msu.edu
Institution:	Michigan State University
Name:	Richard Brandt
Email:	brandt@cga.msu.edu
Institution:	Michigan State University
Name:	Patrick Chain
Email:	chain2@llnl.gov
Institution:	Lawrence Livermore National Laboratory
Name:	James Cole
Email:	colej@msu.edu
Institution:	Michigan State University
Name:	David Gilichinsky

Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Sarah Gilmour
Email:	gilmour@msu.edu
Institution:	Michigan State University
Name:	Loren Hauser
Email:	hoi@ornl.gov
Institution:	Oak Ridge National Laboratory
Name:	Rawle Hollingsworth
Email:	holling7@msu.edu
Institution:	Michigan State University
Name:	Sophie Kathariou
Email:	skathar@unity.ncsu.edu
Institution:	North Carolina State University
Name:	A. Kholodov
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Frank Larimer
Email:	larimerfw@ornl.gov
Institution:	Oak Ridge National Laboratory
Name:	K. Laurinavichius
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Richard Lenski
Email:	lenski@pilot.msu.edu
Institution:	Michigan State University
Name:	David Lubman

Email:	dmlubman@umich.edu
Institution:	University of Michigan
Name:	Susan Lucas
Email:	lucas11@llnl.gov
Institution:	DOE Joint Genome Institute
Name:	Pamela McDonald
Email:	pmcdonal@uci.edu
Institution:	University of California, Irvine
Name:	Robert North
Email:	rnorth@umich.edu
Institution:	University of Michigan
Name:	K. Novototckaya−Vlasova
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	L. Petrovskaya
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Monica Ponder
Email:	nuttmoni@pilot.msu.edu
Institution:	Michigan State University
Name:	Yinghua Qiu
Email:	yqiu@umich.edu
Institution:	University of Michigan
Name:	Michelle Riehle
Email:	mriehle@uci.edu
Institution:	University of California, Irvine
Name:	Elizaveta Rivkina

Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Debora Rodriguez
Email:	rodri257@msu.edu
Institution:	Michigan State University
Name:	Uwe Rossbach
Email:	plnthelp@msu.edu
Institution:	Michigan State University
Name:	V. Scherbakova
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Lycely Sepúlveda
Email:	lycely@caribe.net
Institution:	Universidad Metropolitana
Name:	A. Shatilovich
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	L. Shmakova
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Sean Sleight
Email:	sleght3@msu.edu
Institution:	Michigan State University
Name:	Elena Spirina
Email:	gilichin@issp.serpukhov.su
Institution:	Russian Academy of Sciences
Name:	Michael Thomashow

Email:	thomash6@msu.edu
Institution:	Michigan State University
Name:	James Tiedje
Email:	tiedjej@msu.edu
Institution:	Michigan State University
Name:	Nicholas Wigginton
Email:	wigginto@msu.edu
Institution:	Michigan State University
Name:	Daniel Zarka
Email:	zarkadan@msu.edu
Institution:	Michigan State University
Name:	Suping Zheng
Email:	zhengs@umich.edu
Institution:	University of Michigan

Pennsylvania State University
Executive Summary
Principal Investigator: Hiroshi Ohmoto

The Penn State Astrobiology Research Center (PSARC), created five years ago as part of the NASA Astrobiology Institute, is composed of 16 (Co)−PIs and their research teams from The Pennsylvania State University (13), The University of Pittsburgh (2), and SUNY Stony Brook (1). The investigators represent a wide range of disciplines: geochemistry (Michael Arthur, Susan Brantley, Rosemary Capo, Lee Kump, Hiroshi Ohmoto, Martin Schoonen, and Brian Stewart), paleontology (Mark Patzkowski), atmospheric chemistry (Jim Kasting and Robert Minard), geomicrobiology (Kate Freeman and Chris House), evolutionary genomics (Blair Hedges and Masatoshi Nei), and biochemistry and microbiology (Jean Brenchley and Greg Ferry). The proximity of all members has enabled close interaction and a variety of collaborative research, teaching, and public outreach programs. During the fifth year, PSARC has supported all or part of the research/education/PO activities carried out by 142 persons (16 (Co−)PIs, 22 research associates and postdoctoral fellows, five research assistants, two technicians, 49 graduate students, 37 undergraduate students, and five staff in administration/IT/EPO).

The primary research goal of PSARC over the past five years (under the theme Coevolution of the Earth and Life) has been to increase understanding of the connections between the rise of major life forms during the early history of Earth (between ~3.8 and 0.5 billion years ago) and the evolution of the environment (especially atmospheric O_2, CO_2, and CH_4). This goal has been pursued primarily from multidisciplinary and multidimensional research focused on the following seven topics (Tasks):

1. Environment of prebiotic Earth and the origin of life
    a. Experimental approach (Schoonen)
    b. Prebiotic chemistry of hydrogen cyanide (Minard)
2. Biochemistry of Archea and Bacteria
    a. Enzymes of ancient metabolic pathways (Ferry)
    b. Biochemistry of psychrophilic organisms (Brenchley)
    c. Microbe−mineral interactions (Brantley)
3. GEOPULSE: Gene Expressions Observations for Planetary Life Study (House, Ferry, Freeman, Brantley)
4. Timescale for the evolution of life on Earth: Molecular evolutionary approach (Hedges and Nei)
5. Evolution of atmospheric O_2, climate, and biosphere (Kump, Kasting, Freeman, Capo, Stewart, and Ohmoto)

6. Neoproterozoic variations in carbon and sulfur cycling (Arthur)
7. Causes and consequences of the diversification and extinction of metazoans (Patzkowsky)

Progress in each of the above topics is reported separately in the following pages. Excellent progress has been made in all phases of our research projects. The new discoveries made and the new theories developed from these investigations during the fifth year have been presented in 34 published papers (including those in press) and 20 papers (submitted, in review, or in revision) in refereed journals and book chapters, and 71 abstracts presented at international and national meetings.

Highlights

Topic 1: Prebiotic Environment

Martin Schoonen's group has conducted a series of photochemical experiments using pyrite, and suggests pyrite−induced OH radical formation may have placed an important constraint on the stability of biomolecules, such as ribonucleic acid (RNA), on early Earth. Protective mechanisms, such as encapsulation of biomolecules by lipids, may have been a prerequisite to escape decomposition via OH radical attack.

Robert Minard has synthesized $H_{13}C_{15}N$ polymers under a variety of conditions, and analyzed their structures using solid−state nuclear magnetic resonance (NMR). Based on these data, Minard suggests the HCN polymer structural model provides a mechanism for the formation of heteropolypeptides on the primitive Earth.

Topic 2: Biochemistry of Archea and Bacteria

Greg Ferry has discovered a novel flavoprotein family (archaeoflavoprotein) that is unique to the Archaea domain of life.

Jean Brenchley's group has demonstrated that a wide, and perhaps surprising, diversity of organisms have survived entrapment in a Greenland glacier for over 120,000 years. They have analyzed nearly 800 isolates, grouping them into taxonomic and phylogenetic categories.

Susan Brantley's group has found that Fe (II) released from goethite by siderophore−producing soil bacteria has a $_{56}$Fe value −1.6‰ relative to goethite. They have also found that nitrogen−fixing bacteria may secrete molybdenum−complexing ligands to solution in order to extract Mo for nitrogenase: for example, Azotobacter vinelandii secretes aminochelin when grown in Mo−deficient but Fe−replete conditions.

Topic 3. Gene Expression for Planetary Life Study

Using whole genomic analysis, Chris House's group has deduced that sulfur reduction is the most geologically plausible for the base of the Archaea. They have also found that: (a) *Methanosarcina acetevorans* have surprisingly high

oxygen tolerance, allowing them to grow even at about 1% oxygen; (b) Archaeoglobus does not oxidize methane in spite of the similarity of Archaeoglobus to ANME−1 and ANME−2; and (c) there are conditions that increase trace methane oxidation by methanogens, providing some insight into how anaerobic methane oxidation occurs.

Topic 4. Evolutionary genomics

Blair Hedges's group has found, using molecular clock studies of large numbers of genes (50−200), that plants, animals, and fungi diverged about 1.5 billion years ago, with living groups in each kingdom diverging relatively soon thereafter. This is as much as one billion years earlier than indicated by the fossil record.

Masatoshi Nei, a member of the National Academy of Science, was awarded the 2002 International Prize for Biology in the field of "Biology of Evolution" for his contributions in evolutionary genomics.

Topic 5. Evolution of atmospheric O_2, climate, and biosphere

Lee Kump's group has found from numerical modeling of microbial mats that O_2 levels in Archean cyanobacterial mats may have exceeded modern atmospheric saturation values by a factor of 2−3, as modern mats do during afternoon hours. This conclusion is independent of the oxygen or sulfide content of the overlying water. From carbon isotope analyses of Paleoproterozoic carbonate, Kump also suggests that pelagic marine organisms in the Paleoproterozoic (1.8 billion years ago) apparently were modifying the nutrient and carbon chemistry of the ocean in much the same way and to a similar extent as modern organisms do. Kump also suggests the banded iron formations in the Neoproterozoic "Snowball Earth" period may have been the result of high iron fluxes from mid−ocean ridges, which were enhanced by a sea−level change and the low−sulfate oceans.

Jim Kasting's group, based on photochemical modeling, suggests that: (a) enhanced methane concentrations could provide a plausible explanation for the extended warmth of the Mid−Proterozoic Era, 2.2−0.8 Ga; and (b) ozone and methane might be observed simultaneously in a Mid−Proterozoic−type terrestrial planet atmosphere. The simultaneous presence of O_2 (or O_3) and reduced gases is considered the firmest remote evidence for extraterrestrial life.

Based on molecular analyses of organic matter from sedimentary rocks of late Archean age, Kate Freeman's group suggests diverse life already existed in the Late Archean. There is evidence for all three domains existing at that time. Isotopic and stratigraphic data reveal ecological differences associated with lithofacies. Shallower facies were more oxygenated, a phenomenon that is reflected in the recorded microbial processes. Deeper waters were largely anoxic, although there is evidence for redox cycling between elemental sulfur and sulfide. Isotopically enriched tetramethyl− and trimethylbenzene released via pyrolysis can be linked to inputs from green sulfur bacteria in ancient (Cretaceous) lake deposits. This may extend the available biomarkers for this

source of organic matter.

Rosemary Capo and Brian Stewart's group has found that the Sm−Nd isotope system can be used to evaluate the pedogenic mobilization and possible later remobilization of geochemical tracers in ancient soil profiles. Soil carbonate is a significant repository for rare Earth elements (REE), an important paleoatmospheric tracer, and must be considered in working out the REE budgets of ancient soil profiles formed under arid conditions. They further suggest the REE patterns of the ~3 Ga Steep Rock paleosol, Canada, reflect pedogenic processes.

Hiroshi Ohmoto has organized the Archean Biosphere Drilling Project (ABDP), an international collaborative research project under the Astrobiology Drilling Program (ADP). The drilling, which began in the Pilbara district, Western Australia, in June 2003, has already revealed unequivocal evidence that the hematite (ferric oxide) crystals in the 3.46 Ga Marble Bar chert/jasper sequence were not formed by the modern oxidation of ferrous−rich carbonate (siderite) as postulated by many previous investigators, but instead formed by the mixing of Fe_2+−bearing submarine hydrothermal fluids and oxygenated local seawater when the rocks accumulated on the ocean floor. This is important evidence suggesting the oceans and atmosphere were already oxygenated 3.46 Ga ago. The ABDP has also recovered a large amount of black shales, containing remnants of microbes that lived in the Archean oceans. The mineralogical and geochemical investigations (e.g., C, N, and S isotopes; rare Earth elements) by Ohmoto's group on Archean shales and banded iron formations from the Abitibi district, Canada, the Pilbara−Hamersley district, Australia, and other places have also revealed that the redox structure of the Archean oceans was probably identical to that of modern oceans: globally oxic oceans with locally developed anoxic basins that sustained complexed ecosystems. Based on analyses of thermodynamic data and carbon isotope data on siderite ($FeCO_3$), which is abundant in banded iron formations older than ~1.8 Ga, Ohmoto and Watanabe suggest the CO_2 level of the Archean atmosphere was at least 100 times greater than today, implying CO_2, rather than methane, was the major green−house gas in Archean, as well as in the later geologic time.

Figure 1 *The first drilling site of the ABDP.*

Figure 2 *Hiroshi Ohmoto examines the first core with Bruce Runnegar (incoming NAI Director) at the site.*

Topic 6. Neoproterozoic carbon and sulfur cycles

Based on sulfur isotope analyses of trace sulfate in carbonates, Mike Arthur's group suggests the seawater sulfate concentrations in the mid− to late−Proterozoic were perhaps 10% of those at present. These low concentrations led to profound changes in ocean and atmospheric chemistry, ultimately producing near−global glaciations.

Topic 7. The Ordovician extinction of metazoans

Mark Patzkowski's group has made significant progress in understanding the

environmental causes of the Late Ordovician glaciation and the evolutionary consequences of the Late Ordovician mass extinction. Based on numerical modeling, they suggest the pCO_2 level was 8 times the present atmospheric level (PAL) when the glaciation began and > 10 PAL when it ended.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: A timescale for the evolution of life on Earth − Hedges

Lead Team:	***Pennsylvania State University***
Project Title:	***A timescale for the evolution of life on Earth − Hedges***
Project Investigator:	***S. Blair Hedges***

Project Progress

The following discoveries were made during Year 5:

1. An early origin for the rise in complex multicellular life. We found, using molecular clock studies of large numbers of genes (50−200), that plants, animals, and fungi diverged about 1.5 billion years ago, with living groups in each kingdom diverging relatively soon thereafter. This is as much as one billion years earlier than indicated by the fossil record. (Manuscript in preparation).
2. Colonization of land by animals (arthropods) in late Precambrian. Using molecular phylogenetic analyses of multiple nuclear and mitochondrial genes, including newly collected data, we found that land was colonized independently by various groups of arthropods, some in latest Precambrian. (Manuscript in preparation).
3. A robust method for estimation of the mode. We conducted simulations and used real data to test various methods for estimating the mode of distributions (an important statistic used in molecular clock analysis). We discovered that a bootstrap method lowers the variance of estimates and accordingly devised an improved method for estimation of the mode. (Manuscript submitted.)
4. Review papers published. One review paper covered the tree and timescale of life, including recent advances from genomics (Nature Reviews Genetics 3:838−849, 2002). The other paper reviews the latest molecular clock methods for use with genomic data (Trends in Genetics 19:200−206, 2003).

Highlights

- Early rise in complex life: Molecular clock studies of large numbers of genes revealed that complex multicellular life appeared about a billion years earlier than indicated by the fossil record

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	TPF	background research
3	Mars	background research
3	Europa	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This research contributes to the predictive ability of NASA to identify life elsewhere with the use of biomarkers. Identification of these biomarkers (e.g., oxygen) and their temporal sequence is accomplished through studying the relationship between biotic and environmental evolution. The persistence of life during environmental extremes (e.g., global glaciations) is another mission?related aspect. In the case of TPF, the elaboration of historical patterns of early life on Earth and correlations with development of the atmosphere provides an ?atmospheric biomarker? for interpreting spectral analyses. In the case of Mars and Europa, the biomarkers are temporal and environmental (e.g., in drawing comparisons with the history of life on Earth),

and any living organisms discovered will require biochemical understanding based on experience with the genetic and genomic complexity of life on Earth.

Cross Team Collaborations

Hedges co−chairs the Evolutionary Genomics Focus Group with James Lake (UCLA) and collaborates with members of other NAI teams (See Annual Report of the Focus Group for details). He and Lake chaired a Special Session on evolutionary genomics at the NAI General Meeting (2003), Arizona State University, in February, where speakers were invited from within and outside NAI (James Staley, Monica Riley, Janet Siefert, Herve Philippe). Also at the meeting, a breakout session was held and attended by 30−40 persons. It featured discussion of previous talks and short presentations by graduate students. It was proposed to have focused discussion sessions on evolutionary genomics at the Gordon Research Conference on Origin of Life (Maine) in July; this will be partly supported by NAI.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: A timescale for the evolution of life on Earth − Nei

Lead Team:	***Pennsylvania State University***
Project Title:	***A timescale for the evolution of life on Earth − Nei***
Project Investigator:	***Masatoshi Nei***

Project Progress

The main goal of this research is to develop statistical methods for estimating the times of origin of major groups of organisms from molecular data as well as those of major groups of gene families and infer early evolutionary events on Earth. The most relevant work from my laboratory bearing on these questions appeared earlier this year (Glazko and Nei, 2003). In that study, we compared several methods of time estimation. We examined the effects of several factors on the estimates of divergence times and reached the following conclusions: (1) It is advisable to concatenate many gene sequences and use a multigene gamma distance for estimating divergence times rather than using the individual gene approach. (2) When sequence data from many nuclear genes are available, protein sequences appear to give more robust estimates than deoxyribonucleic acid (DNA) sequences. (3) Nuclear proteins are generally more suitable than mitochondrial proteins for time estimation. (4) It is important first to construct a phylogenetic tree for a group of species using some outgroups and then estimate the branch lengths. (5) It appears to be better to use a few reliable calibration points rather than many unreliable ones.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
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- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Causes and consequences of the diversification and tetinction of metazoans: Neoproterozoic variations − Arthur

Lead Team:	***Pennsylvania State University***
Project Title:	***Causes and consequences of the diversification and tetinction of metazoans: Neoproterozoic variations − Arthur***
Project Investigator:	***Michael Arthur***

Project Progress

Persistent deep ocean anoxia and relatively low terrestrial weathering rates that prevailed during Neoproterozoic "Snowball" episodes led to significant perturbations of the sulfur cycle, as evidenced by some of the largest and most rapid sulfur isotope variations known for the past 750 million years. These variations have been documented in marine strata from three continents. We have also presented the first comprehensive evidence that indicates low oceanic sulfate concentrations (perhaps 10% of modern) for most of the late Meso− to Neoproterozoic. As a result of this conclusion, we provided a new model for Neoproterozoic atmospheric chemistry and paleoclimate. As the result of very low oceanic sulfate concentrations, methane production rates and flux to the atmosphere were much higher than at present, enabling methane to prevail as an important greenhouse gas at that time. Thus, as long as sulfate concentrations remained low, most organic matter oxidation was accomplished by methanogenesis and global climate remained relatively warm. However, increasing oxygenation of the atmosphere and ocean in the late Proterozoic caused sulfate concentrations to rise, promoting sulfate reduction and decreasing rates of methanogenesis. This led to an abrupt decrease in atmospheric methane concentration and rapid cooling to cause the first "Snowball Earth" event. "Molar tooth structure", and unusual fabric found in Proterozoic carbonate rocks, disappeared after about 750 Ma. We interpret this texture as resulting from shallow methanogenesis, methane saturation and bubbling of gas out of sediments as the result of little or no bacterial sulfate reduction. Nearly all organic matter was degraded under oxic conditions in shallow water environments or by a consortium of bacteria favoring methanogenesis.

Highlights

- Seawater sulfate concentrations in the mid− to late Proterozoic were perhaps 10% of those at present. These low concentrations led to

profound changes in ocean and atmospheric chemistry, ultimately producing near−global glaciations.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Svalbard Neoproterozoic	
Start Date: July 27, 2002	***End Date:*** Aug 20, 2002
Continent: Europe	***Country:*** Norway
State/Province: Svalbard	***Nearest City/Town:***
Latitude: 78°N	***Longitude:*** 12°E
Name of site(cave, mine, e.g.): west coast	***Keywords:*** carbon, sulfur, Neoproterozoic, Snowball
Description of Work: sampling of Neoproterozoic carbonate sequences	
Members Involved: Matthew Hurtgen	

Field Trip Name: Canada Neoproterozoic	
Start Date: July 9, 2003	***End Date:*** August 7, 2003
Continent: North America	***Country:*** Canada
State/Province: NW Territories	***Nearest City/Town:***
Latitude: 65°	***Longitude:*** 128°W
Name of site(cave, mine, e.g.): Mackenzie Mts.	***Keywords:*** carbon, sulfur, Neoproterozoic, Snowball
Description of Work: sampling of Neoproterozoic carbonate sequences	
Members Involved: Matthew Hurtgen	

Cross Team Collaborations

We are collaborating with the Harvard−MIT−Rochester group (Paul Hoffman and doctoral student Galen Halverson) on field work and stable isotope analyses of stratigraphically well−controlled sequences of Neoproterozoic age.

Hurtgen participated in field work and sampling in Namibia and Svalbard. These data are being prepared for publication by Halverson and Hurtgen.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Environment of Prebiotic Earth and the Origin of Life: Experimental Approach − Schoonen

Lead Team:	***Pennsylvania State University***
Project Title:	***Environment of Prebiotic Earth and the Origin of Life: Experimental Approach − Schoonen***
Project Investigator:	***Martin Schoonen***

Project Progress

During this period, we have continued our research on the stability of formate at elevated temperatures and in the presence of mineral surfaces. An autoclave system with a closed−loop sampling system is now operational. We are re−investigating the stability of formate as a function of temperature to address questions raised during the review of an earlier manuscript. Secondly, we have completed a theoretical modeling study of the thermodynamic driving force for dinitrogen reduction as a function of mineral−assemblage and temperature. A new direction of research that has been added to our effort is to investigate the effect of pyrite on the stability of biomolecules. In an earlier reporting period, we discovered that exposure of pyrite to water leads to the formation of hydrogen peroxide and OH radical, which was hitherto unknown. Illumination with visible light enhances the effect. Given the ubiquitous presence of pyrite on early Earth, its reaction with water may have been the dominant mechanism for the formation of OH radicals during the emergence of life. Our experimental work thus far has been focussed on the stability of ribonucleic acid (RNA). RNA decomposes rapidly in the presence of pyrite; however, encapsulation of RNA with lipid slows down the reaction. Alternatively, the decomposition reaction can be inhibited by coating pyrite with lipid. The results suggest a possible protective mechanism that could have been an important prerequisite for the origin of life.

Highlights

- Pyrite−induced OH radical formation may have placed an important constraint on the stability of biomolecules, such as RNA, on early Earth. Protective mechanisms, such as encapsulation of biomolecules by lipids, may have been a prerequisite to escape decomposition via OH radical attack.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Enzymes of Ancient Metabolic Pathways

Lead Team:	***Pennsylvania State University***
Project Title:	***Enzymes of Ancient Metabolic Pathways***
Project Investigator:	***James Ferry***

Project Progress

The protein (AfpA, archaeoflavoprotein) encoded by AF1518 in the genome of *Archeoglobus fulgidus* was produced in *Escherichia coli* and characterized. AfpA was found to be a homodimer with a native molecular mass of 43 kDa containing two noncovalently bound FMN. Cell extract of A. fulgidus catalyzed the CO−dependent reduction of AfpA that was stimulated by the addition of ferredoxin. Ferredoxin was found to be a direct electron donor to AfpA, whereas rubredoxin was unable to substitute. Neither NADH + H+ nor NADPH + H+ was an electron donor. Ferricyanide, 2,6−dichlorophenolindophenol, several quinones, ferric citrate, bovine cytochrome c, and O_2 accepted electrons from reduced AfpA (AfpAred), whereas coenzyme F420 did not. The FMN in AfpAred was fully oxidized by all the quinones tested with a 1:1 ratio. No evidence for a flavin semiquinone was observed in absorbence spectra of AfpAred during oxidation by the electron acceptors. The rate of cytochrome c reduction was enhanced in the presence of O_2, suggesting that superoxide is a product of the interaction of AfpAred with O_2. Sequence analyses of AfpA homologs identified a strictly conserved FMN binding motif unique to the homo−oligomeric flavin−containing cysteine decarboxylase (HFCD) superfamily. A search of the databases suggests that AfpA is the prototype of a previously unrecognized family unique to the Archaea domain for which the name archaeoflavoprotein is proposed. The genomes of several diverse Archaea contained afpA homologs clustered with open reading frames annotated as putative homologs of genes encoding proteins involved in the oxidative stress response of anaerobes. In summary, the results demonstrate that AF1518 encodes the prototype of a previously unrecognized family of FMN−containing flavoproteins identified only in A. fulgidus and methane−producing species from the Archaea domain.

Highlights

- A novel flavoprotein family (archaeoflavoprotein) has been discovered that is unique to the Archaea domain of life.

Roadmap Objectives

- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Evolution of Atmospheric O2, Climate and the Terrestrial Biosphere − Capo

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O2, Climate and the Terrestrial Biosphere − Capo***
Project Investigator:	***Rosemary Capo***

Project Progress

Preserved ancient soils (paleosols) record the interaction of Earth's lithosphere with its atmosphere and hydrosphere, thus providing one of the few records of ancient atmospheric composition and Precambrian paleoclimate. Capo and her Ph.D. student Sherry Stafford, in collaboration with J. Marmo, are completing their investigation of the Paleoproterozoic Hokkalampi paleosol of eastern Finland, which has the potential to provide constraints on the rise of oxygen in the Earth's early atmosphere. Their Sm−Nd work demonstrates that the rare Earth elements (REE), important pedogenic and atmospheric tracers, have not been substantially remobilized since pedogenesis at ~2.4 Ga, despite obvious resetting of the Rb−Sr system around 1.8 Ga, and provide the basis for evaluating mobility and "pedogenic fidelity" of selected geochemical tracers. Stafford has begun initial work on an iron isotope investigation of the paleosol to identify possible biologic and/or pedogenic mass fractionation processes.

An important part of these investigations is evaluating modern analogues of ancient geochemical systems, providing a framework for interpreting the geologic record. In ongoing work centered on the formation of soil carbonate, significant variations in rare Earth element abundance and fractionation were observed in pedogenic carbonate from a single profile in the U.S. desert southwest. The preliminary results indicate a complicated interplay between different sources of REE to the profile (atmospheric and weathering of parent material), and mobility of REE within the profile. These processes must be understood in order to interpret REE variations in Precambrian soils. In another modern analogue investigation, iron isotope ratios are being measured in sedimentary pyrite from different depositional environments. Ultimately, the isotopic variations could be correlated with specific biological processes that would then be extended to the Precambrian Earth.

Highlights

- Isotopic investigations of paleosols indicate that the Sm−Nd system

can be used to evaluate the pedogenic mobilization and possible later remobilization of geochemical tracers in ancient soil profiles.

- Soil carbonate is a significant repository for REE, an important paleoatmospheric tracer, and must be considered in working out the REE budgets of ancient soil profiles formed under arid conditions.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Cross Team Collaborations

Capo continues her collaboration with A. D. Anbar (University of Rochester, Harvard and JPL Teams) on iron isotope investigations of sedimentary and pedogenic environments. The collaboration includes scientific as well as technical exchanges. She is also a member of the NAI Mission to Early Earth (MtEE) Focus Group.

Project Report: Evolution of atmospheric O2, climate, and biosphere − K. Freeman

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of atmospheric O2, climate, and biosphere − K. Freeman***
Project Investigator:	***Katherine Freeman***

Project Progress

Excellent progress was made on the study of Late Archean kerogens and biomarkers. (This work is largely funded by the National Science Foundation (NSF), with NAI support for personnel.) The integration of a rich molecular and isotopic data set is under way, with initial results documenting shallow−water facies as ancient "oxygen oases" (see highlights below). Additional work on molecular and isotopic biomarker studies as "life signatures" for ancient microorganisms continues. We have established trimethyl and tetramethyl benzenes as markers for green sulfur bacteria (see below). In addition, the research team is using molecular analyses of ether−linked lipids from archea to study the distribution of Chrenarchaeota in fresh to hypersaline salinities. We are also progressing on growing a methanogen that consumes small amounts of methane. We are testing and expanding the growth conditions for this organism in order to understand ecological constraints on its ability and mechanism(s) for growth.

Highlights

- Molecular analyses reveal diverse life in the Late Archean. We have evidence for all three domains existing at that time.

- Isotopic and stratigraphic data reveal ecological differences associated with lithofacies. Shallower facies were more oxygenated, and this is reflected in the recorded microbial processes. Deeper waters were largely anoxic, although we have evidence for redox cycling between elemental sulfur and sulfide.

- Isotopically enriched tetramethyl− and trimethylbenzene released via pyrolysis can be linked to inputs from green sulfur bacteria in ancient (Cretaceous) lake deposits. This extends the available biomarkers for this source of organic matter; however, isotopic analyses are required for confirmation.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MSL	instrument development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

K. Freeman is a member of a team of investigators who are preparing a proposal for a science package for MSL. The teams efforts are directed by Hunter Waite at the University of Michigan. Freeman is involved in the development of analytical strategies for analyses of carbon−containing materials; she is also involved in the development of evaluation criteria.

Cross Team Collaborations

Freeman's group is collaborating with Roger Summons (MIT) and with Doug Rumble (Carnegie Inst. of Washington, Geophysical Lab.). Collaborations include molecular analyses of extracts from late−Archean kerogens, and multiple S isotope analyses from the same samples.

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Project Report: Evolution of atmospheric O2, climate, and biosphere − Kump

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of atmospheric O2, climate, and biosphere − Kump***
Project Investigator:	***Lee Kump***

Project Progress

Ellen Herman (MS Student) has received some support from the Pennsylvania State Astrobiology Research Center (PSARC) to develop a numerical model of the microbial mat. The model is used to evaluate how microbial mats may have differed during Archean and Proterozoic times, when the overlying water may have been O_2 poor and/or sulfide rich. Her thesis is now completed and will be published soon.

I've collaborated with Bill Seyfried (U. Minn.) on the response of seafloor hydrothermal systems to depressurization during sea−level lowstands. That work is in review with Nature.

Roberta Hotinski (NSF), Michael Arthur (PSU) and I have concluded a study of the Paleoproterozoic biological pump in the Northwest Territories of Canada. The paper is in review in the Bulletin of the Geological Society of America.

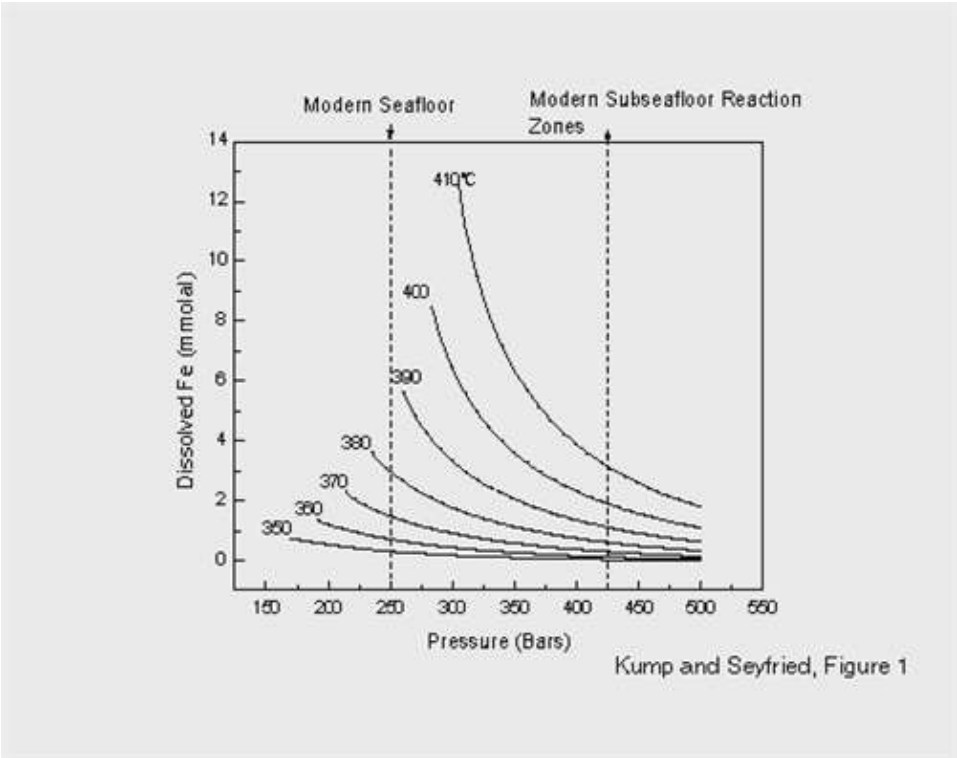

Figure 1. *Effect of pressure and temperature on dissolved Fe in 3.2% NaCl (seawater) coexisting with basalt and its alteration products. Termination of isotherms at low pressure defines a region very near the two−phase boundary of seawater.*

Kump and Seyfried (Fig. 2)

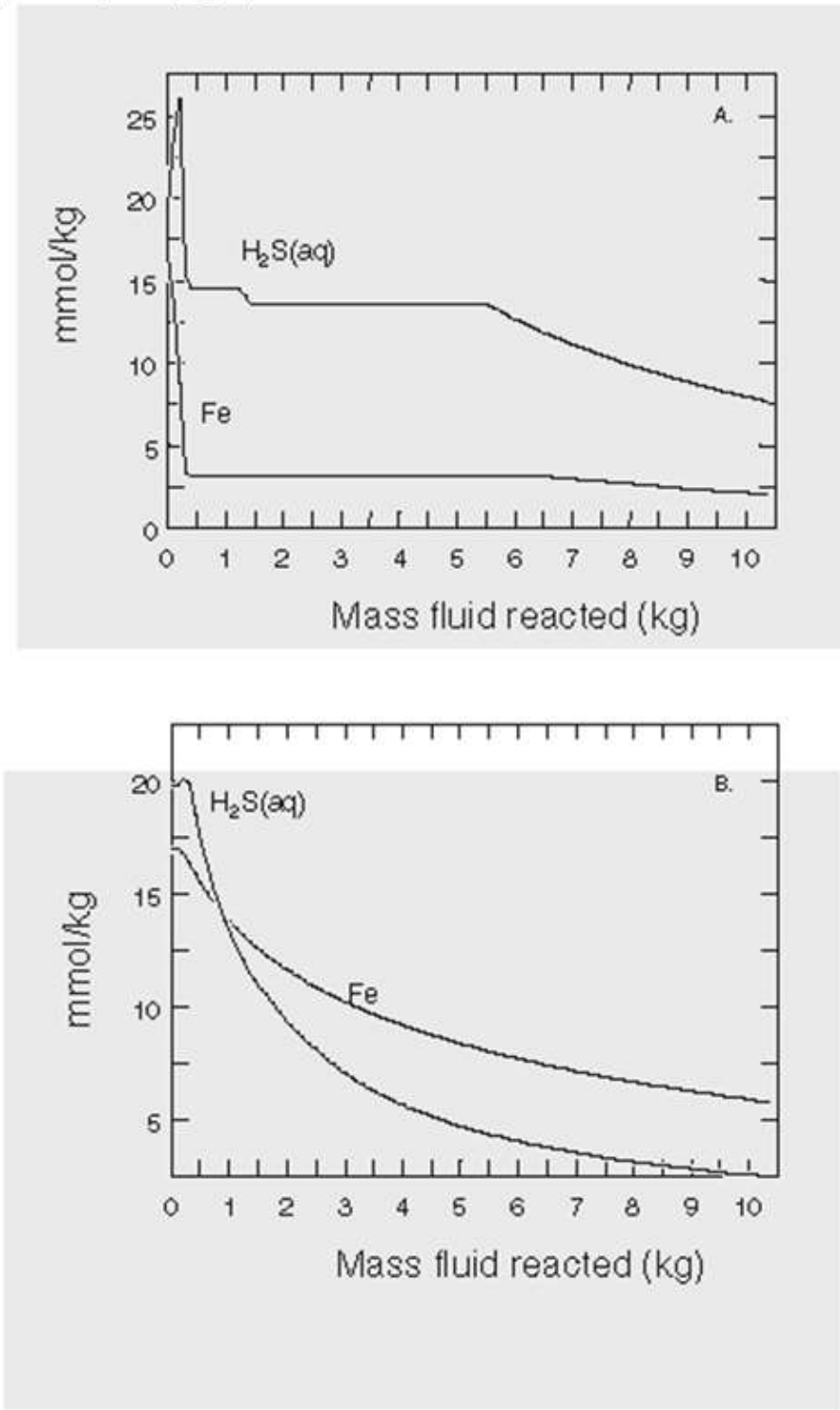

Figure 2. *Reaction path model depicting the effect of dissolved sulfate in a seawater source fluid on dissolved Fe and H_2S(aq) concentrations in solutions coexisting with basalt and its alteration products at 400°C, 500 bars.*

Simulations involve reaction of 1 kg of basalt (MORB) with incrementally greater amounts of sulfate bearing (28 mmol/kg) (A) and sulfate−free source fluid (B) to a final mass of fluid of 10 kg.

Highlights

- Oxygen levels in Archean cyanobacterial mats may have exceeded modern atmospheric saturation values by a factor of 2−3, as modern mats do during afternoon hours, based on modeling experiments performed at Penn State. This conclusion is independent of the oxygen or sulfide content of the overlying water.

- Pelagic marine organisms in the Paleoproterozoic (1.8 billion years ago) apparently were modifying the nutrient and carbon chemistry of the ocean in much the same way and to a similar extent as modern organisms do. The evidence for this is a substantial vertical gradient in the carbon isotopic composition of the Paleoproterozoic Ocean, preserved in marine carbonates.

- The occurrence of banded iron formations in Neoproterozoic "Snowball Earth" deposits may have been the result of high iron fluxes from midocean ridges. The ridge iron flux would have been enhanced because 1) the Fe concentration of these fluids would be increased by the physicochemical effects of ridge depressurization associated with sea−level drawdown (Figure 1), and 2) low sulfate concentrations in the Neoproterozoic ocean would have resulted in more oxidizing, low sulfide, iron−rich hydrothermal fluids (Figure 2).

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Field investigation of a chemocline	
Start Date: multiple trips 2002	***End Date:*** 2003
Continent: North America	***Country:*** USA
State/Province: New York	***Nearest City/Town:***
Latitude: 43°03'	***Longitude:*** 75°58'
Name of site(cave, mine, e.g.): Fayetteville Green Lake	***Keywords:*** microbial biogeochemistry, sulfur cycle, nitrogen cycle, [PLS VERIFY SPELLING] meromictic lakes,

	cyanobacteria, sulfur bacteria
Description of Work: Water column profiling of dissolved oxygen, hydrogen sulfide, temperature, conductivity, sulfur and carbon isotopic composition, PAR light, turbidity; samples collected for trace metal analysis, culture work, identification of protozoan and bacterial communities by microscopy and PCR amplification	
Members Involved: Lee Kump	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
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Project Report: Evolution of atmospheric O2, climate, and biosphere − Ohmoto

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of atmospheric O2, climate, and biosphere − Ohmoto***
Project Investigator:	***Hiroshi Ohmoto***

Project Progress

Our research has focused on (i) the chemistry of atmosphere and oceans and (ii) the nature of marine and terrestrial ecosystems on early Earth, especially before ~2.0 Ga (billion years ago). The research goals have been pursued by the following four approaches: (1) field investigations of geological environments (tectonics, paleogeographical, igneous, hydrothermal) for the accumulation of some key geologic formations ~3.5 − ~2.0 Ga in age; (2) biogeochemical investigations on selected rock samples from (1); (3) laboratory experiments on mineral−gas−solution experiments; and (4) thermodynamics and kinetic analyses of mineral−gas−solution reactions. Investigations in (3) and (4) have been carried out to understand the geochemical data from (2). Important achievements have been made in all phases of research, including the following:

(1). We have initiated the Archean Biosphere Drilling Project (ABDP), an international collaborating research project involving four organizations (Kagoshima University, The University of Western Australia, Geological Survey of Western Australia, and Pennsylvania State Astrobiology Research Center (PSARC), representing the NAI). The ABDP aims to: (i) recover through deep drilling "fresh" Archean−age (>2.5 Ga) rocks that were least affected by alteration since their formation, such as by metamorphism, hydrothermal mineralization, and modern weathering; and (ii) use these rocks for detailed and systematic biogeochemical investigations. We selected six drilling sites in the Pilbara district, Western Australia, during fieldwork in the summer of 2002, and began drilling in June 2003. The drilling has already produced unequivocal evidence that the abundant hematite (ferric oxide) crystals in the 3.46 Ga Marble Bar chert/jasper sequence were not formed by the modern oxidation of ferrous−rich carbonate (siderite) as postulated by many previous investigators, but by the mixing of Fe^{2+}−bearing submarine hydrothermal fluids and oxygenated local seawater while the rocks were accumulating on the ocean floor. This is important evidence suggesting the oceans and atmosphere were already oxygenated 3.46 Ga ago. The ABDP has also recovered a large amount of black shales, containing remnants of

microbes that lived in the Archean oceans.

(2). Our mineralogical and geochemical investigations (e.g., C, N and S isotopes; rare Earth elements) on Archean shales and banded iron formations from the Abitibi district, Canada, the Pilbara−Hamersley district, Australia, and other places have revealed that the redox structure of the Archean oceans was essentially identical to that of modern oceans: the oceans were globally oxic, but locally developed anoxic basins sustained complexed ecosystems. Distinct differences were found in the carbon isotopic characteristics between the microbial communities in submarine hydrothermal environments and those in normal oceans.

(3). Siderite ($FeCO_3$) is a major constituent of carbonate−rich rocks and banded iron formations older than ~1.8 Ga. Our analyses on the formational conditions for siderite based on thermodynamic data and carbon isotope data suggest the CO_2 level of the Archean atmosphere was at least 100 times greater than today, implying that CO_2, rather than methane, was the major green−house gas in the Archean, as well as in later geologic time.

Highlights

- The Archean Biosphere Drilling Project (ABDP), a new initiative of the NAI to explore the Earth's earliest biosphere, has begun in the Pilbara district, Western Australia. The drilling has already recovered "fresh" (modern−weathering free) rocks containing abundant remnants of microbial communities in the oceans and lakes 3.46−2.7 billion years ago.

- The abundance of siderite in pre−1.8 Ga rock formations suggests CO_2, rather than methane, has been the main greenhouse gas through geologic history.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Site Selections for the Archean Biosphere Drilling Project

Start Date: August 2, 2002	***End Date:*** August 20, 2002
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Port Hedland, Marble Bar
Latitude: S20.5° − 21.5°	***Longitude:*** E117.5° − 120.5°
Name of site(cave, mine, e.g.):	***Keywords:*** Archean biosphere, Archea oceans, Archean jaspers, Archean black shales
Description of Work: Geologic investigations of seven areas which were previously selected as potential sites for the Archean Biosphere Drilling Project, and planning of the logistics of drilling operations for the summer 2003.	
Members Involved: Hiroshi Ohmoto	

Field Trip Name: The Archean Biosphere Drilling Project	
Start Date: June 2, 2003	***End Date:*** July 15, 2003
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Port Hedland, Marble Bar
Latitude: S20.5° − 21.5°	***Longitude:*** E117.5° − 120.5°
Name of site(cave, mine, e.g.):	***Keywords:*** Archean biosphere, Archean oceans, Archean jaspers, Archean black shales
Description of Work: Supervision of drilling, core logging, and surface geologic surveys at six sites	
Members Involved: Hiroshi Ohmoto	

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Evolution of Atmospheric O2, Climate, and the Terrestrial Biosphere − Stewart

Lead Team:	***Pennsylvania State University***
Project Title:	***Evolution of Atmospheric O2, Climate, and the Terrestrial Biosphere − Stewart***
Project Investigator:	***Brian Stewart***

Project Progress

Geochemical Tracers in Earth's Oceans

Precambrian marine sediments record important information about the geochemical and redox evolution of the Earth's earliest oceans. In collaborative work with former Pennsylvania State Astrobiology Research Center (PSARC) postdoc Michael Bau (now at International University Bremen), we find that the rare Earth element (REE) patterns in ~2.6 Ga carbonate from the Hamersley Basin, western Australia, are remarkably close to those of the present−day oceans, and that Nd isotopes of shallow carbonate are similar to those of the deeper banded iron formations. However, the Sm−Nd system shows evidence of resetting at 2.1 Ga from a regional metamorphic event, so ancient marine carbonate REE patterns must be interpreted with great care. In a parallel study of a present−day terrestrial drainage basin (Owens River system, eastern California), we find that coexisting clastic and chemical sediments derived from the eastern Sierra Nevada range show a small but systematic offset in Nd isotope composition. In this case, selective weathering of different minerals or parent lithologies appears to bias the Nd isotope record preserved in carbonate. This is consistent with our previous Sr isotope work, where we found that the Sr isotopic composition of the dissolved load is heavily weighted toward hydrothermal systems and acid generation by pyrite oxidation. In another study of REE behavior in organic−rich sediments (Permian coals), we find evidence for REE remobilization and incorporation in the organic matrix, although clastic mineral matter exerts the primary control on REE patterns.

Weathering in the Terrestrial Environment

Paleosols (ancient weathering profiles) preserve a record of Earth's early atmospheric and climatic conditions. A neodymium isotopic investigation of the Archean Steep Rock paleosol, Canada, has allowed us the opportunity to quantify possible alteration effects on weathering REE patterns. We find that the REE patterns are substantially preserved at this ~3 Ga paleosol, despite

later metamorphism and K−metasomatism. Graduate student K. Walden is currently applying this technique to the 2.6−2.4 Ga Kalkkloof paleosol, South Africa, which shows significant cerium anomalies (indicating possibly oxidizing conditions).

Highlights

- Coexisting clastic and chemical sediments in a Quaternary lacustrine basin show a systematic offset in neodymium isotope composition, demonstrating care must be taken in interpreting the Precambrian record preserved in chemical sediments (carbonates and banded iron formations).

- A model has been developed based on the Sm−Nd isotope system to evaluate the mobility and post−pedogenic redistribution of REE in paleosols. The REE distributions in the ~3 Ga Steep Rock paleosol, Canada, appear to reflect pedogenic processes.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
3	In situ measurement of isotope biosignatures	Science collaborator
3	In situ laser ablation analysis of planetary surfaces	Team member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Stewart is a collaborator and co−investigator, respectively, of pending ASTID and MIDP proposals to develop instruments suitable for elemental and isotopic

analysis of planetary surfaces. These instruments are designed to use geochemical biosignatures commonly employed in the study of the ancient Earth record to search for evidence of life on other planets, especially Mars.

Cross Team Collaborations

Stewart is a member of the NAI Mission to Early Earth (MtEE) Focus Group, and continues collaboration with A. D. Anbar (University of Rochester, Harvard and JPL NAI Teams) on techniques for Fe isotope measurement.

NASA ASTROBIOLOGY INSTITUTE
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Project Report: GEOPULSE

Lead Team:	***Pennsylvania State University***
Project Title:	***GEOPULSE***
Project Investigators:	***Christopher House , Katherine Freeman , Susan Brantley***

Project Progress

This last year saw significant progress on several related projects. We published a paper on the carbon isotopic fractionation in Prokaryotes. We also had several publications related to Leg 201 of the ocean drilling program related to the subsurface microbial ecosystem. Finally, we have papers in press in Geobiology and Astrobiology. The former paper uses genomics to deduce the most geologically plausible early metabolism for the Archaea. We have also continued to make great progress in studying trace metals in microbial communities, exploring tungsten extraction by Pyrobaculum aerophilum, exploring trace anaerobic methane oxidation in methanogens, observing oxygen tolerance by Methanosarcina, and creating a gas chromatography and mass spectroscopy (GC−MS) method for analyzing the carbon isotopic composition of ribonucleic acid (RNA).

Highlights

- Using whole genomic analysis, we have deduced that sulfur reduction is the most geologically plausible for the base of the Archaea.
- We have observed surprisingly high oxygen tolerance in Methanosarcina acetevorans, allowing growth at about 1% oxygen.
- We have found that Archaeoglobus does not oxidize methane in spite of the similarity of Archaeoglobus to ANME−1 and ANME−2.
- We have found that there are conditions that increase trace methane oxidation by methanogens, providing some insight into how anaerobic methane oxidation occurs.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

Bill Schopf (UCLA) collaborated on our recent paper looking at carbon isotopic fractionation.

House collaborated with Steve D'Hondt (URI), Kai Hinrichs (Woods Hole), David Smith (URI), Art Spivack (URI), and Andreas Teske (UNC) on Leg 201 of the ocean drilling program.

Bruce Runnegar (UCLA) and Sorel T. Fitz−Gibbon (UCLA) collaborated on our recent research using genomes to look at ancient archaeal metabolism. The paper is in press.

House collaborated with Vicki Orphan and Kai Hinrichs on another paper relating to microbial methane oxidation near Eel River vent. The paper has been submitted to Chemical Geology.

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Isolation of psychrophilic microorganisms

Lead Team:	***Pennsylvania State University***
Project Title:	***Isolation of psychrophilic microorganisms***
Project Investigator:	***Jean Brenchley***

Project Progress

We are examining the diversity of psychrophilic (cold−loving) microorganisms as models for the possible origin, evolution, and survival of organisms from other cold, non−terrestrial sources. Of specific interest to NASA is our analysis of the microbial diversity of an ice core taken from a > 120,000 year old Greenland glacier ice core sample. Epifluorescence microscopy showed that the ice sample contained over 60 million cells/ml. We inoculated a sterile, melted sample into anaerobic media and incubated cultures for several months at minus 2°C. The microorganisms in this sample were characterized in two ways. First, deoxyribonucleic acid (DNA) was extracted from the community and the ribosomal ribonucleic acid (rRNA) gene polymerase−chain−reaction (PCR) amplified. Approximately 60 bacterial inserts were screened by restriction endonuclease analysis and grouped into 27 unique types, and 24 sequences were compared phylogenetically. These sequences represented a wide physiological diversity, including Gram positive anaerobic rods and cocci and alpha, beta, and gamma Proteobacteria. In our second approach, we cultivated nearly 800 hundred aerobic isolates, many with pigmented and different colony morphologies. We amplified, cloned, and aligned rRNA gene sequences for 28 of these isolates. Phylogenetic analyses showed representatives from many different physiological groups, many of which had not been represented in the clone library. Several conclusions derive from these results. A rich, viable, microbial diversity was preserved in the >120,000 year old ice core. Both the extraction of DNA and isolation of organisms are needed to provide a comprehensive view of the microbial diversity. Many rRNA genes differed from known sequences and may represent the discovery of novel genera or families. Anaerobic incubation may aid the recovery of isolates that cannot grow when taken directly from the ice core sample. Further studies are important for understanding the possible existence, survival, and recovery of organisms in other extremely cold environments.

Highlights

- We have demonstrated that a wide, and perhaps surprising, diversity of

organisms have survived entrapment in a Greenland glacier for over 120,000 years and have grouped and analyzed nearly 800 isolates into taxonomic and phylogenetic categories.

- We have found that anaerobic incubation may facilitate the recovery of stressed organisms such as those in the ice core and will examine this possibility to determine if it aids in the isolation of organisms that had been considered uncultivable.

Roadmap Objectives

- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Microbe−mineral interactions

Lead Team:	***Pennsylvania State University***
Project Title:	***Microbe−mineral interactions***
Project Investigator:	***Susan Brantley***

Project Progress

Fe, Mn, Zn, Ni, Cu, Co, and Mo are extremely low in abundance in natural waters, but each of these metals is used in bacterial enzymes, coenzymes, and cofactors. While it is well known that microbes secrete siderophores to extract Fe from their environment, it is not understood how these siderophores attack minerals to provide the FeIII, nor is it understood how bacteria extract other micronutrients. In previously reported work, we have shown that microbes can mobilize Mo (Azotobacter vinelandii), Ni (Methanobacterium thermoautotrophicum), and Cu (Bacillus mycoides) from silicates.

Mineral dissolution experiments with a siderophore−producing soil bacterium (closely related to *Bacillus mycoides*) from Gore Mountain, NY, show that this microbe enhances Fe release from goethite. Dissolved Fe released from goethite in the presence of the bacillus yields ^{56}Fe = −1.6‰. The Fe isotope fractionation is attributed to several factors: isotopic equilibration between Fe(II) and Fe(III) in solution followed by uptake of Fe(III) by bacteria; adsorption of isotopically heavy Fe(II) on goethite surfaces. We also have completed adsorption experiments abiotically to show that adsorption of Fe(II) is an important mechanism in the fractionation of Fe isotopes.

Last year we documented that Mo that is taken up by azotobacter into cell mass is isotopically light compared to the Mo source material (an Fe−containing silicate). The Mo released to solution in the presence of azotobacter is not isotopically fractionated. This documents that fractionation occurs during cellular uptake, but not during extraction from the host material. Mo extraction has now been shown to be related to the production of aminochelin, a siderophore with high affinity for Mo known to be produced by azotobacter.

We continue to search to identify the ligand responsible for extraction of Ni from an Fe silicate glass in the presence of a methanogen. We have documented for the first time that supernatants from the methanogen cultures are also capable of extraction of Ni. We are now working fulltime on identification of the putative Ni ligand.

Anabaena, a cyanobacterium, was grown with fluorapatite as sole phosphorous (P−) source for 7 days. Cell growth was compared with cultures that contained a dissolved P−source, as well as a P−depleted control. An inorganic control, apatite + medium, was also run without inoculation. At the end of the experiment, fluorapatite grains from the various treatments were compared using a scanning electron micrograph (SEM). Enhanced etching of the apatite in the presence of the cyanobacterium as compared to the abiotic control, despite the same pH in each experiment, documents that either i) extracellular ligands or polymers secreted by the Anabaena attack the mineral surface or ii) uptake of P by the Anabaena changes the affinity of the reaction and enhances apatite dissolution. Dissolution of apatite in spent supernatant (cells filtered out) is not enhanced relative to medium alone, contrary to our earlier observations. The ability of microorganisms to change the affinity of reacting solutions may be an important characteristic that has generally been ignored.

Very preliminary results have been collected investigating the isotopes of Cu related to bacterial chalcopyrite and chalcocite oxidation. This work is with Joaquin Ruiz and Ryan Mathur.

We have exciting new results from work with biochemists Ming Tien and Shane Ruebush of Penn State, where we are working on isolating the enzymes responsible for iron reduction by dissimilatory iron reduction. Tien and Ruebush, in collaboration with Brantley and Icopino, have shown reduction in vitro of goethite, birnessite, hematite, and pyrolusite. These are the first known mineral reductions in vitro.

Highlights

- Nitrogen fixing bacteria may secrete molybdenum complexing ligands to solution in order to extract Mo for nitrogenase: for example, Azotobacter vinelandii secretes aminochelin when grown in Mo deficient but Fe replete conditions.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Cross Team Collaborations

We are working actively with Dr. Ariel Anbar of the Univ of Rochester on the measurement of Fe and Mo isotopes. Drs. Gary Icopini and Towhid Hasan both traveled to Rochester to participate in sample preparation and isotope measurement.

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Project Report: Modeling early atmospheric composition and climate

Lead Team:	***Pennsylvania State University***
Project Title:	***Modeling early atmospheric composition and climate***
Project Investigator:	***James Kasting***

Project Progress

We have been working on two separate, but related, projects. The first is concerned with predicting the concentration and climatic impact of methane in Earth's early atmosphere. Work performed by former graduate student Alex Pavlov and colleagues Matt Hurtgen and Mike Arthur here at Penn State has shown that methane concentrations could have been high during the Mid−Proterozoic, as well as during the Archean. This could explain Mid−Proterozoic warmth and could provide a trigger for Neoproterozoic Snowball Earth events if methane levels were to suddenly decline near the end of this period. Current work by graduate student Pushker Kharecha, in collaboration with biologist Janet Siefert at Rice, is focused on estimating methane fluxes from an anaerobic Archean biosphere.

Our other major project has been a collaboration with Vikki Meadow's VPL Astrobiology group. Former student Kara Krelove and current postdoc Antigona Segura have run coupled photochemical−climate simulations of Earth−like planets with various amounts of O_2 in their atmospheres circling different types of stars (F2V, G2V, and K2V). Vikki and her colleagues have produced simulated visible and thermal−infrared (IR) spectra of these atmospheres. The goal is to build up a library of spectra of possible Earth−like planets for future use in interpreting data from NASA's proposed Terrestrial Planet Finder (TPF) mission. A second goal is to produce estimates of surface ultraviolet (UV) fluxes on such planets and determine what constraints these might provide on biological evolution.

Highlights

- We have shown that enhanced methane concentrations could provide a plausible explanation for the extended warmth of the Mid−Proterozoic Era, 2.2−0.8 Ga.

- We have shown that ozone and methane might be observed simultaneously in a Mid−Proterozoic−type terrestrial planet atmosphere. The simultaneous presence of O_2 (or O_3) and reduced

gases is considered the firmest remote evidence for extraterrestrial life.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
0	Terrestrial Planet Finder	Former science team member. We are doing background research for this project.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Our work in modeling planetary atmospheres and calculating simulated spectra thereof could eventually be useful in analyzing TPF (Terrestrial Planet Finder) data. We are trying to determine what are the best bioindicator species and whether they could be observed in different types of atmospheres.

Cross Team Collaborations

See above. Task 2 of our research is a direct collaboration with Vikki Meadows' VPL Astrobiology group. We are simulating the atmospheres of Earth−like planets (with varying O_2) around different stars and calculating simulated spectra for use by NASA's TPF project.

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Project Report: Studies of Hydrogen Cyanide Chemistry

Lead Team:	***Pennsylvania State University***
Project Title:	***Studies of Hydrogen Cyanide Chemistry***
Project Investigator:	***Robert Minard***

Project Progress

The role of hydrogen cyanide polymer chemistry in the origin of life has provoked much speculation. In spite of extensive efforts by many groups, a satisfactory understanding of this polymer's structure and mechanism of formation still eludes us. Our studies involve the synthesis of HCN polymers under a variety of conditions and the application of modern powerful analytical methods for structure elucidation. Several significant results have been obtained in the last year.

Synthesis of $H^{13}C^{15}N$ polymers and solids NMR analysis.

Despite the profound implications for prebiotic chemistry raised by these materials, full characterization of these intractable heteropolymers has not yet been achieved. As a non−degradative analysis tool, Solid−State Nuclear Magnetic Resonance (SS−NMR) lends itself well to the structural investigation of such complex materials. For this work, $^{13}C/^{15}N$ labeled (30%) samples of the HCN heteropolymer were prepared and analyzed before and after treatment with H_2O using $^{1}H/^{13}C$ and $^{1}H/^{15}N$ Cross−Polarization (CP), $^{1}H/^{13}C/^{15}N$ Double Cross Polarization (DCP) and single resonance SS−NMR experiments. Spectral assignment of ^{13}C and ^{15}N SS−NMR data verifies that (HCN)x exists as a complex heteropolymer with a wide range of functionality and that a high concentration of N heteroaromatics is present. The initially formed sample is high in DAMN, D in Figure 1, which is removed upon the contact with water. Amide− and acid−like functionalities are seen to increase upon water treatment as well, consistent with the polyamidine model, B (Minard et al. 1975). Little signal attenuation is seen for the ^{13}C DCP result (relative to CP) on the native sample, and this result may suggest that the structure C seen in Figure 1 is not present to a significant extent. In contrast, ^{15}N DCP spectra of the native sample show more prevalent signal attenuation (relative to CP) and lend support for the structures A and E.

A Test for Polyaminomalononitrile as an Intermediate in HCN Polymerization

In 1966, Matthews proposed that HCN polymerizes through a series of reactions depicted in Figure 2, leading to the direct formation of "primordial

proteins." In order to test the validity of Matthews' pathway, the presence of the intermediate polyaminomalononitrile or poly−a−cyanoamidine, 3, is examined by looking for its reaction with acrylonitrile, an experiment suggested by Eschenmoser. Increased amounts of glutamic acid are observed in the final hydrolysis products of HCN polymer treated with base and acrylonitrile, presumably via the Michael addition reaction shown. Likewise, addition of formaldehyde to HCN polymer leads to the formation of significant quantities of the amino acid serine in its hydrolysis products.

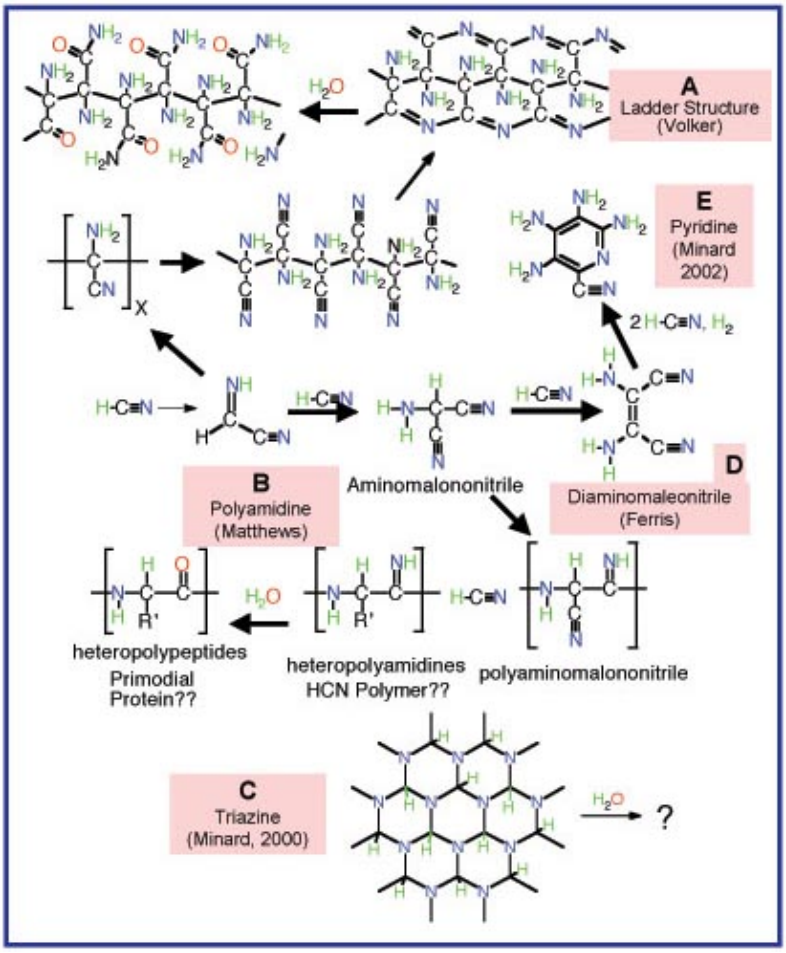

Figure 1 *Hypotheses for the structure of HCN polymer, its mechanism of formation, and its reaction products with water.*

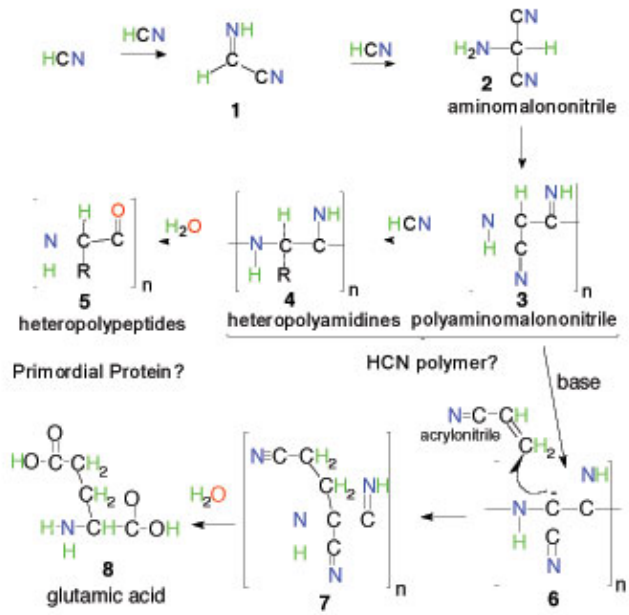

Figure 2 - Matthews' hypothetical model for the formation and structure of HCN polymer (polyamidines **3** and **4**) its reaction with water to yield heteropolypeptides, **5**. Reaction of the anionic species **6**, derived from **3** in the presence of base, with acrylonitrile would yield **7** which could be hydrolyzed to glutamic acid, **8**.

Figure 2. *Matthews' hypothetical model for the formation and structure of HCN polymer (polyamidines 3 and 4) its reaction with water to yield heteropolypeptides, 5, Reaction of the anionic species 6, derived from 3 in the presence of base, with acrylonitrile would yield 7 which could be hydrolyzed to glutamic acid, 8.*

References:

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Highlights

- HCN polymer structural model provides a mechanism for the formation of heteropolypeptides on the primitive Earth.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

Cross Team Collaborations

I prepared a sample of 98% C−13/N−15 enriched HCN polymer for Simon Platts at Carnegie Institution for use in a study to examine the possibility of asymmetric induction in extraction of amino acids from macromolecular materials like those found in meteorites. Antonio Salgado Serrano, who works at the new 'Centro de Astrobiologi-a' (CAB) in Madrid, Spain, working with Bob Hazen at Carnegie are also involved in this project.

I have also prepared HCN polymer samples and sent them to Nicolas Fray at the University of Paris; he is investigating the sources of elevated levels of HCN in the comas of comets. This is part of the work of the European Space Agency (ESA) (Francois Raulin et al.) in preparation for missions such as Rosetta.

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Project Report: The Late Ordovician glaciation and mass extinction: environmental causes and evolutionary consequences − Mark Patzkowsky

Lead Team:	***Pennsylvania State University***
Project Title:	***The Late Ordovician glaciation and mass extinction: environmental causes and evolutionary consequences − Mark Patzkowsky***
Project Investigator:	***Mark Patzkowsky***

Project Progress

In the last year, our group made significant progress in understanding the environmental causes of the Late Ordovician glaciation and in understanding the evolutionary consequences of the Late Ordovician mass extinction. Using atmosphere and ocean general circulation models and a dynamic ice−sheet model, we found that pCO_2 must have been no higher than 8 times pre−industrial atmospheric levels in order to initiate ice−sheet growth in the Late Ordovician. Furthermore, paleogeographic changes, sea level, and poleward ocean heat transport played an important role in priming the Late Ordovician climate system for glaciation. Most significantly, we found that when obliquity forcing was added to the dynamic ice−sheet model to simulate Late Ordovician glaciation, pCO_2 must drop to 8 times pre−industrial levels to initiate glaciation, but then CO_2 must rise to above 10 times pre−industrial levels in order to melt the ice sheets. Such hysteresis effects may have played an important role in other glaciations in Earth history, such as the Snowball Earth. In investigating geographic variability in the Late Ordovician mass extinction, we performed a sample−standardized analysis (diversity estimates based on equal sized samples) of Late Ordovician through the Early Silurian diversity for the Laurentian paleocontinent. We found that diversity on Laurentia rebounded to pre−extinction levels within 5 million years, approximately 10 million years faster than global diversity rebounded. This suggests that the rebounds of regional and global diversity were decoupled following the Late Ordovician mass extinction, but it also raises the question whether sample standardization at the global level would show that global diversity also rebounded to pre−extinction levels in 5 million years.

Highlights

- Ice sheets and orbital forcing introduce nonlinearities to the global climate system that can significantly alter the response to CO_2 and CO_2 thresholds necessary for the initiation and termination of

icesheets.

Roadmap Objectives

- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Fellowships: Pennsylvania State University

There are no Postdoctoral Fellowships for this team.

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EPO: Pennsylvania State University

These are the Education and Public Outreach activities for the Pennsylvania State University.

Space Day 2003 at Penn State

During Space Day 2003 at Penn State, scientists, engineers, and students shared presentations and hands−on activities with over 1200 adults and children as they explored Earth, air, and space research at Penn State, including research on the origin, evolution, distribution, and destiny of life in the universe. Five graduate students associated with the Penn State Astrobiology Research Center participated in the event. The PSARC students collaborated with students from the science education program at Penn State to develop activities and lesson plans that were aligned with the national science education standards and the Pennsylvania Academic Standards for Science and Technology.

Space Day 2003 at Penn State included tours of the Space Shuttle Blake, a 4/10 replica of NASA's Space Shuttle, presentations by former astronaut Dr. Jim Pawelczyk and JPL Solar System Ambassador Ann Schmiedekamp, a How to Access NASA Education booth and Star Lab planetarium tours.

Astrobiology: The Search for Life in the Universe (Magazine)

This color publication provides an overview of the field of Astrobiology written at the high school level. The piece was originally published by Research Penn State magazine in their January 2001 issue and is based on a lecture series that was held at Penn State University in January 2000. The lecture series and the magazine supplement features NASA Astrobiology Institute scientists from Penn State University, The University of Colorado, and Harvard University as well as researchers from the SETI Institute and Rice University. The Penn State Astrobiology Research Center and Pfizer, Inc. provided funding for the publication. The Pennsylvania Space Grant Consortium is distributing the publication to interested educators, students, researchers and others across the country and internationally. PDF and Web versions are also available.

Astrobiology: The Origins and Early Evolution of Life (educator workshop)

This five−day residential workshop for in−service teachers was designed to expose middle and high school science teachers to current thinking about the origin and early evolution of life in a way that they can pass on to their

students. The course combined lectures by several Penn State faculty, hands−on classroom activities, lab tours, and a field trip to a local bog. Classroom activities were drawn from TERC's Educator Resource Guide and draft high school curriculum as well as the SETI Institute's Voyages Through Time curriculum. Classroom activities were facilitated by a graduate student at the Penn State Astrobiology Research Center and by two Pennsylvania teachers who attended the workshop in previous years. Following the workshop, the teachers were added to our existing listserv discussion group to facilitate and track the application of knowledge from the workshop back in the classrooms. The Penn State Astrobiology Research Center and the Pennsylvania Space Grant Consortium provided funding for the workshop. Housing, meals and some travel support were provided. Teachers were charged tuition for two graduate credits from Penn State. The workshop was approved by the Pennsylvania Department of Education for Act 48 Professional Development credits.

Women In Science and Engineering Research (WISER)

Faculty members from the Penn State Astrobiology Research Center participate in this two−semester research internship program, which is sponsored by the Pennsylvania Space Grant Consortium. The program is designed to retain women students in the science and engineering fields by providing first−year students invaluable experience and mentoring at the critical early stages of their undergraduate career. Students begin their research in the spring semester and continue during either the subsequent summer or fall semester. Since the program began in 1994, 393 women students have been hosted by 80 faculty members from all of the science and engineering colleges at Penn State.

Astrobiology Public Lectures and Short Courses − Penn State Astrobiology Research Center

The Penn State Astrobiology Research Center team gave a number of lectures for the general public, civic groups, and for various short courses. This year's presentations were as follows: Dr. Blair Hedges: 1) "A molecular timescale for primate evolution" (University of Michigan National Institutes of Health (NIH) Genetics Lecture Series on Genomics, 5−March−2003); Dr. Chris House: 1) "The Carbon Isotopic Analysis of Individual Modern or Fossil Cells, a Geochemical Approach to Studying Biochemistry." (University of North Carolina at Chapel Hill, Fall 2002); 2"Astrobiology: The search for life in the Universe" (AstroFest at Penn State, 12−13−July−2002); Dr. Lee Kump: 1)"The Rise of Oxygen" (Boston University, September, 2002); Dr. Jim Kasting: 1)"Climate evolution on Venus, Earth, and Mars", "The rise of Oxygen and Ozone", and "Habitable zones around stars and the search for extraterrestrial life" (European Research Course on Atmospheres, Grenoble, France, Feb−2003), 2)"Climate evolution on Venus, Earth, and Mars", "The rise of atmospheric O2", "Habitable zones around stars and the search for extraterrestrial life", "Water on Mars", "Snowball Earth", and "The origin of life" (First International Postgraduate Course on Geobiology, Catalina Island, CA,

20−26−July−2002), 3)"Habitable zones around stars and the search for extraterrestrial life" (invited seminar, University of Delaware, Sept. 2002), 4)"Atmospheric composition and climate on the early Earth" (Northwestern University, Oct. 2002).

Astrobiology Summer Program

The Astrobiology Summer Program (ASP), an undergraduate summer training program in astrobiology, was established at Penn State with the help of a 3−year NSF REU−Site award (S. Blair Hedges, PI). Beginning in summer 2003, it supports 10 students (sophomores, juniors) from colleges and universities other than Penn State to participate in research training under the guidance of Penn State Astrobiology Research Center (PSARC) faculty mentors. Women and minorities are encouraged to apply. The program has a director (Dr. Blair Hedges) and a coordinator (Dr. Carla Hass). Five PSARC faculty hosted students during the 2003 summer: Drs. Michael Arthur, Chris House, Lee Kump, and Hiroshi Ohmoto in the Department of Geosciences and Dr. S. Blair Hedges in the Department of Biology. Besides laboratory research, ASP students also have the opportunity to participate in a research excursion to a modern analog of a Precambrian ocean (Green Lake, New York), attend weekly seminars and laboratory tours, stargaze, and participate in a discussion group and a research symposium.

Astrobiology Undergraduate Minor

Undergraduate students at Penn State can participate in the Astrobiology Undergraduate Minor, which is designed to educate students in the varied scientific disciplines that contribute to our general understanding of life, the origin of life, the past history of life on Earth, possible futures for life on Earth, and the possible existence of life on other planetary environments. The principle goal of the minor is to develop students' literacy in astrobiology so that they can critically evaluate claims related to this field. During the 2002−2003 academic year, eight Penn State students graduated with the Astrobiology minor. One student is currently enrolled in the program.

Astrobiology Graduate Courses

Penn State Astrobiology Research Center (PSARC) scientists teach a variety of graduate courses each year. During Fall 2002, the following courses were offered: 1) Astrobiology Graduate Seminar: Advancements in Astrobiology, which included participation via videoconference by PSARC faculty and graduate students at the University of Pittsburgh and State University of New York Stony Brook, 2) Methane: Its Biochemistry, Biogeochemistry, and Paleoclimatology, which covers topics ranging from biochemistry to seismic stratigraphy, and 3) Microbial Diversity, which covers methods for studying microbial diversity, microbial development, and transcription regulation of gene expression. During Spring 2003, the following course was offered: 1) Evolution of the Biosphere.

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Publications: Pennsylvania State University

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NASA ASTROBIOLOGY INSTITUTE
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Members: Pennsylvania State University

Team Members sorted by current team.

Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Name:	Michael Arthur
Email:	arthur@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Mark Barley
Email:	mbarley@geol.uwa.edu.au
Institution:	University of Western Australia
Name:	Jane Barling
Email:	barling@earth.rochester.edu
Institution:	University of Rochester
Name:	Fabia Battistuzzi
Email:	fxb142@psu.edu
Institution:	Pennsylvania State University
Name:	Michael Bau
Email:	m.bau@iu−bremen.de
Institution:	International University of Bremen
Name:	Ekaterina Bazilevskaya
Email:	eab204@psu.edu
Institution:	Pennsylvania State University
Name:	Caleb Bell III

Email:	Cbb120@psu.edu
Institution:	Pennsylvania State University
Name:	David Bevacqua
Email:	david_bevacqua@hotmail.com
Institution:	Pennsylvania State University
Name:	Jen Biddle
Email:	Jfg150@psu.edu
Institution:	Pennsylvania State University
Name:	Jaime Blair
Email:	Jeb322@psu.edu
Institution:	Pennsylvania State University
Name:	Michelle Bonsell
Email:	mbonsell@psu.edu
Institution:	Pennsylvania State University
Name:	Susan Brantley
Email:	brantley@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Jean Brenchley
Email:	jeb7@psu.edu
Institution:	Pennsylvania State University
Name:	Christie Brosius
Email:	Clb178@psu.edu
Institution:	Pennsylvania State University
Name:	Lisa Brown
Email:	lisabrown@psu.edu
Institution:	Pennsylvania State University
Name:	Donald Bryant

Email:	dab14@psu.edu
Institution:	Pennsylvania State University
Name:	Heather Buss
Email:	hlb167@psu.edu
Institution:	Pennsylvania State University
Name:	Vyllinniskii Cameron
Email:	cvyllinn@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Tom Canich
Email:	tcanich@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Rosemary Capo
Email:	rcapo@pitt.edu
Institution:	University of Pittsburgh
Name:	Greg Cardell
Email:	greg.cardell@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Martin Cohen
Email:	mcohen@astron.berkeley.edu
Institution:	University of California, Berkeley
Name:	Corey Cohn
Email:	ccohn@ic.sunysb.edu
Institution:	SUNY, Stony Brook
Name:	David Crisp
Email:	david.crisp@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Francisco Cruz

Email:	Fxc142@psu.edu
Institution:	Pennsylvania State University
Name:	Linda Decker
Email:	ldecker@psu.edu
Institution:	Pennsylvania State University
Name:	Yanhuai Ding
Email:	yud1@psu.edu
Institution:	Pennsylvania State University
Name:	Jennifer Eigenbrode
Email:	eigenbro@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Albert Eschenmoser
Email:	eschenmoser@org.chem.ethz.ch
Institution:	ETH Zurich
Name:	James Ferry
Email:	jgf3@psu.edu
Institution:	Pennsylvania State University
Name:	Tracy Frank
Email:	tfrank2@unl.edu
Institution:	University of Nebraska
Name:	Nicolas Fray
Email:	fray@lisa.univ−paris12.fr
Institution:	Lisa−Univ. of Paris
Name:	Katherine Freeman
Email:	kate@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Brian Games

Email:	bgames@pitt.edu
Institution:	University of Pittsburgh
Name:	Cheryl Gardner
Email:	cugl@psu.edu
Institution:	Pennsylvania State University
Name:	Galina Glazko
Email:	gvg2@psu.edu
Institution:	Pennsylvania State University
Name:	Towhid Hasan
Email:	hasantowhid@yahoo.com
Institution:	Pennsylvania State University
Name:	Libby Hausrath
Email:	emh191@psu.edu
Institution:	Pennsylvania State University
Name:	Ken−ichro Hayashi
Email:	khayashi@mail.cc.tohoku.ac.jp
Institution:	Tohoku University
Name:	S. Blair Hedges
Email:	sbh1@psu.edu
Institution:	Pennsylvania State University
Name:	Ellen Herman
Email:	ekherman@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Achim Herrmann
Email:	achim@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	A. Hickman

Email:	arthur.hickman@mpr.wa.gov.au
Institution:	Geological Survey of Western Australia
Name:	Roberta Hotinski
Email:	rhotinsk@nsf.gov
Institution:	National Science Foundtion (NSF)
Name:	Christopher House
Email:	chouse@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Matthew Hurtgen
Email:	mhurtgen@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Gary Icopini
Email:	gicopini@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Hiroaki Ikemi
Email:	hikemi@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Clark Johnson
Email:	clarkj@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Kelsey Johnson
Email:	kpj105@psu.edu
Institution:	Pennsylvania State University
Name:	Daniel Jones
Email:	djones@chem.psu.edu
Institution:	Pennsylvania State University
Name:	Frank Kachurak

Email:	kachurak@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Takeshi Kakegawa
Email:	kakegawa@mail.cc.tohoku.ac.jp
Institution:	Tohoku University
Name:	James Kasting
Email:	kasting@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Yasuhiro Kato
Email:	ykato@geosys.t.u−tokyo.ac.jp
Institution:	University of Rochester
Name:	Alan Kaufman
Email:	Kaufman@umd.edu
Institution:	University of Maryland
Name:	Pushker Kharecha
Email:	pushker@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Robert Killoren
Email:	bobk@psu.edu
Institution:	Pennsylvania State University
Name:	Kara Krelove
Email:	kjk176@cox.net
Institution:	Arizona State University
Name:	Andrew Krug
Email:	akrug@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Lee Kump

Email:	kump@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Laura Liermann
Email:	ljl8@psu.edu
Institution:	Pennsylvania State University
Name:	Jennifer Loveland−Curtze
Email:	jel126@psu.edu
Institution:	Pennsylvania State University
Name:	Timothy Lyons
Email:	LyonsT@missouri.edu
Institution:	University of Missouri, Columbia
Name:	Gwendolyn Macpherson
Email:	glmac@ku.edu
Institution:	University of Kansas
Name:	Julia Maresca
Email:	jam636@psu.edu
Institution:	Pennsylvania State University
Name:	Jukka Marmo
Email:	jukka.marmo@gsf.fi
Institution:	Finland Geological Survey
Name:	Clifford Matthews
Email:	hcnmattews@cs.com
Institution:	University of Illinois
Name:	Susan Mattingly
Email:	ssm22@psu.edu
Institution:	Pennsylvania State University
Name:	Paul Maurizzo

Email:	pmauriz1@swarthmore.edu
Institution:	Swarthmore College
Name:	Brighid McGowan
Email:	bmm208@psu.edu
Institution:	Pennsylvania State University
Name:	Victoria Meadows
Email:	Vsm@ipac.caltech.edu
Institution:	Jet Propulsion Laboratory
Name:	Robert Minard
Email:	rminard@psu.edu
Institution:	Pennsylvania State University
Name:	Vanya Miteva
Email:	vim1@psu.edu
Institution:	Pennsylvania State University
Name:	Jim Moran
Email:	jmoran@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Karl Mueller
Email:	ktm2@psu.edu
Institution:	Pennsylvania State University
Name:	Hiroshi Naraoka
Email:	naraoka−hiroshi@c.metro−u.ac.jp
Institution:	Tokyo Metropolitan University
Name:	Munetomo Nedachi
Email:	nedachi@sci.kagoshima−u.ac.jp
Institution:	Kagoshima University
Name:	Masatoshi Nei

Email:	nxm2@psu.edu
Institution:	Pennsylvania State University
Name:	Jessica Nienstedt
Email:	Jessica.Nienstedt@sunysb.edu
Institution:	SUNY, Stony Brook
Name:	Hiroshi Ohmoto
Email:	ohmoto@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Tsubasa Otake
Email:	ohtake@mine.kyushu−u.ac.jp
Institution:	Kyushu University
Name:	Mark Patzkowsky
Email:	brachio@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Alexander Pavlov
Email:	pavlov@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Nikolai Pedentchouk
Email:	nikolai@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Angela Phelps
Email:	axp41@psu.edu
Institution:	Pennsylvania State University
Name:	Davide Pisani
Email:	dep16@psu.edu
Institution:	Pennsylvania State University
Name:	Nick Platts

Email:	s.platts@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Susan Rockey
Email:	sxw6@psu.edu
Institution:	Pennsylvania State University
Name:	Shane Ruebush
Email:	ssr123@psu.edu
Institution:	Pennsylvania State University
Name:	Michael Rumrill
Email:	mrumrill@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Irene Schaperdoth
Email:	ius2@psu.edu
Institution:	Pennsylvania State University
Name:	Martin Schoonen
Email:	Martin.schoonen@sunysb.edu
Institution:	SUNY, Stony Brook
Name:	Antigona Segura
Email:	Antigona@essc.psu.edu
Institution:	Pennsylvania State University
Name:	William Seyfried
Email:	wes@tc.umn.edu
Institution:	University of Minnesota
Name:	Prachi Shah
Email:	pss11@psu.edu
Institution:	Pennsylvania State University
Name:	Erin Shields

Email:	eps122@psu.edu
Institution:	Pennsylvania State University
Name:	Janet Siefert
Email:	siefert@stat.rice.edu
Institution:	Rice University
Name:	Steinn Sigurdsson
Email:	steinn@astro.psu.edu
Institution:	Pennsylvania State University
Name:	Alexander Smirnov
Email:	asmirnov@ic.sunysb.edu
Institution:	SUNY, Stony Brook
Name:	Don Smith
Email:	dfs141@psu.edu
Institution:	Pennsylvania State University
Name:	Kate Spangler
Email:	kxp164@psu.edu
Institution:	Pennsylvania State University
Name:	Sherry Stafford
Email:	slsst52@pitt.edu
Institution:	University of Pittsburgh
Name:	Brian Stewart
Email:	bstewart@vms.cis.pitt.edu
Institution:	University of Pittsburgh
Name:	Fabienne Thomarat
Email:	fet2@psu.edu
Institution:	Pennsylvania State University
Name:	Ming Tien

Email:	mxt3@psu.edu
Institution:	Pennsylvania State University
Name:	Akiko Uchida
Email:	Akikoushida800@hotmail.com
Institution:	Kyushu University
Name:	Katherine Walden
Email:	kaw9@pitt.edu
Institution:	University of Pittsburgh
Name:	Dennis Walizer
Email:	walizer@geosc.psu.edu
Institution:	University of Pennsylvania
Name:	Yumiko Watanabe
Email:	yumiko@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Naoki Watanabe
Email:	jibanken@cc.niigata−u.ac.jp
Institution:	Niigata University
Name:	Kosei Yamaguchi
Email:	kosei@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Name:	Takushi Yokoyama
Email:	yokotscc@mbox.nc.kyushu−u.ac.jp
Institution:	Kyushu University
Name:	Aubrey Zerkle
Email:	azerkle@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Zhidan Zhang

Email:	zuz1@psu.edu
Institution:	Pennsylvania State University

Scripps Research Institute
Executive Summary
Principal Investigator: M. Reza Ghadiri

What is life, the requirements for its origins and evolution, and how living systems may be identified elsewhere in the universe are some of the most fundamental questions in astrobiology. Under the auspices of the Scripps Research Institute, a multi−institutional research team has been assembled to explore a variety of interdisciplinary experimental approaches to self−reproducing molecular systems and Darwinian chemistry. Through the design and study of diverse and novel chemical systems in the laboratory, we seek to garner a better understanding of life and its origins.

In the past year our team has continued to make significant discoveries and progress in several areas of research. Benner's group at the University of Florida has established a multidisciplinary research program that addresses issues relevant to astrobiology from several distinct but interrelated perspectives. They have hypothesized that genetic molecules in water will contain a repeating charge, universally in the galaxy. They have completed studies on a series of molecules that test this hypothesis, a step towards developing tools to detect universal biosignatures in NASA missions. Furthermore, a key step towards a synthetic biology involves the generation of artificial genetic systems that can be copied, and then have their copies copied. They reported a six letter genetic alphabet has supported a polymerase chain reaction. A long−standing debate in the history of life asks the temperature at which primitive microorganisms live. Benner's group have resurrected proteins from ancient bacteria, studied their behaviors at different temperatures, and concluded that these bacteria lived at temperatures between 60 and 70°C. Finally, considering that the most abundant solvent in the solar system is not water, rather supercritical mixtures of dihydrogen, helium, and molecules such as methane and ammonia, Benner and coworkers have begun exploring, from a theoretical perspective, how organic molecules might behave differently in such environments. Ellington's laboratory at the University of Texas−Austin is interested in generating novel self−replicating biopolymers in order to better identify self−replicating molecular ensembles that may be encountered on other planets. During the past year Ellington's group has designed a cross−catalytic amplification system based on the fast and efficient deoxyribozyme. In this system complementary deoxyribozyme cleavases are inactivated by circularization. Linearization results in activation of the deoxyribozyme and leads to the initiation of a cascade of cleavage reactions that display exponential growth kinetics. This system represents the first *in vitro* system capable of exponential growth in the absence of protein

enzymes. Ongoing in vitro selection experiments using larger and more diverse pools are expected to allow elucidation of some of the parameters surrounding the evolution of sequence and function in exponential replicating systems. The goal of Ghadiri's research program at the Scripps Research Institute is to design, discover, and understand the primary factors responsible for directing self−organization of inanimate molecules into the animate chemistry of living systems. Ghadiri's and coworkers' approach has been to rationally design and recreate various forms of autocatalytic peptide networks in the laboratory and study how the interplay of molecular information and nonlinear catalysis can lead to self−organization and expression of emergent properties. Recently they have completed the design of the first de novo "small world" synthetic chemical network based on template−directed coiled−coil peptide fragment condensation reactions. The self−organized chemical network is composed of nine nodes and 21 edges including three autocatalytic processes. Their studies indicate for the first time that relatively complex networks can be rationally designed and constructed and its properties experimentally analyzed in order to gain insights into the dynamics of complex nonlinear chemical networks. This approach is expected to allow rigorous experimental and theoretical analysis of network architecture and aid in better understanding of factors contributing to system self−organization and display of emergent phenomena in living systems. Rebek and coworkers have continued their pioneering efforts in the design of novel abiotic molecular replicators and proto−cells. They have continued to explore synthetic systems in which compartmentalization leads to nonlinear, autocatalytic behavior. The compartments are reversibly formed capsules in which small molecular guests are temporarily surrounded by larger molecular hosts. They represent an extreme form of molecular recognition −− molecules within molecules. The complexes are held together by weak intermolecular forces and their lifetimes vary from milliseconds to days. This range allows their applications as nanometric reaction chambers, as means to stabilize reagents and as spaces where new forms of stereochemistry can emerge. The capsule provides a mechanical barrier that imposes restrictions on the motion of guests held inside. The primary goal of the Switzer laboratory is to synthesize Alternative Nucleic Acids (ANAs) to attempt the optimization of polymer structure subject to the constraints of prebiotic availability, template−directed reproduction, replication conservative mutation, and fitness. Switzer and coworkers have designed and successfully evaluated a novel metallo−base−pair for deoxyribonucleic acid (DNA) that has greater thermal stability than natural base−pairs. This discovery expands the bounds of environmental conditions suitable for the transfer of genetic information by increasing the fitness of nucleic acid−like molecules in thermal environments, while also adding another orthogonal base−pair to the "genetic alphabet." In an ongoing study, Switzer's laboratory has been studying a new peptide nucleic acid that transcends previous known shortcomings of this molecular chimera of nucleic acids and peptides, opening the way to the creation of long polymer chains and highly functional proto−biopolymers that could serve as transitional polymers on the way to the present DNA/ribonucleic acid (RNA)/protein world.

Project Report: Benner − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Benner − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Steven Benner***

Project Progress

The specific details of the organic chemistry that is found in the life that we know on Earth need not be universal. Nevertheless, the organic molecules that support life universally must have features that enable Darwinian evolution, believed to be the only mechanism for obtaining function from inanimate matter within the context of living systems. We have concluded a five year study that combines synthetic chemistry with studies of the structure of modern terrean biochemistry and genomics, set within the context of the types of environments that exist in the solar system, to ask what type of chemistry might support life. This has relevance to NASA missions, as it defines the kinds of biosignatures that they must seek. By expanding our understanding of the intimate connection between molecular reactivity and living processes, however, it supports a research strategy that moves forward in time from the most primitive replicating systems to complex life.

At the same time, the explosion of genome sequence information is enabling a research strategy that moves backwards in time from modern day life on Earth to antiquity. Extracting information about the historical past from genomic sequence data requires advanced models for how proteins and DNA change their sequence when these molecules are subjected to selection pressure. Coupling these models with laboratory experiments that resurrect proteins from extinct forms of life for study, this program has defined the temperature environments of some very early bacteria, correlated the emergence of new ecological strategies in fungi during the time of the dinosaurs, and explored the use of historical models to the understanding of human disease. Interactions within the evogenomics focus group have been critical to this effort.

Several of the specific advances are captured in the "highlights" section.

Highlights

- We have hypothesized that genetic molecules in water will contain a repeating charge, universally in the galaxy. NAI researchers have

completed studies on a series of molecules that test this hypothesis, a step towards developing tools to detect universal biosignatures in NASA missions.

- A historical view of complex life on Earth is key to understanding diseases in contemporary life. NAI researchers have used historical models to analyze protein families for their role in infectious diseases, including HIV and SARS, and diseases of metabolism, such as leptin.

- Synthetic biology is a goal that combines concepts from the origin and history of life on Earth with the ability of organic chemists to make new molecules. A widely read article in Nature discusses planetary biology, a subdivision of astrobiology, as a new horizon in molecular science.

- A long−standing debate in the history of life asks the temperature at which primitive microorganisms live. NAI scientists have resurrected proteins from ancient bacteria, studied their behaviors at different temperatures, and concluded that these bacteria lived at temperatures between 60 and 70°C.

- Instruction in organic chemistry is key to any program in teaching Astrobiology. The NAI researchers have prepared a chapter on "organic chemistry for astrobiologists" to be included in an upcoming volume on astrobiology, as part of an ongoing effort to make key ideas in organic chemistry accessible to non−chemists.

- A key step towards a synthetic biology involves the generation of artificial genetic systems that can be copied, and then have their copies copied. NAI scientists in 2003 reported the first time a six letter genetic alphabet has supported a polymerase chain reaction.

- A historical view of life is a key to interpreting the human genome. NAI scientists have published an extensive treatment of evolution−based tools that analyze genomes for functional information.

- The most abundant solvent in the solar system is not water, but rather supercritical mixtures of dihydrogen, helium, and molecules such as methane and ammonia. NAI researchers have explored, from a theoretical perspective, how organic molecules might behave differently in such environments.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life

- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Exploration	Consultant for Hunter Waite and his team at the University of Michigan for the design of instrumentation to search for organic molecules on Mars
1	MEPAG	Consultant to help design the search for biosignatures on Mars

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In 1999, we suggested that a particular class of organic molecules might be found on the accessible surface of Mars. These are benzenecarboxylic acids, and are expected to be derived from the kerogen delivered to Mars via meteorite. Much of our effort in mission design has been related to the design of instruments that detect these, and the design of instruments that might detect biosignatures of endogenous life where benzenecarboxylic acids are n undesirable background.

Cross Team Collaborations

In an outreach effort that involved several NAI Co−Principal Investigators (Andrew Ellington, Christopher Switzer, and Jack Szostak), we developed and presented a course in "organic chemistry for geobiologists". This was funded by the Agouron Foundation and took place on Catalina Island in the summer of 2002. The course included both lectures (ca. 20 hours) plus laboratory work that showed how chirality might emerge spontaneously without life, how morphological structures that appear to look like "stromatolites" might emerge abiotically, and how phenomenon evolve over time with a life−like regularity without the intervention of living systems.

In a longstanding effort, collaboration was initiated between the Ellington and Benner groups to examine unnatural nucleic acids as a component of molecular evolution.

Project Report: Ellington − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Ellington − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Andrew Ellington***

Project Progress

During the past year the Ellington Lab has focused on the design of self−evolving nucleic acid enzymes. We have designed a cross−catalytic amplification system based on the fast and efficient 10−23 deoxyribozyme (Ellington and Levy, 2003). In this system complementary deoxyribozyme cleavases are inactivated by circularization (Figure 1). Linearization results in activation of the deoxyribozyme and leads to the initiation of a cascade of cleavage reactions that displays exponential growth kinetics (Figure 2). This system represents the first in vitro system capable of exponential growth in the absence of protein enzymes.

The conformational change from circular substrate to linear catalyst resulting in exponential growth suggested the potential for the evolution of both sequence and function. To test this hypothesis, we randomized opposing portions of the binding arms generating two pools of deoxyribozymes (Figure 3; CE.1 and CE.2). When incubated together, members of each population that were capable of activating their complements were preferentially amplified. A portion of this reaction was then transferred to a new tube containing a population of un−reacted circular pool. After four rounds of serial transfer, sequence analysis indicated the sequences expected to dominate in the selection had indeed been selected (Figure 4, GTG and TCC). In addition to these two species other variants were also isolated. Examination of these sequences suggested that they might form 2 out of 3 base pairs with their complement. If selection had occurred, then it is expected that these minor variants would also be active catalysts, albeit to a lesser extent. To test this we assayed the alternate variant GGG in exponential growth assay. As expected, the GGG variant is not as good a catalyst as the dominant GTG variant (Figure 5). The successful design and implementation of this scheme for selection via serial transfer represents an in vitro selection experiment conducted in the absence of any protein enzymes. To our knowledge this is the first time this has been accomplished.

Currently we are continuing our work with the cross catalytic clevase cascade.

To this end we have designed two new circular deoxyribonucleic acid (DNA) pools (Figure 6). Unlike the previous pool design in which the random region opposed a constant region, the new pools have been designed such that random regions oppose random regions. In vitro selection experiments using these larger and more diverse pools should allow us to begin to elucidate some of the parameters surrounding the evolution of sequence and function in this exponential replicating system.

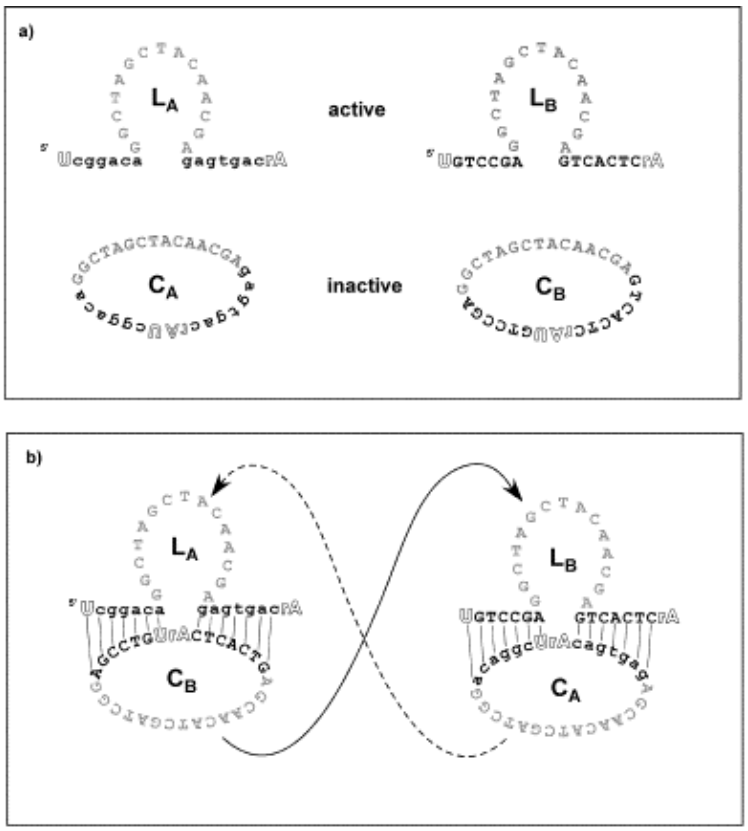

Figure 1.

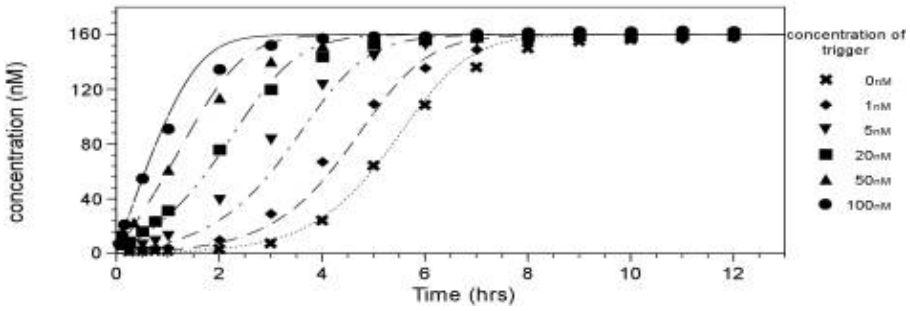

Figure 2.

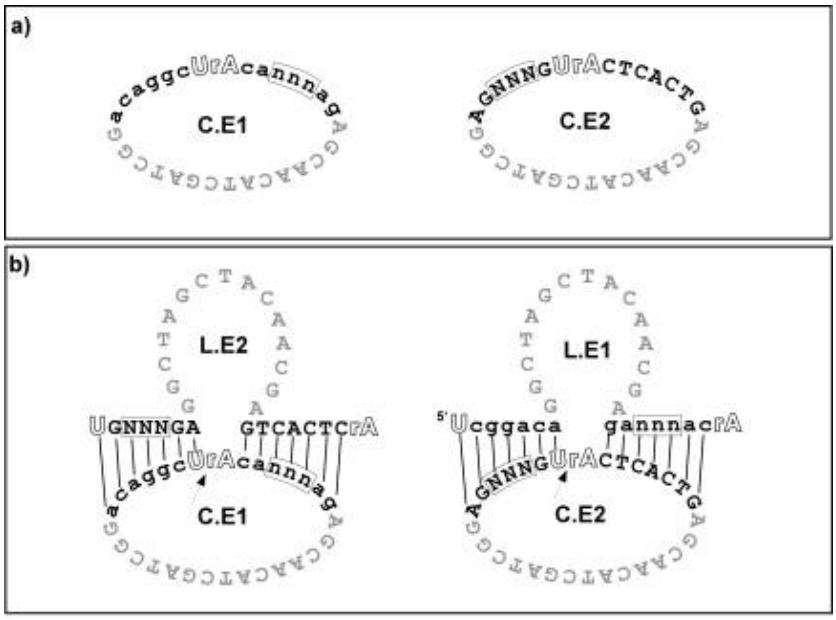

Figure 3.

C.E1 round 0		C.E1 round 4		C.E2 round 0		C.E2 round 4	
aagga	3	agtga	13	GGTAG	2	GTCCG	20
acata	2	aggga	9	GGCCG	2	GGCCG	3
aggga	2			GTCTG	2	GTCAG	3
acaga	2			GTAGG	2	GCCCG	
agcaa	2			GCTCG		GATCG	
agaga	2			GAGCG		GCGGG	
agcca				GGTTG		GCAGG	
atgga				GACCG		GCGTG	
ataga				GATGG			
agtga				GTCAG			
accta				GCTAG			
atcga				GTTTG			
aagga				GTTGG			
accga				GCGAG			
aataa				GCATG			
agtca				GTATG			
				GCCCG			
				GGGTG			

Figure 4.

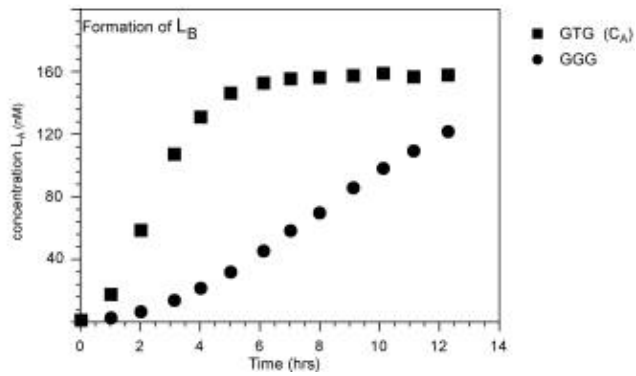

Figure 5.

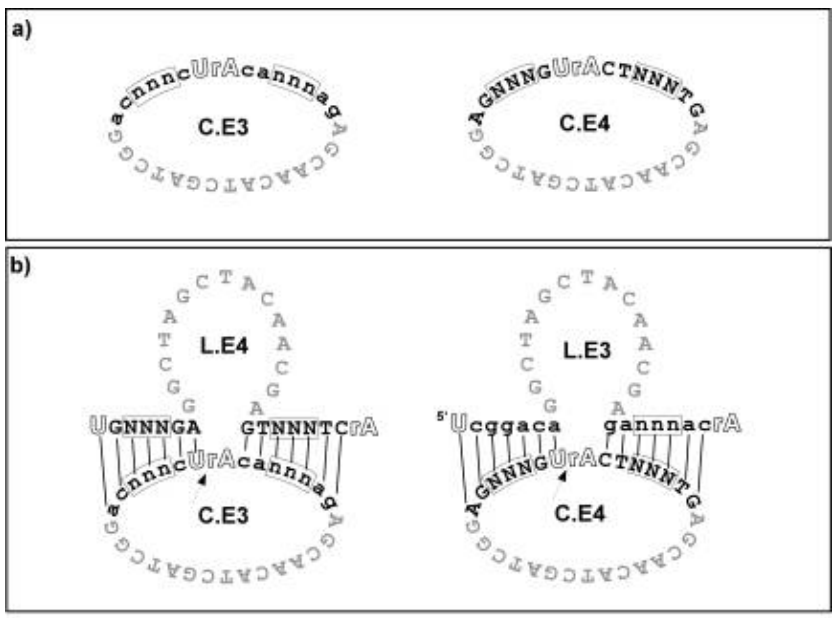

Figure 6.

Highlights

- Design of a cross−catalytic cleavage cascade capable of exponential growth (Levy and Ellington, 2003) has been accomplished.
- The first in vitro selection experiment conducted in the absence of protein enzymes has been demonstrated (Levy and Ellington, 2003).

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Origins of Life	PI

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The research we carry out is critical for understanding how life can originate, and what forms life can take. Therefore, it is of direct relevance to missions to Mars or other planets that intend to look for evidence of living systems, past or present.

Field Expeditions

Field Trip Name: Institut de Astrobiologia	
Start Date: 2/03/03	***End Date:*** 02/15/03
Continent: Europe	***Country:*** Spain
State/Province:	***Nearest City/Town:*** Madrid
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Tim Riedel, a graduate student, won a competition to attend the opening ceremony of the Institut de Astrbiologia in Madrid, Spain.	
Members Involved: Timothy Riedel	

Cross Team Collaborations

As part of our efforts to develop unnatural organisms (currently unfunded, but under the general aegis of the Astrobiology Institute), we have interacted with Dr Chris McKay at NASA−Ames. One of my graduate students, Tim Riedel, spent a year at Ames working with Dr. McKay.

Project Report: Ghadiri − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Ghadiri − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***M. Reza Ghadiri***

Project Progress

The goal of our research program is to design, discover, and understand the primary factors responsible for directing the self−organization of inanimate molecules into the animate chemistry of living systems. We have envisioned that a rational process that can be used to design, predict, and manipulate complex self−organized nonlinear chemical systems would be an invaluable tool in this regard as well as for modeling network architectures of biological processes and for better understanding of the collective behavior of large networks of interacting dynamical systems. In the past year we have succeeded in developing the first de novo synthetic system that can be theoretically and experimentally analyzed at various desired levels of complexity. The self−organized nonlinear chemical system is based on template−directed coiled−coil peptide fragment condensation reactions that we have previously shown to exhibit substrate specific ligase and replicase activities. A scoring algorithm was devised to analyze and graph plausible coiled−coil interactions resulting from 81x81 template−directed auto− and cross−catalytic reaction pathways. The resulting "small−world" network was predicted to have global and local efficiencies similar to the natural systems and appear to be clustered and have hierarchical organization. Nine nodes were selected from the graph and their network formation was experimentally analyzed. The resulting self−organized chemical system displays 21 edges, including three autocatalytic processes in close agreement with the graph analysis predictions. The synthetic network shows graph architecture that is strikingly similar to the organization of complex biological systems. Our studies indicate that complex networks can be rationally designed and constructed and their properties experimentally verified in order to gain insights into the dynamics of complex nonlinear chemical networks. We hope that this synthetic "bottom−up" approach would serve as a model for addressing the large−scale structural and functional organization of cellular networks and their plausible origins. This approach should allow rigorous experimental and theoretical analysis of network architecture and aid in better understanding of factors contributing to system self−organization and display of emergent phenomena in living systems.

Highlights

- A relatively complex "small−world" synthetic chemical network with nine nodes and 21 edges (reaction pathways) has been designed. This novel system is expected to serve as a model for the study and better understanding of functional organization of animate networks and their plausible contributions to the origins of life of Earth.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Rebek − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Rebek − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Julius Rebek***

Project Progress

Chemical amplification is characteristic of living systems, and is necessary for increased sensitivity, responsiveness, and self−replication. We continue to explore a synthetic system in which compartmentalization leads to nonlinear, autocatalytic behavior. The compartments are reversibly formed capsules in which small molecular guests are temporarily surrounded by larger molecular hosts. They represent an extreme form of molecular recognition − molecules within molecules. The complexes are held together by weak intermolecular forces and their lifetimes vary from milliseconds to days. This range allows their applications as nanometric reaction chambers, as means to stabilize reagents and as spaces where new forms of stereochemistry can emerge. The capsule provides a mechanical barrier that imposes restrictions on the motion of guests held inside.

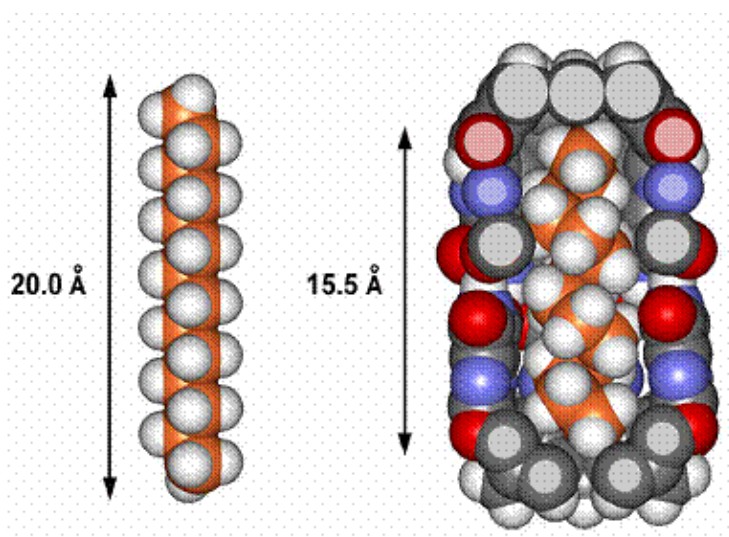

Figure 1. *The straight chain hydrocarbon $C_{14}H_{30}$ exists in an extended conformation (left); on encapsulation (right), the helical shape is assumed to match the size and shape of the cavity.*

Highlights

- The encapsulation of long chain hydrocarbons causes them to coil into helical structures.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Switzer − Self−Reproducing Molecular Systems and Darwinian Chemistry

Lead Team:	***Scripps Research Institute***
Project Title:	***Switzer − Self−Reproducing Molecular Systems and Darwinian Chemistry***
Project Investigator:	***Christopher Switzer***

Project Progress

The primary goal of the Switzer laboratory is to synthesize Alternative Nucleic Acids (ANAs) to attempt the optimization of polymer structure subject to the constraints of prebiotic availability, template−directed reproduction, replication conservative mutation, and fitness. We have identified ANAs by taking small steps in "structure−space" away from ribonucleic acid (RNA) (the best model for a molecule bearing features both universal and unique to life) that may avoid some of the problems inherent in fulfillment of the aforementioned constraints. Specifically, the Switzer laboratory is examining ANAs with novel changes to (i) base−pairing domains and (ii) backbone charges and (iii) sugar. These studies will help to define chemical parameters for molecular evolution. Moreover, our work addresses whether nucleic acid−like molecules are sufficient to enable the origin of life and what limitations exist for life elsewhere in the universe based on a single biopolymer (eg. RNA) rather than multiple biopolymers (deoxyribonucleic acid (DNA), RNA, proteins, carbohydrates). Accomplishments by our group for the past year include:

(i) discovery of a novel metallo−base−pair with increased thermal stability over all natural base−pairs,

(ii) the discovery that non−standard, 2',5'−linked DNA is a template for enzymatic synthesis of natural DNA with a variety of DNA polymerases and reverse transcriptases, directing the incorporation of all four natural nucleotides with fidelity. This finding demonstrates that, surprisingly, DNA replication does not require double helix formation as 2',5'−linked DNA is known not to associate with 3',5'−linked−DNA. In the present case, it appears that the enzyme can serve as a "template for the template" and make up for structural and functional deficiencies.

(iii) the design and initial evaluation of a new peptide nucleic acid that transcends previous known shortcomings of this molecular chimera of nucleic acids and peptides, opening the way to the creation of long polymer chains and highly functional proto−biopolymers that could serve as transitional

polymers on the way to the present DNA/RNA/protein world.

Highlights

- We have designed and successfully evaluated a novel metallo−base−pair for DNA that has greater thermal stability than natural base−pairs. Our discovery expands the bounds of environmental conditions suitable for the transfer of genetic information by increasing the fitness of nucleic acid−like molecules in thermal environments, while also adding another orthogonal base−pair to the −genetic alphabet.

- We have discovered that 2',5'−linked DNA is a template for enzymatic synthesis of natural DNA with a variety of DNA polymerases and reverse transcriptases, directing the incorporation of all four natural nucleotides with fidelity. This finding demonstrates that, surprisingly, DNA replication does not require double helix formation as 2',5'−linked DNA is known not to associate with 3',5'−linked−DNA from past and present experiments. Thus, it appears that the enzymes serve as a "template for the template" and are thereby able to make up for functional deficiencies that would otherwise be fatal to an informational biopolymer.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Using functional genomics to infer the biology and chemistry of the Last Common Ancestor

Lead Team:	***Scripps Research Institute***
Project Title:	***Using functional genomics to infer the biology and chemistry of the Last Common Ancestor***
NAI−NRC Postdoctoral Fellow :	***Eric Gaucher***

Project Progress

The goal of the proposed project is to test the thermostability of an ancestral reconstructed protein from bacteria using a combination of laboratory and computational approaches. To this end, phylogenetic analyses have been performed in order to determine extant bacterial relationships (phylogenetic tree) using sophisticated maximum likelihood models. The ancestral sequence at the base of the bacterial lineage was subsequently inferred. Due to uncertainties in the reconstructions, multiple topologies were considered. The next step of the project entailed the resurrection of the ancestral sequences in the laboratory using standard molecular biology techniques. The thermostabilities of these resurrected proteins were assayed by their ability to bind nucleotide. All proteins optimally bound GDP between 55−65 degrees C. This suggests that the ancient organisms hosting these proteins were thermophilic, and neither hyperthermophilic nor mesophilic. In addition, I have studied the molecular evolution of the obesity protein Leptin and proposed an evolutionary hypothesis to explain functional differences between primates and rodents. This type of analysis demonstrates the utility of Astrobiology within the medical community.

Highlights

- **Resurrected Ancestral Proteins**
  Reconstruction and subsequent resurrection of ancient proteins suggest that bacteria originated in a thermophilic environment, and neither a hyperthermophilic nor mesophilic environment.

- **Concepts of Functional Divergence**
  Our ability to detect functional divergence among genomic sequences can be greatly influenced by our perception of function/behavior. The goal is to inform the genomics community of possible biases that limit the exploration of genomic sequences as they relate to biological

systems in general.

- **Approaches for Detecting Functional Divergence**
  We are interested in elucidating the various patterns of protein divergence. Specifically, we are analyzing shifts in evolutionary rates as an approach to detect altered biological function.

- **Validation of Functional Divergence Predictions**
  Predictions based on our previous analyses have recently been confirmed. This highlights the power of combining computational and experimental biology.

- **Bridging Astrobiology and Medical Sciences**
  Combining evolutionary analyses with structural and biochemical data provides unique approaches for studying genomic sequences. A molecular evolutionary analysis of the obesity protein Leptin provides clues to explain functional differences between primates and rodents. Although practiced throughout the Astrobiology Institute, such polydisciplinary approaches are novel within the medical community.

- **Resurrected Ancestral Proteins**
  Reconstruction and subsequent resurrection of ancient proteins suggest that bacteria originated in a thermophilic environment, and neither a hyperthermophilic nor mesophilic environment.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: Scripps Research Institute

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Eric Gaucher
Project Title: Using functional genomics to infer the biology and chemistry of the Last Common Ancestor
Advisor: Steven Benner, Advisor
NAI Lead Team: Scripps Research Institute
Fellowship Began In: July 1, 2002

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
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EPO: Scripps Research Institute

These are the Education and Public Outreach activities for the Scripps Research Institute.

Publications: Scripps Research Institute

Gaucher, E.A. Thomson, J.M. Burgan, M.F. Benner, S.A. (2003). Inferring the paleoenvironment of ancient bacteria based on resurrected proteins [Abstract]. *Annual Meeting of the Society of Molecular Biology and Evolution, Newport Beach, CA*.

Gaucher, E.A., Miyamoto, M.M. Benner, S.A. (2003). Evolutionary, structural and biochemical evidence for a new interaction site of the leptin obesity protein. *Genetics*, 163(4): 1549−1553.

Gaucher, E.A., Thomson, J.M, Burgan, M.F. Benner, S.A. (2002). Experimental paleogenomics as a tool to analyze protein function and predict environmental temperature during early life [Abstract: NASA *Astrobiology* Institute General Meeting 2003]. *Astrobiology*, 2(4): 501.

Gaucher, E.A., Thomson, J.M., Burgan, M.F. Benner, S.A. (Submitted, 2003). Inferring the paleoenvironment of ancient bacteria based on resurrected proteins. *Nature*.

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Members: Scripps Research Institute

Team Members sorted by current team.

Name:	Gonen Ashkensay
Email:	gonena@scripps.edu
Institution:	Scripps Research Institute
Name:	Travis Bayer
Email:	tsbayer@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Steven Benner
Email:	benner@chem.ufl.edu
Institution:	University of Florida
Name:	Michelle Burgan
Email:	burgan@ufl.edu
Institution:	University of Florida
Name:	Yu−Lin Chung
Email:	tinierenie@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Dan DeKee
Email:	Dekee@chem.ufl.edu
Institution:	University of Florida
Name:	Andrew Ellington
Email:	andy.ellington@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Stela Filipovic−sadic

Email:	stelasadic@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Kathryn Gannon
Email:	kgannon@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Eric Gaucher
Email:	gaucher@ufl.edu
Institution:	University of Florida
Name:	M. Reza Ghadiri
Email:	ghadiri@scripps.edu
Institution:	Scripps Research Institute
Name:	V. Haridas
Email:	hariv@scripps.edu
Institution:	Scripps Research Institute
Name:	Benjamin Heuberger
Email:	bheub001@student.ucr.edu
Institution:	University of California, Riverside
Name:	Randall Hughes
Email:	Hughes@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Reshma Jagasia
Email:	reshma@scripps.edu
Institution:	Scripps Research Institute
Name:	Paul Kim
Email:	phkim@citrus.ucr.edu
Institution:	University of California, Riverside
Name:	Scott Knudsen

Email:	sknud@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Dong−Kye Lee
Email:	leed13@student.ucr.edu
Institution:	University of California, Riverside
Name:	Matthew Levy
Email:	mattlevy@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Tang Li
Email:	Tli@cise.ufl.edu
Institution:	University of Florida
Name:	Tom McCormack
Email:	tmccormack@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Edward Minor
Email:	eddieminor@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Subbarao Nallagatal
Email:	srnallagatla@yahoo.com
Institution:	University of California, Riverside
Name:	Liam Palmer
Email:	lpalmer@scripps.edu
Institution:	Scripps Research Institute
Name:	Julius Rebek
Email:	jrebek@scripps.edu
Institution:	Scripps Research Institute
Name:	Alonso Ricardo

Email:	aricardo@chem.ufl.edu
Institution:	University of Florida
Name:	Timothy Riedel
Email:	triedel@mail.arc.nasa.gov
Institution:	University of Texas, Austin
Name:	Alessandro Scarso
Email:	alesca@scripps.edu
Institution:	Scripps Research Institute
Name:	Jenny Shipway
Email:	jennys@scripps.edu
Institution:	Scripps Research Institute
Name:	Surajit Sinha
Email:	surajit_sinha@hotmail.com
Institution:	University of California, Riverside
Name:	A. Sismour
Email:	msismour@chem.ufl.edu
Institution:	University of Florida
Name:	Christopher Switzer
Email:	switzer@mail.ucr.edu
Institution:	University of California, Riverside
Name:	J. Michael Thomson
Email:	mthomson@grove.ufl.edu
Institution:	University of Florida
Name:	Teresa Williams
Email:	teresawilliams@mail.utexas.edu
Institution:	University of Texas, Austin
Name:	Stephanie Wyles

Email:	swyles@chem.ufl.edu
Institution:	University of Florida
Name:	Maneesh Yadav
Email:	Yadavm@scripps.edu
Institution:	Scripps Research Institute

University of California, Los Angeles
Executive Summary
Principal Investigator: Edward Young

The broad spectrum of physical and life sciences comprising the field of astrobiology is reflected in the research activities of the UCLA lead team in its fifth year of participation in the NASA Astrobiology Institute (NAI). Astrobiological research conducted by the UCLA lead team ranges from devising methods for imaging planets outside of our Solar System to studies of the evolution of life at the scale of individual genes. These seemingly disparate activities comprise a chain of informed inquiry that seeks to define the range of possible habitable environments in our Solar System and beyond and the manifestations of life that might arise in these diverse habitats.

During the fifth year of UCLA's involvement in the NAI, progress was made on six projects dedicated to improving our understanding of planetary habitats and the evolution and diversity of life. These projects are: 1) Extrasolar planetary systems; 2) Origins of habitable environments in the solar system; 3) Celestial influences on planetary environments; 4) Characterization of Earth's early life; 5) Geobiology and the geochemistry of early Earth; and 6) Genomic evolution and the tree of life. References listed in this report are grouped according to these project titles.

The six projects include a significant interdisciplinary component. Examples of interdisciplinary research at UCLA in year five are: collaboration between astronomers, atmospheric chemists, and cosmochemists leading to new insights into the way that planets capable of sustaining life evolve from gas and dust around stars; the bringing together of paleontologists, atmospheric chemists, and isotope geochemists to study Earth's ancient atmosphere; application of advanced spectroscopy methods to characterize the most ancient vestiges of life on Earth; and the integration of fossil morphology and genetics to understand the evolution of complex forms of life beginning more than 550 million years before present.

Education and public outreach activities of the UCLA lead team during the 2002/2003 year included public lectures by team members in the Los Angeles area, publication of the proceedings of the Rubey Colloquium on impacts and the origin and evolution of life, continuation of the highly successful general education course entitled "Origin of the Cosmos and Life," sponsorship of the student−run Astrobiology Society and their activities, including hosting of a public symposium held this Spring on the UCLA campus featuring well−known speakers from the scientific community. The speakers articulated their views of

astrobiology in an entertaining and accessible format. In addition to these education and public outreach activities, members of the UCLA team participated in several NAI Focus Groups and were active in efforts to establish a new Astronomy Focus Group during 2002/2003.

Extrasolar Planetary Systems

Astronomy research with consequences for astrobiology is beginning to accelerate at UCLA. Research in this area includes searching for stars that might harbor planets suitable for imaging and characterization of the composition and distribution of dust related to planets or planet formation surrounding other stars. The astronomical studies of the UCLA lead team involved observing sessions at Las Campanas Observatory in La Serena, South America, the Siding Spring Observatory in New South Whales, Australia, the W.M. Keck Observatories in Hawaii, and the Lick Observatory in California. Collaborations continue with astronomers at the Carnegie Institution of Washington, among others.

Members of the UCLA team added to the list of stars that are prime targets for attempts to image directly extrasolar planets using photons (Figure 1). Only when planets are imaged directly will it be possible to measure their spectra and determine their compositions. Advances in astronomy from the ground, including adaptive optics and the infrared capabilities of the Hubble Space Telescope, improve prospects for imaging of planets with masses comparable to that of Jupiter. But such detections must be of thermal emissions from young, warm planets rather than reflected starlight that illuminates cold, older planets like Jupiter. The targets for imaging planets must therefore be young stars. Stars that are young and close to our own star offer the greatest prospects for imaging orbiting planets and need to be identified. The accomplishments of this year's search raise the total of such "hot prospects" to more than 200 stars.

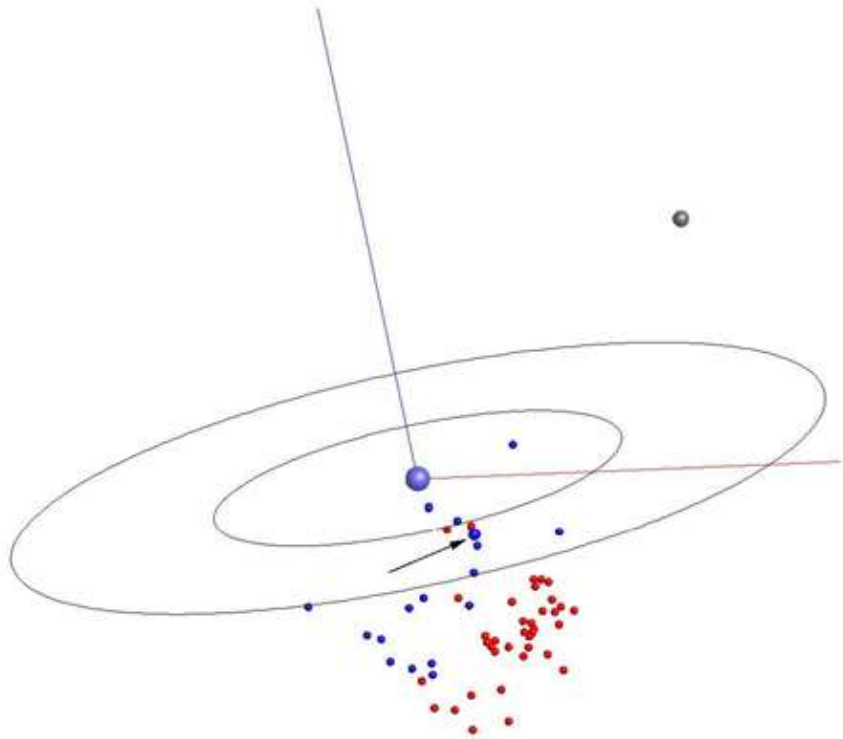

Figure 1. *Map showing several recently discovered groups of newborn stars that lie near Earth (large blue ball) and are "hot prospects" for imaging extrasolar planets. In this view from the northern sky, two circles in the equatorial plane have radii of 165 and 300 light years, respectively. Red dots depict the Tucana/Horologium group and blue indicates the beta Pictoris moving group. Gray represents the Pleaides cluster.*

Astronomical work continued on the detection and characterization of dust surrounding main sequence stars. In one instance, a ring of dust similar to that found around Saturn was detected around a white dwarf star, suggesting that asteroids existed there. In another case, it was observed that silicate dust (terrestrial−like planets are composed largely of silicate) is found 5 to 10 AU from the star Beta−Pic but not at larger distances, suggesting rocky bodies surrounding the star, if they exist, reside at circumstellar radii not too different from the planets of our Solar System.

Team members made progress in adapting NASA's flying observatory mission, Stratospheric Observatory for Infrared Astronomy (SOFIA), to include instrumentation relevant to astrobiological research. The fruits of these efforts will be the ability to detect dust composed of organic compounds.

Understanding the factors that influenced the prospects for life in our Solar System is essential for assessing the likelihood for life in extrasolar planetary

systems. Calculations by members of the UCLA lead team reported this year describe impacts between bolides (asteroids, comets) and Earth−like planets, suggesting that rather than blowing away nascent atmospheres, bombardment by small planetesimals may actually have contributed to the volatile reservoirs of rocky planets. This means that while impacts of asteroids or comets may be responsible for frustrating the evolution of life to complex forms, the most well−known example being the mass extinction at the end of the Cretaceous period on Earth, impacts may also be at least partly responsible for creating life−sustaining atmospheres and hydrospheres similar to those of the Earth.

Collaborations between UCLA's cosmochemists, astronomers, and astrobiology researchers resulted in new studies of the chemical evolution of protoplanetary systems. Regardless of whether Earth's complement of volatiles are of exogenous or indigenous origin, mechanisms for mixing dust and water ice in the protoplanetary nebula that surrounded our nascent Sun was clearly an important process leading to habitable environments in the Solar System. Investigations were begun this year into the role that water played in establishing the chemical and isotopic characteristics of primitive rock materials accessible today in the form of meteorites. Results suggest that heterogeneous reactions involving dust grain surfaces, oxygen, and water may have had a significant influence on the chemical and isotopic evolution of planet precursors in the solar nebula. Photochemistry is a significant component of this complicated chemical network that may also include organic compounds.

Celestial Influences on Planetary Environments

The long−term consequences of planetary and satellite orbits for habitability was a central theme for several theoretical studies here at UCLA in 2002/2003. These studies reveal possible connections between bolide impacts and chaos in the motions of the inner planets of the Solar System, suggesting that the extent to which life is permitted to evolve may depend on the stability of orbital systems. As if to underscore the point of these theoretical studies, this year the UCLA team reported new geological evidence for the influence of Solar System dynamics on Earth history. They found that rock layers from South Africa laid down 3.2 billion years ago contain significant quantities of asteroid material. This large amount of extraterrestrial material, representing three giant impacts that occurred over an interval of only 20 million years, testifies to a ten−fold enhancement in the flux of asteroidal material to Earth relative to the present day.

Orbital dynamics calculations were also used to predict which of the extrasolar planetary systems discovered to date, each containing at least one Jupiter−like giant planet, could also harbor terrestrial planets in stable orbits. Other calculations carried out by our team shed new light on the ways that Jupiter's Galilean moons respond to gravitational stresses that are compatible with stable rotational states. In addition, equilibrium models of conductive and convective heat transfer published by members of our team this year show that the Galilean moons Europa, Ganymede, and Callisto may all have subsurface liquid water oceans. These studies indicate that although Europa is the most likely to contain liquid water, a warm layer may exist beneath a stagnant lid of ice on both Ganymede and Callisto due to the temperature

dependence of the viscosity of water.

Characterization of Earth's Early Life

The antiquity of life on Earth remains controversial. Doubts about the veracity of examples of extremely ancient life on Earth are a significant impediment to astrobiology (if we can't find it here, how can we find it out there) and have stimulated the UCLA research program. Studies seeking to establish or refute evidence for life prior to ~3 billion years ago were buoyed this year by development of new techniques for characterizing what appear to be 3.4 billion year old microscopic fossil organisms. With these techniques, researchers at UCLA are examining these purported microfossils in order to apply and refine criteria for biogenicity. Among the new capabilities brought to bear on this problem this year is the ability to image fossil cellular structures at the nanometer scale of observation and spectroscopic methods that quantify the state of preservation of ancient kerogen.

Geobiology and the Geochemistry of Early Earth

Geochemical and biogeochemical cycles on ancient Earth were investigated through several fruitful collaborations between investigators from other NAI lead teams and the UCLA team. The pivotal tool for this area of research was the ion microprobe at UCLA.

Measurements of sulfur isotope ratios in sulfide inclusions in diamonds from a Kimberlite pipe from Botswana were obtained this year. The isotope ratios exhibit a non−mass dependent fractionation that is a signature of atmospheric processing. These exciting new data demonstrate that sulfur that resided in Earth's primitive anoxic atmosphere during the Archean found its way to the depths of Earth's mantle where it ultimately was incorporated into sulfide minerals only to be returned to the surface again by the violent explosion that formed the Kimberlite structure. The sulfur isotope ratios thus provide a long−term tracer of mass movement between the atmosphere and the lithosphere that will have profound consequences for our understanding of the evolution of the sulfur geochemical cycles of the primitive Earth. The sulfur cycle is in turn connected with the development of the biosphere.

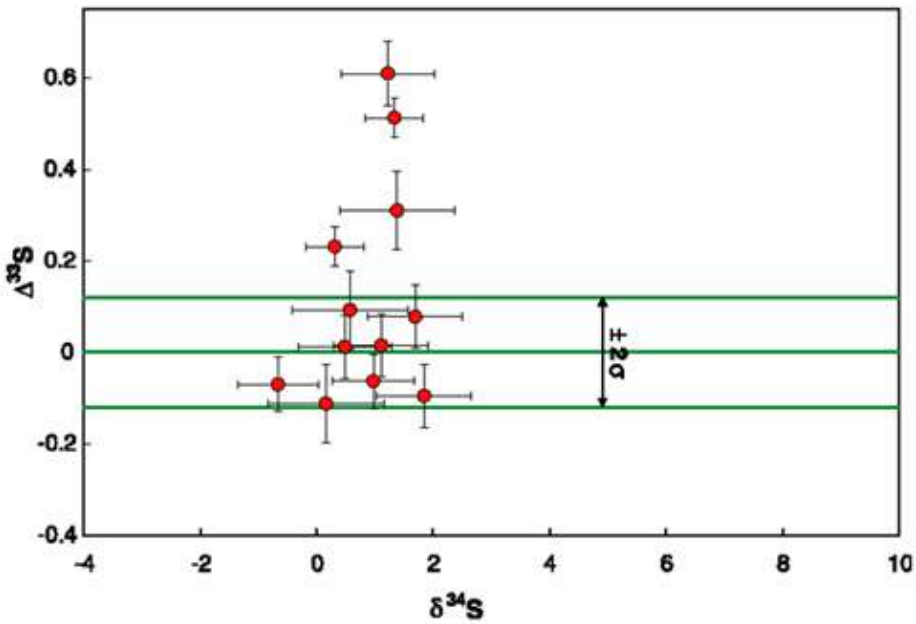

Figure 2. *Plot of ^{33}S and ^{34}S of sulfide inclusions from individual diamonds from the Orapa kimberlite pipe (red points). The shaded region centered around $^{33}S = 0$ represents the mass−dependent field. Four points are distinguished from this field and constitute evidence for S cycling between the atmosphere and the deep mantle of the Earth. Data and plot from Farquhar et al. (2002).*

More sulfur isotope data were obtained that show unequivocally that the non−mass dependent isotopic signature that appears to be a marker for an O_2−free atmosphere is preserved in sulfur bearing minerals greater than 2 billion years old. These new data lay to rest the controversy about whether or not the non−mass dependent isotope effects observed in ancient rocks are artifacts of the analytical technique; the ion probe data collected at UCLA are not subject to the same analytical uncertainties associated with the vacuum line methods used previously.

UCLA began an international collaboration (in particular with workers at the Australian National University) to investigate Earth's earliest surviving minerals during this report period. To date, the UCLA laboratory has been used to identify numerous zircon grains with ages that exceed 4 billion years. The grains, collected from Jack Hills, Western Australia, afford opportunities to investigate the age of Earth's atmosphere and subaerial weathering on the planet. These studies will help to characterize the global habitats that gave refuge to emergent life on Earth.

Like today, primitive organisms likely affected their surroundings and vice versa on primitive Earth. A cross−team collaboration with colleagues at Penn State was begun in year 5 in which mechanisms of element exchange between the biological and inorganic chemical realms on ancient Earth were investigated. In the experiments conducted this year, conversion of olivine, a major constituent of the primitive crust of our planet, to the hydrous mineral

serpentine was performed with and without microbes present. Preliminary results suggest that the microbes have a profound effect on these heterogeneous mineral−water reactions. As part of this project, our team has constructed a new, state−of−the−art laboratory for measuring the isotope ratios of Mg, Fe, and other "metals" that are useful tracers of physicochemical processes mediated by microorganisms.

Genomic Evolution and the Tree of Life

Work continued on the role that horizontal gene transfer may have played in accelerating the evolution of prokaryotic life on Earth. Analyses of various taxa demonstrate that the process of horizontal gene transfer operates between organisms occupying similar environments.

This year also saw publication of the transorientation hypothesis proposed by members of the UCLA team. This hypothesis presents a mechanistic, structural model for decoding and proofreading during protein synthesis. The mechanism described by the transorientation hypothesis is dominated by transfer ribonucleic acid (tRNA) conformational changes as well as tRNA−messenger RNA (mRNA) interactions, and points to these molecules as progenitors of protein synthesis in a pre−existing RNA world.

Explorations of the origin and evolution of eukaryotic energy−generating organelles also progressed during this fifth year of our program. The most recent sequencing and phylogenetic analyses appear to be at odds with the hydrogen hypothesis for the origin of eukaryotes which holds that eukaryotes arose from an anaerobic, hydrogen−dependent archaebacterium host and a eubacterium symbiont that produced molecular hydrogen as a waste product.

Developmental genetics during the Cambrian explosion of evolutionary change was studied with an emphasis on the development of sensory structures. A key aspect of the work in year 5 has been the acquisition of sequence data for genes that may produce identifiable morphological expression in the Cambrian fossil record.

NASA ASTROBIOLOGY INSTITUTE
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[July 2002 - June 2003]

Project Report: Celestial Influences on Planetary Environments

Lead Team:	***University of California, Los Angeles***
Project Title:	***Celestial Influences on Planetary Environments***
Project Investigators:	***Michael Ghil , Gerald Schubert , Bruce Runnegar***

Project Progress

Work continues on reconstructing Earth's orbital and climate history for the past 100 million years. Possible connections between chaos in the motion of inner planets and asteroid impacts are being investigated with new numerical simulations. Our team made significant progress on coupling orbital−dynamical and viscoelastic modeling of the Galilean satellites this past year. We obtained detailed information on the likely rotational states (so−called Cassini states) of the Galilean moons. This information is now being used to interpret data from the Galileo space mission. We have discovered that simple, commonly adopted viscoelastic models of deformations may lead to rotational instabilities. Combining our simulation results with observations is expected to provide new constraints on the internal structures of the Galilean satellites.

Results of a geochemical study of three early Archaen spherule beds from Barberton, South Africa, were reported in 2003. The three units have anomalous Cr isotope ratios that, together with large Ir anomalies, confirm that they contain substantial components of extraterrestrial material resembling carbonaceous chondrite meteorites. The beds appear to be global ejecta from very large−body impacts that were larger than the Cretaceous−Tertiary event. Since all three of these major events occurred within 20 million years of one another, it appears that the flux of impactors at ca. 3.2 Ga was an order of magnitude greater than today.

Papers from the Rubey Colloquium on Impacts and the Origin, Evolution, and Extinction of Life held at UCLA were published this year.

Highlights

- Having completed an exhaustive study of the stability of the most important orbital configurations in the 2:1 orbital resonance, we are now able to predict which extrasolar planetary systems could harbor terrestrial planets in 2:1 orbital resonance with a Jupiter−class planet.

- We have established definitive evidence for a large flux of meteorite

material striking the Earth about 3.2 billion years before present.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Cross Team Collaborations

Results on stable resonant orbits in multi−planet systems have expanded through collaborations with N. Haghighipour. Dr. Haghighipour is a member of the Carnegie Institution of Washington NAI lead team. The collaboration has resulted in two presentations thus far (the NAI General Meeting and the annual meeting of the Division of Dynamical Astronomy of the American Astronomical Society.)

−Dr. Frank Kyte (UCLA) and Dr. Peter Ward P.I. (University of Washington) NAI lead team jointly organized The UCLA Rubey Colloquium. Dr. Kyte was guest editor of the Spring 2003 issue of Astrobiology, which contains the Rubey Volume, available for free on the internet at http://www.liebertpub.com/AST/.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Characterizing Earth's Early Life

Lead Team:	***University of California, Los Angeles***
Project Title:	***Characterizing Earth's Early Life***
Project Investigator:	***J. William Schopf***

Project Progress

During this past year, results from this project have established the means to correlate biological cellular morphology with biological organic chemistry −− a long−sought but technically difficult advance. Direct measurements of microfossils in situ have yielded new evidence by which to discriminate between true fossils and pseudofossil look−alikes and, thereby, a significantly firmer basis by which to evaluate putative evidence of ancient life on Earth.

Specifically, two papers published this past year present results of development and first application of laser−Raman imagery to exceedingly ancient microscopic fossils (3,375 and 3,465 Myr old). The spectra establish the carbonaceous (kerogenous) composition of these microscopic objects and demonstrate the usefulness of this new technique for eludication of the biogenicity of minute fossil−like bodies of putative biological origin (Schopf et al., 2002). Atomic force microscopy (AFM) has also been applied to what appear to be ancient microscopic fossils (650 Ma old). The AFM study not only established the carbonaceous (kerogenous) composition of these objects but also demonstrated the usefulness of this novel technique (as applied here) for establishing the nanometer−scale structure of the organic matter (kerogen) comprising these objects, data that also provide means to discriminate between true biological fossils and mineralic "look−alikes" (Schopf et al., 2002). Both laser−Raman spectroscopy and AFM are well established techniques but are relatively new as tools for investigating the biogenicity of putative ancient fossil materials. Both provide means for one−to−one correlation of fine structural morphology with chemical composition. Both provide new insight into the chemical makeup of ancient microscopic fossils. Both seem certain to be applied to any putative fossils or fossil−like objects detected in rock samples to be returned from Mars.

Based on the work completed this year, studies are underway that are designed to develop means to: (1) map optically −− at a micron−level scale and in three dimensions −− individual microscopic fossils (by use of new digitized, computer−aided techniques); (2) correlate such optically discernable micron−scale morphologies with chemical composition by mapping chemically,

in three dimensions, individual microscopic fossils using digitized Raman images and computer−aided techniques; and (3) use Raman spectroscopy/imagery of ancient carbonaceous matter to develop a geologically useful pre−metamorphic low−temperature (

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere

Field Expeditions

Field Trip Name: International Field Workshop on the Vhyndian Basin	
Start Date: December 3, 2002	***End Date:*** December 11, 2002
Continent:	***Country:*** India
State/Province: Uttar Pradesh (Varanasi)	***Nearest City/Town:***
Latitude: 82°E	***Longitude:*** 26°N
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Examination of one of the world's best Paleoproterozoic to Neoproterozoic basin successions and the paleontological/geochemical evidence for early life and its environment	
Members Involved: James Lyons	

Cross Team Collaborations

Ongoing collaborative work of the University of Alabama (UAB) team (Kudryavtsev, Wdowiak, and Agresti) with members of the UCLA Astrobiology Institute (Schopf and Czaja) continues. In addition to the Raman imaging facility, this work has benefited from the presence of a Lindberg tube furnace in the Schopf laboratory capable of heating fossil−bearing samples up to 1500 C under argon, thus providing a means to simulate the natural transformations that have affected over the eons the once−living specimens under study. Raman spectra obtained at different heat−treatment temperatures resemble spectra of various fossil specimens; correlation with degree of preservation may help clarify the chemical species and processes giving rise to these spectra.

Written expressions of support (transmitted late February to Ed Young) for maintaining the UAB Raman facility and placing it in the service of the wider Astrobiology community have been obtained from five distinguished researchers, who also express the desire to personally avail themselves of the facility at a future date. A strong effort will be made during the next few months to coordinate their visits to UAB for this purpose. With their affiliations, these researchers are:

- Raymond E. Arvidson, Washington University
- David J. Des Marais, NASA Ames Research Center (ABI)
- Jack D. Farmer, Arizona State University (ABI)
- Andrew H. Knoll, Harvard University (ABI)
- David A. McKay, NASA Johnson Space Center (ABI)
- Curso de Astrobiologi-a: UCLA's Bruce Runnegar jointly organized the five day course with the Spanish Centro de Astrobiologi-a, (Juan Perez Mercader) San Lorenzo de El Escorial, July 21, 2003. http://astrobiology.ucla.edu/CAB/Escorial.html.

NASA ASTROBIOLOGY INSTITUTE
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[July 2002 - June 2003]

Project Report: Constraining the effects of taphonomic bias on the Cambrian explosion

Lead Team:	***University of California, Los Angeles***
Project Title:	***Constraining the effects of taphonomic bias on the Cambrian explosion***
NAI−NRC Postdoctoral Fellow :	***Susannah Porter***

Project Progress

My proposed project was to understand how preservational biases influenced the early fossil record of animals, with implications for understanding the pattern of the "Cambrian explosion". During the last nine months, I completed and submitted a study on the role of phosphatization in influencing the record of the earliest skeletal animals. This study found that these organisms are preferentially preserved through secondary phosphatic replacement, and that the prevalence of phosphatization declined by a factor of two from the Early to the Middle Cambrian, with a significant drop at the boundary. Disappearance of most of these early animals at the Early/Middle Cambrian boundary has traditionally been considered to signal the first major extinction of the Phanerozoic Eon; this study calls into question that assumption and indicates that much of the drop may reflect the closure of a "preservational window". This paper has been accepted to the journal, PALAIOS.

Since then, I have reconsidered the feasibility of assessing the role of preservational bias in the Cambrian explosion. Instead I have spent time developing two new projects, both of which would contribute to our understanding of the Neoproterozoic−Cambrian biological transition. One focuses on the paleoecology and evolution of middle Neoproterozoic microbial communities, with the goal of understanding the links between the extreme environmental changes that occurred during this interval of Earth history and the concomitant radiation of microbial eukaryotes. A second project explores the early evolution of a suite of complex life that is often overlooked: the seaweeds. Although early representatives appear 1200 million years ago, seaweeds do not become diverse until the latest Neoproterozoic and Cambrian. This project will focus on the flora of the Burgess Shale and other lagerstätten of similar age; surprisingly, these diverse seaweeds have not been well studied since Walcott's initial work in 1919.

Highlights

- The fossil record of the earliest animals may be significantly influenced by preservational bias.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Exploration for Life in the Solar System

Lead Team:	***University of California, Los Angeles***
Project Title:	***Exploration for Life in the Solar System***
Project Investigators:	***William Newman , David Paige , Gerald Schubert***

Project Progress

Progress was made concerning the origin and nature of the earliest terrestrial atmospheres, specifically with regards to the heavy bombardment period of the early solar system. Mischna and Newman showed that large impacts (up to perhaps 100x the K/T impactor in mass) may contribute to a planet's volatile reservoir, thus serving as a source for early atmospheres, as long as the planet is sufficiently large (~Earth−sized). For Mars−sized planets, it is difficult to retain a substantial atmosphere through impact accretion. The culmination of this work has been the submission of a manuscript detailing the numerical and analytic calculations. In the upcoming year, Mischna and Newman hope to extend this work to include statistical simulations of the impact conditions of the inner solar system both during the heavy bombardment and in subsequent time.

Significant progress has been made on the theoretical basis for tidally heated habitable zones in general, and in Europa in particular during this past year. A new methodology for solving the coupled orbital and rotational dynamics of rigid bodies was developed by Varadi, Musotto Moore, and Schubert and was submitted for publication (Varadi et al., 2003). A study of the orbital evolution of the Galilean satellites was also published (Musotto et al., 2002), in which the influence of Jupiter's oblateness on the shape of the satellites' orbits was shown to be quite significant, especially in the case of Io. The extension of this theory to deformable bodies is underway. The development of a semi analytical technique for studying the stability of orbits in the three body problem was developed in collaboration with Nader Haghighipour of the Carnegie Institute (Haghighipour et al., 2003).

The thermal evolution of tidally heated bodies is the critical link between tidal heating and habitability, and Io, though not very biologically promising, provides important constraints on the dynamics of such bodies. The nature of Io's thermal equilibrium was studied in a paper by Moore (Moore, 2003), where it was demonstrated that Io's heat is probably transported by melt segregation rather than thermal convection.

Progress was made this year on studies of the likelihood for subsurface liquid water oceans within the icy Galilean satellites. The work of Spohn and Schubert suggests that a liquid water ocean is likely to exist on Europa beneath a few tens of kilometers of ice even in the absence of tidal heating. A liquid water ocean beneath about a hundred kilometers of ice is also plausible for Ganymede and perhaps Callisto. The effects of possible subsurface oceans on the tidal dynamics of Ganymede and Callisto were studied by Moore and Schubert.

We also studied the conditions under which pore water in carbonaceous chondrite parent bodies would have undergone thermal convection in the protoplanetary phase of Solar System history (Young et al., 2003). The goal was to constrain the volumes of water that were contained in the building blocks of rocky planets; estimates of water volume in asteroidal bodies represented by meteorites depend critically on whether or not the water moved. The main parameters controlling whether or not pore water undergoes convection are the concentration of primordial heat sources and the permeability and size of the bodies. Pore water convection is expected to occur in bodies larger than several tens of kilometers in radius.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Field Expeditions

Field Trip Name: 2002 Licancabur Expedition	
Start Date: October 16,2002	***End Date:*** November 9, 2002
Continent: South America	***Country:*** Chile
State/Province: Antofagasta, Chile	***Nearest City/Town:***
Latitude: 22	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Geophysics Task Lead characterizing physics of the environment at the highest lake on Earth−−search for evidence of hydrothermal circulation/geothermal heat input determine analogy to similar (ancient) environments on Mars (volcanic lakes, impact crater lakes); http://www.extremeenvironment.com/team/index.htm	
Members Involved: Andrew Hock	

Field Trip Name: Licancabur Training Excursions	
Start Date:	***End Date:***
Continent:	***Country:***

State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: North America; Lassen Volcano, Lassen Volcanic National Park, CA; Mount Elbert, CO (Leadville, CO); Freediving in Lake Helen−−Lassen Volcanic National Park, CA.; All aforementioned field training for training in field methods and high altitude safety for Ames Code Q−−selected data (heart rate, O2 saturation) relayed to Dr. Peter Hackett, collaborating high altitude physiologist.	
Members Involved: Andrew Hock	

Field Trip Name: Rapolano Terme Hot Spring Investigation	
Start Date: April 12, 2003	***End Date:*** April 13, 2003
Continent: Europe	***Country:*** Italia−Morroco
State/Province: Siena	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collaborator in MIT survey of hot springs−− measured pH, temperature, flow rate, TDS of springs to support microbiological survey;	
Members Involved: Andrew Hock	

Cross Team Collaborations

2002 Licancabur Expedition Education and Public Outreach: Website: http://www.extremeenvironment.com/ Students nationally and internationally submitted questions online, which were answered live from the field, as well as throughout the year. Field updates were listed frequently, and two student contests were held. Teacher resources developed (lesson plans and links for Chile, Bolivia, Astrobiology, etc. at (http://www.extremeenvironment.com/resources/index.htm) School visits, lectures: following the expedition, we visited and spoke at one public and one private school in Antofagasta, Chile.

Collaboration with project ARISE (http://www.projectarise.org/) to enhance public science education in rural areas, through the Shasta County Office of Education.

NASA ASTROBIOLOGY INSTITUTE
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[July 2002 - June 2003]

Project Report: Extra Solar Planetary Systems

Lead Team:	***University of California, Los Angeles***
Project Title:	***Extra Solar Planetary Systems***
Project Investigators:	***Eric Becklin , Andrea Ghez , Brad Hansen , Michael Jura , Ian McLean , Benjamin Zuckerman***

Project Progress

Work continued on the search for young nearby stars that are prime targets for direct imaging detection of extra solar planets. Advances included discovery of about a dozen more members to the nearest, youngest stellar group known to date, the Beta Pictoris moving group. We also identified a handful of new TW Hydrae members and about a dozen new Tucana/HorA members. To date, ~200 young nearby stars have been identified. Observational search for massive planets around young main sequence stars continues.

Work also continued on adapting Stratospheric Observatory for Infrared Astronomy (SOFIA) instrumentation for astrobiology research. This included defining the GRISM spectrometry and filters needed in the UCLA FLITECAM 1−5m cameras and the Cornell FORCAST 5−40m camera. Organic dust signatures are seen throughout this wavelength range.

The properties of dust orbiting main sequence stars with the Keck telescopes remained an area of active research this past year. A paper published this year on the debris disk around Beta−Pic shows that the crystalline silicate feature at 9.6m is strong in the region 5 to 10 AU from the star, but disappears at 15 to 20 AU from the star. A paper on the dust content of stars in the TW Hydra association is ready for submittal.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Siding Spring Observatory	
Start Date: 07/25/02	***End Date:*** 08/01/02
Continent: Australasia	***Country:*** Australia
State/Province: New South Wales	***Nearest City/Town:***
Latitude: 31D16M	***Longitude:*** 49D03M
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Astronomical observation for young nearby stars.	
Members Involved: Inseok Song	

Field Trip Name: W.M. Keck Observatory	
Start Date: 11/12/02	***End Date:*** 11/15/02
Continent:	***Country:*** United States
State/Province: Hawaii	***Nearest City/Town:***
Latitude: 19D49M	***Longitude:*** 155D28M
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Observation of planetary disks around young stars.	
Members Involved: Inseok Song	

Field Trip Name: Lick Observatory	
Start Date: 1/10/03	***End Date:*** 1/14/03
Continent: North America	***Country:*** United States
State/Province: California	***Nearest City/Town:***
Latitude: 37D21M	***Longitude:*** 121D38M
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Astronomical observation of young nearby stars.	
Members Involved: Inseok Song	

Field Trip Name: Lick Observatory	
Start Date: 2/19/03	***End Date:*** 2/20/03
Continent: North America	***Country:*** United States

State/Province: California	***Nearest City/Town:***
Latitude: 37D21M	***Longitude:*** 121D38M
Name of site(cave, mine, e.g.):	***Keywords:*** Astronomical observation of young nearby stars.
Description of Work: Inseok Song	
Members Involved: Inseok Song	

Field Trip Name: Las Campanas Observatory	
Start Date: 03/22/03	***End Date:*** 03/31/03
Continent: South America	***Country:*** Chile
State/Province: La Serena	***Nearest City/Town:***
Latitude: 29D00M	***Longitude:*** 70D42M
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Astronomical observation of young nearby stars	
Members Involved: Inseok Song	

Field Trip Name: Siding Spring Observatory	
Start Date: 04/11/03	***End Date:*** 04/17/03
Continent: Australasia	***Country:*** Australia
State/Province: New South Wales	***Nearest City/Town:***
Latitude: 31D16M	***Longitude:*** 149D03M
Name of site(cave, mine, e.g.):	***Keywords:*** Astronomical observation of young nearby stars.
Description of Work: Astronomical observation of young nearby stars.	
Members Involved: Inseok Song	

Cross Team Collaborations

Becklin, Song and Zuckerman continued their collaboration with Alycia Weinberger of the Carnegie DTM NAI. Two joint papers were published on Dust Disk's around young stars. Three joint observing runs at Keck in Hawaii and Carnegie Observatgory in Chile were also conducted.

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Genomic Evolution and the Tree of Life

Lead Team:	***University of California, Los Angeles***
Project Title:	***Genomic Evolution and the Tree of Life***
Project Investigators:	***David Jacobs , Patricia Johnson , James Lake***

Project Progress

Horizontal gene transfer greatly accelerates genome evolution and Innovation. We are comparing the genomes of eight prokaryotes and related horizontal gene transfer (HGT) to environmental and genomic properties of the organisms and their habitats. Extensive statistical analysis of HGT among the ortholog trees for eight taxa has revealed that HGT is strongly influenced by genomic and environmental factors, so that organisms living in similar environments preferentially exchange genes with other organisms that have similar environmental parameters. As a result, we infer that HGT has accelerated prokaryotic genome innovation and evolution by a factor of about 104. In practical terms, the number of unique prokaryotic genes that would be "invented" in a ten thousand year period if HGT were absent, can in fact be "invented" in a single year.

This year also saw publication of the transorientation hypothesis. This hypothesis presents a mechanistic, structural model for decoding and proofreading during protein synthesis. The model invokes a 5'−stacked transfer ribonucleic acid (tRNA) bound to a decoding site, the D−site, which is distinct from the well−known A−site. Upon hydrolysis of GTP by EF−Tu, the D−site tRNA switches from the 5'−stacked conformation to the 3'−stacked geometry. This conformational change causes the tRNA to rotate (transorient) about the relatively fixed codon−anticodon pair, from the D−site into, or close to, the A−site. The mechanism described by the transorientation hypothesis is dominated by tRNA conformational changes as well as tRNA−mRNA interactions, and points to those molecules being the progenitors of protein synthesis in a pre−existing RNA world.

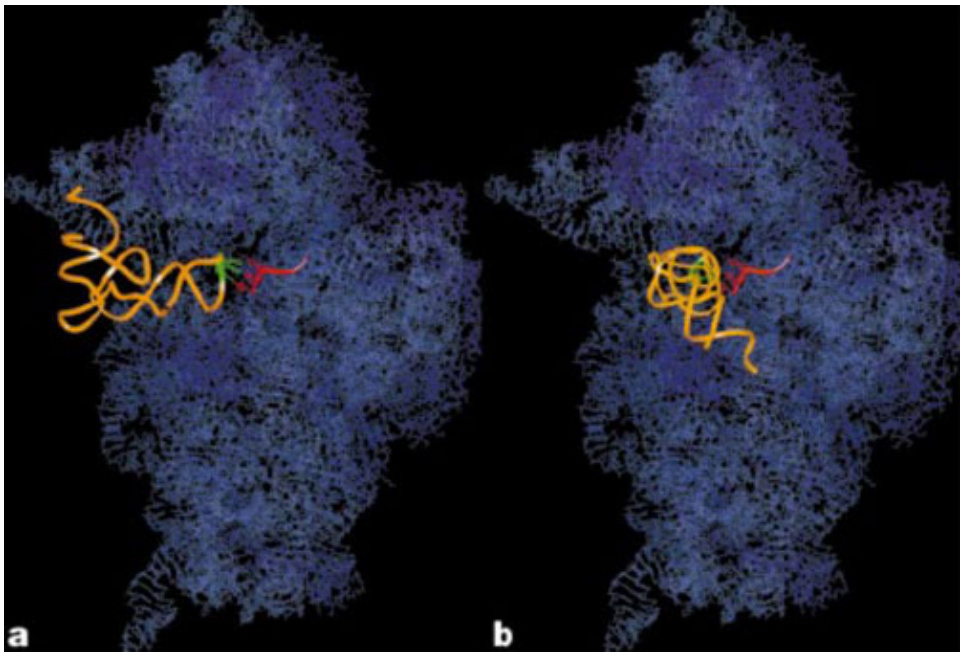

Figure 1. *a) 5'−stack tRNA (yellow ribbon) is shown docked in the D−site, on the 30S ribosome (blue) (PDB ID: 1FJF). The 5'−stacked anticodon (green) base−pairs with the message RNA (red). b) The tRNA is shown docked in the A−site of the 30S tRNA (adapted from Simonson and Lake, 2002).*

Progress was made on our work on the developmental genetics relevant to the rapid evolution of morphology at the base of the Cambrian Period. In terms of sensory structures, our work on the POU gene family indicates the presence of a suite of genes involved in sensory structure development and sensory cell differentiation in cnidarians, ctenophores and sponges. We are examining the expression of these genes in the jellyfish Aurelia. Rapid progress has been made with another family of genes, the sine oculis /Six genes, as well. We have obtained sequence of these genes throughout the basal Metazoa. The sine oculis work is the subject of a recently completed Master's thesis (Ilona Bebenek). We have accumulated data relating to the posterior addition as a basal aspect of the developmental genetic program of Bilateria. We have some sequence data on the gene caudal accumulated by a Ph.D. student (Chris Winchell). We intend to integrate these data with morphologic evidence of the mode of development available in the fossil record. Our previous work on the engrailed gene has suggested the possibility that one aspect of the ancestral function of this gene is in bounding the ectodermal skeletons of bilaterian invertebrates. Artem Kouchinsky, a Russian Post Doc, is joining the lab to further pursue this evolution from the molecular side of the question. Simple analysis for the issue of rates, dates and the timing of the metazoan radiation establish that the early dates of the protostome/deuterostome divergence are based on biased data. The demonstration of this bias is useful as it allows one to understand the disparity in dates recovered in molecular clock analyses.

The long term goals in collaboration with our cross−team partner Dr. Andrew Roger of Dalhousie University, is to determine the origin and evolution of eukaryotic energy−generating organelles derived from eubacterial sources

(e.g. plastids, mitochondria, hydrogenosomes) to test hypotheses for the origin of eukaryotic cells. The mitochondrion arose by an endosymbiotic event involving a proteobacteria that was either subsequent to or concurrent with eukaryogenesis. It is clear that aerobic metabolic capacity came into eukaryotes with the mitochondrion. There are however, diverse anaerobic eukaryote lineages that lack mitochondria, for which it is not clear how they acquired their energy producing pathways. Some of these possess an alternative energy−generating organelle, the hydrogenosome. Phylogenetic evidence suggests that this organelle is derived from the same endosymbiont that gave rise to the mitochondrion; however, it is not clear whether its constituent energy producing enzymes are of the same origin. To address this issue, two genes encoding proteins associated with hydrogenosomal energy production have been analyzed using phylogenetic assays, in two amitochondriate protists, the free living anaerobic flagellate, Trimastix and the anaerobic commensal gut, Retortamonas. The complete sequence of pyruvate:ferredoxin oxidoreductase (PFO) from Trimastix and Retortamonas and gene sequences for two paralogs of a second key enzyme in anaerobic metabolism, hydrogenase, from Retortamonas, have been obtained. Comprehensive phylogenetic analyses reveal that PFO acquisition occurred very early and only once in eukaryotic history. The data, however, do not allow the gene to be traced back to its prokaryotic progenitor. Unlike PFO, hydrogenase has come into eukaryotes multiple times. Interestingly, our phylogenetic trees of hydrogenase have uncovered the best−supported evidence for horizontal gene transfer (HGT) between two distantly related eukaryotic lineages (Retortamonas and Entamoeba). HGT and extensive prokaryotic gene duplications renders these data unsuitable for tracing the ancestries of hydrogenase to any particular bacterial group. Overall, these data do not support the notion that key enzymes in anaerobic metabolism share a common ancestry with the progenitor of the mitochondrion, the so−called 'hydrogen hypothesis' for the origin of eukaryotes. Nevertheless, current data on phylogenies are insufficient to refute this hypothesis, hence relevant gene sequences from additional divergent anaerobic eukaryotes and eubacteria will be necessary to clarify the origin and evolution of energy metabolism in eukaryote.

Sorel Fitz−Gibbon continued her collaboration with Christopher H. House (Penn State University Astrobiology) refining, applying and interpreting phylogenetic trees based on whole−genome sequence data. Their results suggest that the last common ancestor of the Archaea was a sulfur reducer and that methanogenesis arose only once, later, after the divergence of Crenarchaea and Euryarchaea.

Highlights

- We reconstructed phylogenies (one for each orthologous gene set) and calculated HGT.
- We developed novel algorithms to automatically and optimally delineate sets of orthologous and paralogous genes among any number of prokaryotic genomes.

- We developed an algorithm to enumerate and classify all 10395 trees resulting from the HGT process involving eight taxa.

- We analyzed some twenty thousand gene orthologs in eight complete bacterial genomes in order to understand the effect of the environment on horizontal gene transfer.

- The origin of sensory structures as sensory structures and motor response distinguish animals from other multicellular organisms.

- We identified terminal addition as the ancestral mode of development in bilaterian Metazoa.

- We determined the potential homology of bilaterian skeletogenesis.

- We examined issues regarding protein clock dating of the metazoan radiation.

- We constructed phylogenies for two key enzymes in anaerobic energy metabolism from two amitochondriate protists.

- Phylogenetic analyses indicate that PFO acquisition occurred very early and only once in eukaryotic history, but it does not allow its prokaryotic progenitor to be identified.

- Hydrogenase has come into eukaryotes multiple times.

- Phylogenetic analyses of hydrogenase have uncovered strong evidence for horizontal gene transfer (HGT) between two distantly related eukaryotic lineages (Retortamonas and Entamoeba).

- HGT and extensive prokaryotic gene duplications preclude tracing the ancestries of hydrogenase to any particular bacterial group.

- New data do not support the notion that key enzymes in anaerobic metabolism share a common ancestry with the progenitor of the mitochondrion, the so−called 'hydrogen hypothesis' for the origin of eukaryotes; nor do they refute this hypothesis.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Cross Team Collaborations

Study on Protein−Protein Interactions and HGT in collaboration with Dr. Monica Riley, Lake et al. has attempted to define sets of genes that are subject to more frequent horizontal gene transfer (HGT) and genes that are less frequently horizontally transferred. This analysis has been based on protein interactions in metabolic pathways in E. coli. In parallel, this sort of analysis has been extended to yeast, using the Database of Interacting Proteins in collaborations with Dr. Ionnis Xenario and Dr. David Eisenberg. While our results are preliminary, we have found that there are several discriminating factors that influence the frequency of HGT.

−Sorel Fitz−Gibbon (UCLA) and Christopher House (PSU) collaborate on whole−genome based phylogenetic methods and applications, resulting in a publication.

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Geobiology and Geochemistry of Early Earth

Lead Team:	***University of California, Los Angeles***
Project Title:	***Geobiology and Geochemistry of Early Earth***
Project Investigators:	***T. Mark Harrison , Kevin McKeegan , Craig Manning , Bruce Runnegar , Edward Young***

Project Progress

We continue to pursue fruitful cross−team collaborations in the fields of geobiology and geochemistry related to astrobiology. Many new data are being generated and are currently in the final stages of preparation for submittal.

The UCLA ion microprobe laboratory has continued to serve as a unique resource for obtaining data relevant to a number of research projects involving UCLA and other NAI lead teams. The measurement of mass−independent isotope fractionation (MIF) effects in sulfur from a variety of ancient materials was a primary focus for the last year. In one project, with Steve Mojzsis (U. Colorado), we found D33S anomalies ranging up to 2 permil in Archean sedimentary sulfides from Greenland and Western Australia. Our results provide unequivocal supporting evidence, obtained by a completely independent technique, for the existence of mass−independent sulfur isotope anomalies in Archean sulfides, as discovered by James Farquhar (University of Maryland) and collaborators. The data support the notion of an anoxic atmosphere on the Earth before ~ 2Ga. The presence of MIF sulfur in sulfides from a 3.8 Ga Fe−rich quartzite from Akilia Island is consistent with a marine sedimentary origin for this rock. This is significant since this same sample was shown to exhibit isotopically light carbon, suggestive of biogenic fractionation by Mojzsis and coworkers. In a second study, conducted with Farquhar and his postdoc B. Wing, we discovered MIF sulfur effects preserved in sulfide inclusions in diamonds from the Orapa Kimberlite pipe, Kaapvaal−Zimbabwe craton, Botswana. The data indicate that sulfur was transferred from the atmosphere to the source regions of diamonds and thus have implications for sulfur cycling in the Archean. We continue to work on various projects related to understanding sulfur cycling through Earth history, both UCLA−led and in collaboration with the U. Colorado and U. Maryland groups.

Additionally, we have participated in an international consortium, led by T. Mark Harrison, to investigate the Earth's earliest surviving minerals. We have assisted Harrison in performing ion microprobe Pb−Pb analyses of > 10,000

detrital zircons from the Jack Hills, Western Australia. These reconnaissance studies succeeded in identifying individual zircons > 4.2Ga. These ancient samples are designated for a host of geochemical analyses that will address diverse questions from the origin of the atmosphere to the nature of Earth's oldest known crustal materials.

A cross−team collaboration with Penn State was initiated in 2002−2003. In this study UCLA graduate student Tracey Herrera spent one month at Penn State in summer, 2002, conducting experiments on culturing Methanopyrus kandleri. The purpose of the work was to culture this organism during reaction of olivine to serpentine. We succeeded in identifying optimum conditions for Methanopyrus growth, as well as in determining the effects of organism growth on fluid composition. The work was presented at the NAI meeting at Arizona State University.

A new facility for measuring stable isotope ratios was nearly completed this past year at UCLA. the new laboratory will facilitate projects dealing with the origin of carbon isotope ratio excursions in limestones of marine origin that mark major shifts in ocean chemistry and correlate with mass extinctions. Our group will collect carbon isotope ratio data on sections of limestone from Siberia that mark one such global isotopic excursion during the Lower Cambrian. By providing enhanced time resolution in the C isotopic record that can be correlated with biostratigraphic zones, this work should help resolve questions surrounding the causes of these enigmatic times in Earth history that ultimately lead to an expansion in biological diversity.

Work was also completed on a new multi−collector inductively coupled plasma−source mass spectrometer (MC−ICPMS) laboratory at UCLA that will permit us to examine the interchange of metals (e.g., Fe) between the biological and inorganic chemical realms. The capabilities afforded by this new facility completed this year will be used to investigate the ecology of primitive organisms that existed on ancient Earth using the isotopes of Fe and Mg as indicators of the mutual dependence of the organisms and their geochemical surroundings.

Highlights

- Discovery of MIF sulfur in inclusions in diamond: Farquhar J., Wing B. A., McKeegan K. D., Harris J. W., Cartigny P., and Thiemens M. H. (2002) Mass−independent sulfur of inclusions in diamond and sulfur recycling on early earth. Science 298(5602), 2369−2372.

- Confirmation of mass−independent sulfur isotope fractionation in sedimentary sulfides provides further evidence for an anoxic atmosphere in the Archean: Mojzsis S. J., Coath C. D., Greenwood J. P., McKeegan K. D., and Harrison T. M. (2003) Mass−independent isotope effects in Archean (2.5 to 3.8 Ga) sedimentary sulfides determined by ion microprobe analysis. Geochimica Et Cosmochimica Acta 67, 1635−1658.

- Completion of a state−of−the−art new stable isotope facility for

applications in astrobiology, including gas−source and MC−ICPMS mass spectrometers and various sample introduction systems.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement****
1	Stardust	McKeegan, Science Team member − research analysis techniques, background research
2	SCIM	McKeegan, − research analysis techniques
1	Genesis	McKeegan, Co−I

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Development of isotopic analysis methods by SIMS is relevant to these missions, all of which plan to return extraterrestrial materials for laboratory isotopic measurements.

Field Expeditions

Field Trip Name: Paleoproterozoic sediments of Northern Finland	
Start Date: 6/12/02	***End Date:*** 7/1/02
Continent: Europe	***Country:*** Finland
State/Province: Rovaniemi, Lapland	***Nearest City/Town:***

Latitude: N65 57'34.6"	***Longitude:*** E24 28'46.6"
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Sample collection for investigating of sulfur and nitrogen isotopic compositions of sediments spanning the Great Oxidation event.	
Members Involved: Stephen Mojzsis	

Field Trip Name: Early Archean sediments of Western Australia	
Start Date: 6−9−2003	***End Date:*** 7−5 2003
Continent:	***Country:*** Australia
State/Province: Jack Hills	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Sample collection for investigating geochronology, trace elements and inclusion mineralogy of Hadean (pre−4 million year old) zircons.Stephen Mojzsis, T. Mark Harrison, D. Papineau	
Members Involved: Stephen Mojzsis	

Cross Team Collaborations

University of Colorado and UCLA Teams collaborated on various investigations of sulfur isotope geochemistry and geochronology of rocks from West Greenland and Hadean zircons from Western Australia.

University of Maryland and UCLA collaborated on the sulfur isotopic records as preserved in diamond inclusions.

−A cross−team collaboration with Penn State occurred in 2002−2003 in which UCLA graduate student Tracey Herrera spent one month at Penn State in summer, 2002, conducting experiments on culturing Methanopyrus kandleri. The purpose of the work was to culture this organism during reaction of olivine to serpentine. We succeeded in identifying optimum conditions for Methanopyrus growth, as well as in determining the effects of organism growth on fluid composition. The work was presented at the NAI meeting at Arizona State University.

−Alex Pavlov (U Colorado) and James Lyons (UCLA) are starting a

collaborative modeling effort aimed at understanding the relationship between oxygen and sulfur isotopes in the proterozoic atmosphere.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: University of California, Los Angeles

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Susannah Porter
Project Title: Constraining the effects of taphonomic bias on the Cambrian explosion
Advisor: Bruce Runnegar, Advisor
NAI Lead Team: University of California, Los Angeles
Fellowship Began In: September 2002

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

EPO: University of California, Los Angeles

These are the Education and Public Outreach activities for the University of California, Los Angeles.

Astrobiology at UCLA: The Rubey Colloquium

The Rubey Colloquium:
Proceedings of the 10th Rubey Volume were published this year. The volume is a collection of papers based on presentations at the Rubey Colloquium held at UCLA Feb 8 9, 2002. F.T. Kyte was the guest editor of the Spring 2003 issue of Astrobiology, which contains the Rubey Volume. It is available on the Internet at http://www.liebertpub.com/AST/. Collateral activities included initiation of the Impact Focus Group within NAI by F.T. Kyte and Rubey co−chair P.D. Ward and Kyte's participation in the NAI field conference on Archean Surface Processes, held in Barberton, South Africa at the end of this year.

Astrobiology at UCLA: NAI Minority Institution Research Sabbatical

NAI Minority Institution Research Sabbatical

The NAI Minority program completed its first year with three participants.

Dr. Mohammed Mahood, Howard University: Dr. Mahood's research sabbatical was spent at the Carnegie Institution of Washington with Dr. Andrew Steele.

Dr. Lekan Latinwo, Florida A Dr. Lekan Latinwo's research sabbatical was spent with Dr. Michael Thomashow at Michigan State University.

Dr. Todd Gary, Tennessee State University: Dr. Todd Gary's research was spent with Dr. James Lake at UCLA. Dr. Gary has continued his collaboration with the Lake lab. Currently, Dr. Lewis Myles from Tennessee State University is working alongside Dr. Jack Farmer, Arizona State University

UCLA is proud to announce its successful selection for the next five years to the NASA Astrobiology Institute. In doing so, UCLA will be the first NAI team to include a successful minority participant as a member of its team, Dr. Todd Gary, from Tennessee State University.

Team member Laval was a luncheon speaker at Tennessee State's 24th Annual University Wide Research Symposium.

UCLA team members' participation at various Minority Institutions symposia and workshops:

August 2002−Laval − Annual Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) Conference, Anaheim, California.

September 2002 − Laval and Rivera − NASA Goddard Minority Institutions Astrobiology Collaborative Meeting− Baltimore, Maryland.

October 2002 − Rivera − Mexican American Engineering and Science Society Annual meeting, Anaheim, California
March 2003 −Laval and Rivera − Bennett College NASA Science Week, Greensboro, North Carolina.

Astrobiology at UCLA: Curso de Astrobiologia

The Curso de Astrobiologia was held in the Euroforum Infantes training center in San Lorenzo de El Escorial, Spain, July 21−26, 2002. The course was jointly sponsored by the Centro de Astrobiologia (CAB) and the NASA Astrobiology Institute (NAI) and was presented in Spanish and English with simultaneous translation. Course directors were Dr. Juan Pérez Mercader, Director, Centro de Astrobiologia, Madrid, and Dr. Bruce N. Runnegar, Director, Center for Astrobiology, NASA Astrobiology Institute, University of California, Los Angeles.

Course description − Astrobiology is a new field that aims to answer three fundamental questions: How does life begin and evolve? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond? The lecturers for the course are Spanish and American astrobiologists. They presented their perspectives on current ideas, technologies, and missions of importance in Astrobiology the discipline.

Dr. Albert Sacco, Jr., astronaut, was the featured speaker. Dr. Sacco, payload specialist, flew on STA−73, which launched on October 20, 1995, and landed at the Kennedy Space Center on November 5, 1995.

Approximately 20 participants from the United States NAI lead teams attended the Curso de Astrobiologia.

Astrobiology at UCLA: UCLA Superstars Series

The UCLA Center for Astrobiology continues its second season of the bi−monthly public lecture series on Astrobiology called "Astrobiology Super

Stars." The lectures are held at the Midnight Special Bookstore, a popular independent bookstore on the Third Street Mall in Santa Monica, California.

Topics covered a wide variety of Astrobiology subjects and our distinguished researchers this year were faculty and senior researchers at UCLA's Organismic Biology, Ecology and Evolution, Earth and Space Sciences, and The Institute of Geophysics and Planetary Physics departments.

The lectures were video taped to preserve a permanent archive of the events. Future project for the lectures will be to develop a Web−based archiving to stream the lectures for public access.

August 11 Dr. Michael Vendrasco − Lecturer, UCLA Earth Space Sciences Luck or Fate In the History of Life.

October 13 Dr. Ruth Gates − Senior Researcher, UCLA Organismic Biology, Ecology and Evolution, The Evolution of Animal Eyes and Ears.

December 8 Dr. Indira Venkatesan − Senior Researcher, UCLA Institute of Geophysics Planetary Physics DDT in the Santa Monica Bay.

Astrobiology at UCLA: UCLA's Astrobiology Society

The UCLA AstroBiology Society (ABS) was founded in 1999 and is, as far as we know, the first official student group anywhere to be devoted to Astrobiology. ABS is co−sponsored by the NAI UCLA team and the Center for the Study of Evolution and the Origin of Life.

Though astrobiology is a new and exciting field that has a tremendous capacity to engage the imagination of the public, few people know about it or understand its scope. We believe that many more students would be interested in pursuing astrobiology, either professionally or as an extracurricular activity, if they were given proper exposure to the field.

In 2001, the UCLA AstroBiology Society developed the idea to hold an "Astrobiology Symposium" to assist in spreading the word about the field to the UCLA community and the general public. The product was an astrobiology symposium entitled "Life in the Universe" held Sunday June 1, 2003, on the UCLA campus. The featured speakers were Mr. Bill Nye (the science guy) and Dr. Jill Tarter, Director, Center for SETI Research. The event was co−sponsored by: NASA Astrobiology Institute, the UCLA Center for Astrobiology, the Center for the Study of Evolution and the Origin of Life (UCLA), the UCLA

Center for Student Programming, and the Planetary Society.

Astrobiology at UCLA: Invited Foreign Lectures

UCLA team members involved in lectures abroad:

Professor William Schopf:

2002 −Xiamen Univ., China: Keynote All−Campus Lecturer
2002 −Cosmo Ciaxi Museum of Natural History, Madrid, Spain: Distinguished Lecturer
2002 −European Workshop on Exo/Astrobiology, Graz, Austria: Plenary Lecturer
2002 −Cyanobacterial Nitrogen Fixation, Tomar, Portugal: Invited Symposium

Professor James Lake:

Fall 2002 −University of Montreal, Canada: Colloquium "Microbial Revolution: concepts and controversies: The Tree of Life and Horizontal Gene Transfer." Summer 2002 −Fondation des Treilles, France: "The Evolution of Multicellular Animals." Spring/Summer −London Linnean Society Symposium, Burlington House: "Intraclonal Genetic Variation: Ecological and Evolutionary Aspects". Spring/Summer −Cambridge University, U.K. Zoology Department: Does Horizontal Gene Transfer Accelerate Evolution?

Professor T. Mark Harrison:

May 8, 2003 −Canberra Astronomical Society: "When Did Life Emerge on Earth?"

Astrobiology at UCLA: Invited Lectures − USA

UCLA team members invited lectures − USA

Professor James Lake:

Spring 2003 −Santa Barbara, California, University of California: Evolution of the Multicellular Animals MCD Biology Seminar Series.
Spring 2003 −St. Augustine, Florida, Whitney Laboratory of the University of Florida: Evolution of the Multicellular Animals.
Winter 2003 −Horizontal Gene Transfer Accelerates Genome Evolution and Innovation. University of California, Irvine: Ecology and Evolutionary Biology Seminar Series
Winter 2003 â?? DOE Annual Genome Meeting: Horizontal Gene Transfer and Comparative Genomics
Winter 2003 −Astrobiology Annual Meeting, Phoenix, Arizona: Horizontal Gene Transfer Accelerates Genome Evolution and Innovation
Winter 2003 − Astrobiology Annual Meeting, Phoenix, Arizona: A tribute to

Todd Gary, Astrobiologist

Professor William Schopf:
2002 Penn State University Geological Science: Distinguished Lecturer
2002 Carnegie Museum of National History Pittsburgh, Pennsylvania: Earth Explorers Series Lecturer
2002 Georgia Technology: Suddath Symposium Lecturer
2002 Astrobiology Science Conference, NASA Ames: Plenary Lecturer
2002 American Geophysical Union Spring Meeting: Invited Symposium Speaker
2003 San Angelo State University of Texas: All−University Distinguished Lecturer

Dr. Ferenc Varadi
California State University, Northridge, California: Guest Lecturer − Orbital Dynamics

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Astrobiology at UCLA: 2002 Licancabur Expedition

The 2002 Licancabur Expedition involved students nationally and internationally. Students submitted questions online, which were answered live from the field, as well as throughout the year.

The Licancabur volcano (5916 m) located at the boundary of Chile and Bolivia hosts the highest and one of the least explored lakes on Earth. The lake environment combines low−oxygen, low atmospheric pressure, and high−ultraviolet (UV) radiation. Sediments are formed in volcanic material. It is ice−covered most of the year but the bottom water temperature remains above freezing. These conditions make Licancabur a unique analog to ancient Martian lakes. Despite the extreme environment, living organisms are thriving in the lake.
Website: http://www.extremeenvironment.com/

The Licancabur project aims at exploring and understanding this unique environment through two high−altitude expeditions in 2002 and 2003 that will provide:

(1) Critical astrobiological information about the limits of life on Earth

(2) Scientific clues about potential analogous sites on Mars

(3) Elements to design science mission strategies for planetary exploration and search for life in the Solar System

Field updates were listed frequently, and two student contests were held. Teacher resources were developed (astrobiology lesson plans and links for Chile, Bolivia). http://www.extremeenvironment.com/resources/index.htm

School visits and lectures followed the expedition. The team visited and spoke at one public and one private school in Antofagasta, Chile.

There was collaboration with project ARISE to enhance public science education in rural areas, through the Shasta County Office of Education. http://www.projectarise.org/

Astrobiology at UCLA: Educational Outreach @UCLA

The UCLA/NAI Center for Astrobiology team members participated in various UCLA Education Outreach activities:

Professor William Schopf:
April 5, 2002 − Co−organized an all UCLA free−of−charge public symposium, April 5, 2002, "Extinctions in the History of Life"

April 4, 2003
Organized a symposium entitled "Are We Alone in the Universe"?

Professor William Newman:

Presented public lecture on the topic of "WEEG: Physical Constraints and the Nature of Life on Extrasolar Planets" on April 2, 2003 to an audience of 40 affiliated with UCLA's Center for the Study of Evolution and the Origin of Life.

Presented course HC 35 "The Scientific Method and the Search for Extraterrestrial Life" in the Honors collegium at UCLA during the winter quarter (January−March) of 2003. This was a general education offering with 4 lecture hours per week for 10 weeks.

Proposed new course ESS 3 "Astrobiology" to be offered for the first time in the fall of 2003. The course syllabus has been approved by departmental vote and has been submitted to the University's Undergraduate Division for final approval.

Team member Barbara Laval:

Guest speaker for Department of Earth and Space Sciences GE 70 course, Introduction to Astrobiology − Astrobiology: The Search For Life.

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ANNUAL REPORT YEAR 5
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Members: University of California, Los Angeles

Team Members sorted by current team.

Name:	David Agresti
Email:	agresti@uab.edu
Institution:	University Alabama Birmingham
Name:	Eric Becklin
Email:	becklin@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Jocelyn Couetdic
Institution:	University of California, Los Angeles
Name:	Andrew Czaja
Email:	aczaja@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	David Eisenberg
Email:	daivd@mbi.ucla.edu
Institution:	University of California, Los Angeles
Name:	James Farquhar
Email:	jfarquhar@ucsd.edu
Institution:	University of Maryland
Name:	James Ferry
Email:	jgf3@psu.edu
Institution:	Pennsylvania State University
Name:	Jason Finley
Email:	jfinley@ucla.edu

Institution:	University of California, Los Angeles
Name:	Sorel Fitz−Gibbon
Email:	sorel@ucla.edu
Institution:	University of California, Los Angeles
Name:	James Garey
Email:	garey@chuma.cas.usf.edu
Institution:	University of South Florida
Name:	Ruth Gates
Email:	rgates@ucla.edu
Institution:	University of California, Los Angeles
Name:	James Gehling
Email:	gehling@geol.queensu.ca
Institution:	South Australian Museum
Name:	Andrea Ghez
Email:	ghez@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Michael Ghil
Email:	ghil@atmos.ucla.edu
Institution:	University of California, Los Angeles
Name:	Kathleen Grey
Email:	k.grey@dme.wa.gov.au
Institution:	Geological Survey of Western Australia
Name:	Nader Haghighipour
Email:	nader@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Brad Hansen
Email:	hansen@astro.ucla.edu

Institution:	University of California, Los Angeles
Name:	T. Mark Harrison
Email:	tmh@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Tracey Herrera
Email:	therrera@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Andrew Hock
Email:	ahock@ucla.edu
Institution:	University of California, Los Angeles
Name:	Seth Hornstein
Email:	seth@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Christopher House
Email:	chouse@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	David Jacobs
Email:	djacobs@ucla.edu
Institution:	University of California, Los Angeles
Name:	Ravi Jain
Email:	rjain@mbi.ucla.edu
Institution:	University of California, Los Angeles
Name:	Patricia Johnson
Email:	johnsonp@ucla.edu
Institution:	University of California, Los Angeles
Name:	Michael Jura
Email:	jura@astro.ucla.edu

Institution:	University of California, Los Angeles
Name:	Per Jögi
Email:	jogi@physics.ucla.edu
Institution:	University of California, Los Angeles
Name:	D. Keith Kirts
Email:	kkirts@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Paul Knauth
Email:	knauth@asu.edu
Institution:	Arizona State University
Name:	Artem Kouchinsky
Email:	akouchin@ucla.edu
Institution:	University of Southern California
Name:	Dana Kovaric
Email:	dkovaric@gseis.ucla.edu
Institution:	University of California, Los Angeles
Name:	Anatoly Kudryavstev
Email:	akudryav@uab.edu
Institution:	University of Alabama
Name:	Frank Kyte
Email:	kyte@igpp.ucla.edu
Institution:	University of California, Los Angeles
Name:	David LaFreniere
Email:	dlafre@ucla.edu
Institution:	University of California, Los Angeles
Name:	James Lake
Email:	lake@mbi.ucla.edu

Institution:	University of California, Los Angeles
Name:	Barbara Laval
Email:	blaval@ucla.edu
Institution:	University of California, Los Angeles
Name:	Harlan Lebo
Institution:	University of California, Los Angeles
Name:	Crispin Little
Email:	c.little@earth.leeds.ac.uk
Institution:	University of Leeds
Name:	Donald Lowe
Email:	lowe@pangea.stanford.edu
Institution:	Stanford University
Name:	James Lyons
Email:	jrl@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Craig Manning
Email:	manning@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Sabrina Mayerberger
Email:	sabrina@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Caer−Eve McCabe
Email:	mccabe@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Kevin McKeegan
Email:	kdm@ess.ucla.edu
Institution:	University of California, Los Angeles

Name:	Ian McLean
Email:	mclean@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Laurel Methot
Email:	lmethot@ucla.edu
Institution:	University of California, Los Angeles
Name:	Jeffrey Miller
Email:	jhmiller@mbi.ucla.edu
Institution:	University of California, Los Angeles
Name:	Michael Mischna
Email:	mischna@ucla.edu
Institution:	University of California, Los Angeles
Name:	Stephen Mojzsis
Email:	mojzsis@colorado.edu
Institution:	University of Colorado, Boulder
Name:	William Moore
Email:	bmoore@artemis.ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Jonathan Moore
Email:	moore@mbi.ucla.edu
Institution:	University of California, Los Angeles
Name:	James Nakatsuka
Email:	jnakatsu@igpp.ucla.edu
Institution:	University of California, Los Angeles
Name:	William Newman
Email:	newman@ess.ucla.edu
Institution:	University of California, Los Angeles

Name:	Keith Olwin
Email:	kolwin@igpp.ucla.edu
Institution:	University of California, Los Angeles
Name:	David Paige
Email:	dap@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Susannah Porter
Email:	suporter@ucla.edu
Institution:	University of California, Los Angeles
Name:	Monica Riley
Email:	mriley@mbl.edu
Institution:	Marine Biological Laboratory
Name:	Maria Rivera
Email:	rivera@mbi.ucla.edu
Institution:	University of California, Los Angeles
Name:	Andrew Roger
Email:	aroger@is.dal.ca
Institution:	Dalhousie University
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	J. William Schopf
Email:	schopf@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Gerald Schubert
Email:	schubert@ucla.edu
Institution:	University of California, Los Angeles

Name:	Jeffrey Silberman
Email:	silberman@hades.biochem.dal.ca
Institution:	University of California, Los Angeles
Name:	Anne Simonson
Email:	asimonso@ucla.edu
Institution:	University of California, Los Angeles
Name:	Leigh Ann Smith
Email:	lasmith@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Inseok Song
Email:	song@astro.ucla.edu
Institution:	University of California, Los Angeles
Name:	Paul Tackley
Email:	ptackley@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Ference Varadi
Email:	varadi@atmos.ucla.edu
Institution:	University of California, Los Angeles
Name:	M. Indira Venkatesan
Email:	indira@igpp.edu
Institution:	University of California, Los Angeles
Name:	Thomas Wdowiak
Email:	wdowiak@uab.edu
Institution:	University Alabama Birmingham
Name:	Richard Webb
Email:	rwebb@mail.arc.nasa.gov
Institution:	Ames Research Center

Name:	Alycia Weinberger
Email:	alycia@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Stuart Wolpert
Email:	stuartw@college.ucla.edu
Institution:	University of California, Los Angeles
Name:	Edward Young
Email:	eyoung@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Benjamin Zuckerman
Email:	ben@astro.ucla.edu
Institution:	University of California, Los Angeles

University of Colorado, Boulder
Executive Summary
Principal Investigator: Bruce Jakosky

The University of Colorado Center for Astrobiology continued its broad efforts that span the entire range of disciplines within astrobiology. We have substantial components within astrobiology research, teaching, and outreach, and each of these will be described briefly.

Within research, our efforts divide into several overall themes, focussing on the physical sciences, the biological sciences, and the humanities. Each of our nine Co−Investigators fits within one or two of these themes.

In the physical sciences, our efforts emphasize the formation of planetary systems (Co−I John Bally), the earliest environment and potential for life on the Earth (Steve Mojzsis), the nature and evolution of planetary habitability (Brian Toon), and the habitability and potential for life on Mars (Bruce Jakosky).

One of the outstanding questions in planet formation around newly forming stars is under what conditions planets will form and under what conditions they will not. Our new results involve observations in the Carina Nebula. This region is one in which abundant stars are forming. It was anticipated that the high density of massive stars would be destructive to the protoplanetary disks that eventually coalesce into planets. However, evidence for a large number of disks was found, making this nebula host to the largest population of disks outside of the Orion Nebula. Given that most low−mass stars are born in the immediate vicinity of highly destructive massive stars, either planet formation must be very rapid or exo−planets will be relatively rare.

Deciphering the history of the Earth's own habitability as a planet is central to understanding what makes a planet habitable. Our ongoing geological and geochemical approach to this problem included analysis of the so−called "mass−independent" sulfur isotope anomalies in Precambrian sediments. We have unequivocally demonstrated the existence of non−mass−dependent sulfur isotope fractionation in ancient sedimentary sulfides, using a new ion microprobe multicollector technique. This fractionation is thought to result from atmospheric effects involving various photochemical processes, so that its detection in sulfides tells us something fundamentally important about the nature of the atmosphere, the climate, and the oxidation state at the time of sulfide formation, as well as biogeochemical interactions in the sulfur cycle. This work is now being extended to the Great Oxygenation Event between 1.9 and 2.4 Ga ago.

We are applying our results to understanding the nature of the atmosphere, environment, climate, and habitability of Mars. Through a combination of laboratory studies and numerical modeling, we were able to show that carbon dioxide clouds are unlikely to have provided significant greenhouse warming on early Mars. This calls into question the greenhouse model that is the usual explanation for the early warm environment that allowed liquid water to flow (as reflected in the geomorphology of the surface). We also suggested an alternative model for carving the valley networks that involves transient liquid water at extremely high temperatures following impact events early in Martian history, rather than a steady−state greenhouse warming that would allow temperate liquid water to exist at the surface (Fig. 1). While we cannot yet choose between competing models, defining the range of models is important for understanding planetary habitability and our ability to extend our understanding of these processes to extrasolar planetary systems.

Along the same lines, we are examining potential micro−environments on Mars in which liquid water could exist even at sub−zero temperatures. In particular, we are looking at the ability of thin films of liquid water to form at temperatures as high as −20°C in high−latitude ground ice or polar deposits of water ice. These temperatures can occur at moderate and high obliquity values, meaning that liquid water could have been accessible essentially at the surface as recently as a few million to a few tens of millions of years ago on Mars−−essentially at the present epoch. Organisms can survive in these environments, so it is conceivable that evidence for Martian life could be found at relatively shallow depths below the surface (e.g., centimeters to meters, rather than hundreds of meters).

In the biological sciences, our efforts focus on the nature of the ribonucleic acid (RNA) World and the origin of life (Co−I Mike Yarus), gene duplication and the evolution of protein functions (Shelley Copley), microbial ecology and life in extreme environments (Norman Pace), and the evolution and nature of symbiosis (William Friedman).

What is the smallest useful RNA population? This question is key to understanding the accessibility of an RNA World, in that RNA is a very difficult molecule to make under primordial conditions. Therefore, the fewer molecules needed to provide for the evolution of biological functions, the easier it would be for them to occur; this is important both for understanding the origin of life on Earth and for understanding the potential for life to occur elsewhere. In the last year, we have shown theoretically in three different ways (two involving numerical calculations and one computer simulation) that the amount of RNA needed for evolution of an RNA cell (a "ribocyte") is likely to be ten or twelve orders of magnitude smaller than used in all modern selection experiments. Therefore, the RNA World seems to be immensely more accessible than has been previously supposed, and its existence as a real intermediate in the evolution of life on Earth seems much more likely. Of course, this previously unrealized 10^{10}− to 10^{12}−fold advantage must be tested experimentally.

We have begun a new project to probe the evolution of novel enzyme activities by the recruitment of pre−existing proteins. This will allow us to better understand the evolution of metabolic function in already−existing organisms

and the evolution of life beyond the initial organism. While enzymes are highly evolved to perform certain functions, they often have advantageous secondary activities as a consequence of the assemblage of highly reactive groups in their active sites. If these secondary activities become useful to the organism, then the enzyme can be recruited to perform a new function, and subsequent mutations can then lead to improvements in that new function. This process has been profoundly important in the evolution of living organisms, and understanding the ability of organisms to move into new ecological niches requires an understanding of this process. We have begun an experimental program to explore this process. During this past year, we have generated a plasmid−based library containing all of the genes in *E. coli* that we will use to test the ability to recruit genes to replace ones that have been "knocked out".

A new direction involves "ecogenomics", the goal of which is to understand the organismal makeup of extremophile communities and how the individual kinds of organisms contribute to the overall concentration of biomass. We have been investigating hypersaline microbial mats, mainly at Guerrero Negro, Baja California. The results contribute to our knowledge of the diversity of life in extreme environments (Fig 2). Although substantial effort has gone into study of chemical aspects of the Guerrero Negro system, relatively little is known about the organisms that comprise these communities. Using molecular survey methods in which ribosomal RNA genes are obtained directly from the natural environment, our results show promise of revolutionizing our view of the makeup of such communities. For example, we find that cyanobacteria, while conspicuously present in these mats, are only one component, and generally a minor component, of the numerically dominant organisms. The generally more abundant organisms are representative of the "Green Nonsulfur" phylogenetic division of bacteria (Fig. 3). This was an unexpected result that changes fundamentally the way that the community needs to be modeled.

Symbioses, the mutually beneficial relationships between two organisms, have evolved numerous times over the course of evolutionary history of life on Earth. Different forms of symbiosis have resulted in some of the most profound evolutionary radiations, such as the origin of the mitochondrion from a symbiosis between a proteobacterium and early eukaryotes, or the establishment of multicellular photosynthetic organisms (i.e., plants) from a symbiosis of fungus and green algae. We are characterizing the fungal symbiotic partners that may have been critical to the colonization of terrestrial (that is, land) environments by photosynthetic organisms. During the last year, we have discovered a complex relationship between early lineages of multicellular land plants and their fungal partners. During one part of their life cycle, the fungus provides nutrients to the host plant in exchange for a supply of fixed carbon; in another part, the symbiosis involves an entirely different fungal partner, and the plant is essentially a parasite on the fungus. This will allow us to determine whether plants radiated into terrestrial environments alone or whether fungi in association with plants were the key to the single colonization of land by photosynthetic organisms. This will have important implications for the evolution of life both on Earth and potentially on other planets.

In the humanities, Co−I Carol Cleland works on the nature of astrobiology as a (predominantly) historical science and the definition of life. Her results on the nature of definition and the ability to define life are having an impact both nationally and internationally. They suggest that we do not have, at present, the ability to formulate a cogent definition for life, given the difficulty of determining which characteristics of life are specific to terrestrial life and which might be more generally applicable. In this context, attempts to define life are analogous to attempts to define "water" prior to the development of molecular theory−−they just couldn't work.

In our teaching efforts, we offer both undergraduate and graduate courses in astrobiology, and we have recently instituted a graduate certificate in astrobiology that can be earned as an adjunct to a related graduate degree. Our mainstay undergraduate course is "Extraterrestrial Life", an upper−level non−majors course that provides an overview of the entire discipline of astrobiology; it regularly draws the maximum of 75 students each semester, and has been offered every semester for a half−dozen years. At the graduate level, we taught our graduate course in astrobiology; this course is geared toward providing a broad overview of the discipline for graduate students in either the physical or the biological sciences, and the course this year had about 15 students enrolled. In addition, a wide variety of more−specialized courses are taught within the individual disciplines of astrobiology; these include, for example, planetary atmospheres and surfaces, microbiology, and evolution.

Our outreach activities this past year involved two main efforts. First, we continued our very successful series of public symposia with one entitled "Life on Earth−−and Elsewhere?" This forum provided an opportunity in our fifth year of NAI funding to spotlight our own program, with several of the Co−Is presenting their research results across the entire spectrum of topics. Second, we began what we hope will be a long series of outreach symposia in which we take the excitement of astrobiology to other institutions. We sponsored a symposium on "Life in the Universe" at Ft. Lewis College in southern Colorado, with presentations by several of our Co−Is. This allowed us to talk about cutting−edge research and exciting directions to students who don't regularly have a chance to see this type of work, and to interact with both students and faculty in informal settings. Our intent was to use this as a "tune up", and now to begin a regular series of taking the program to other institutions at no cost to them. We have plans for a second symposium, and will be taking it to a variety of institutions that are attended in large part by students from backgrounds that are not well represented in the sciences.

In summary, we have a vigorous and first−rate astrobiology program at the University of Colorado, and we are making major progress in many of the different areas of astrobiology. Through our Center for Astrobiology, we can bring all of the components together into a broader understanding of life on Earth and the potential for life to exist elsewhere.

Figure 1. *This figure is a good summary of the work presented in the paper by T.L. Segura, O.B. Toon, A. Colaprete, and K. Zahnle Science 298, 1977−1980*

on the environmental effects of large impacts on Mars. Panel A shows the amount of water from vaporization of the impactor (dotted curve), target material (dash−one dot curve), and polar caps (dash−two dot curve), from melting the subsurface (dashed curve) and the total (solid curve) as a function of impactor size. Panel B shows the time that the planet's regolith is above 273 K as a function of impactor size. The modeled objects (100−, 200−, 250− km diameter) are shown as data points.

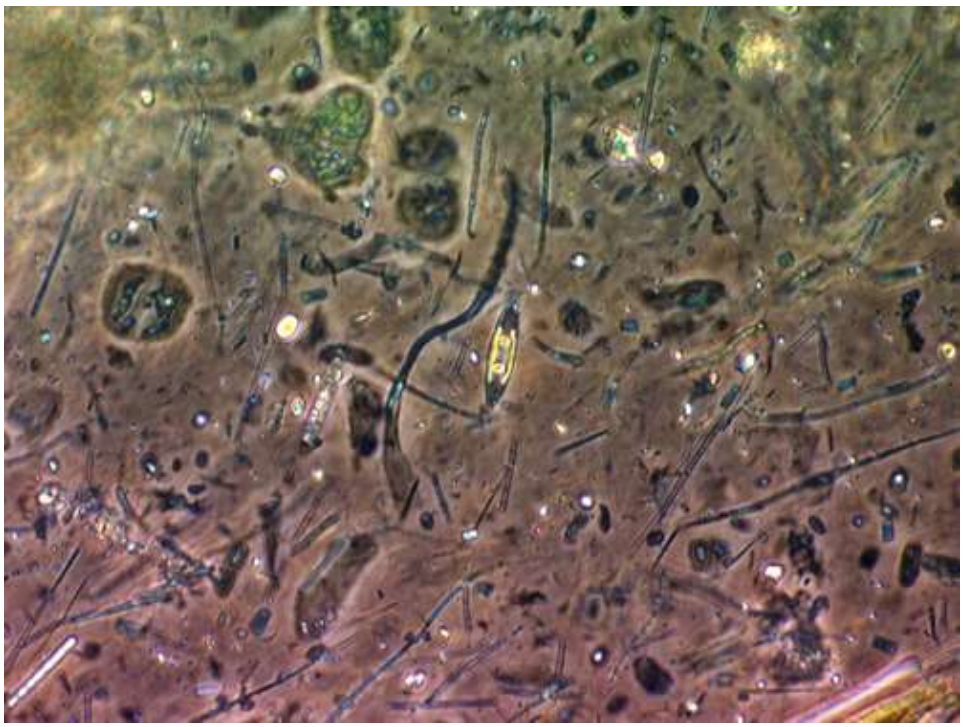

Figure 2. *Microbes in the hypersaline microbial mats of Guerrero Negro. CU Astrobiology Institute researchers, with other members of the NAI Ecogenomics Team, study these photosynthetic microbial mats as an example of extreme ecosystems. Molecular analyses have revealed that the genetic diversity of the communities is enormous.*

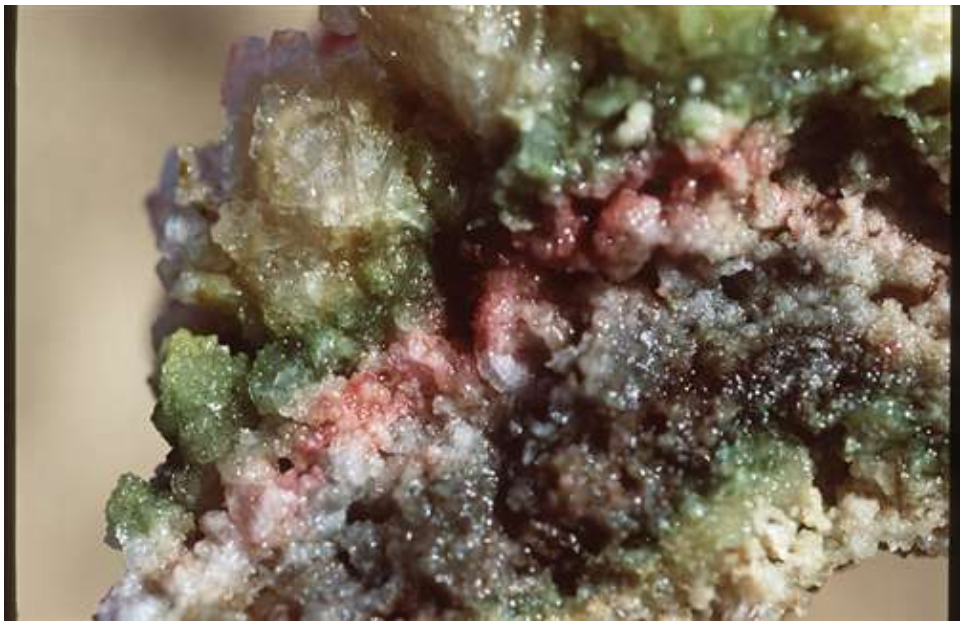

Figure 3. *Photosynthetic microbial communities in brine−saturated halite−gypsum crust from Guerrero Negro, Mexico. The Colorado Astrobiology Team studies these and other unusual microbial communities as models of life in extreme settings.*

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Biogeochemistry of the Early Earth

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Biogeochemistry of the Early Earth***
Project Investigator:	***Stephen Mojzsis***

Project Progress

Our group has been involved in several new projects this past year: (1) Geochronological studies of Archean rocks of southern West Greenland (with Harrison and Manning) and southern India (with Newton and Devaraju); (2) Nitrogen isotope and spectroscopic studies of Archean metasedimentary minerals (with Papineau and Marty); (3) Mass−independent sulfur isotope anomalies in Archean and Proterozoic sediments (with Karhu, Papineau, Coath, Greenwood, McKeegan and Harrison); (4) geochemistry of the oldest known zircons and the nature of the Hadean (pre−4 Ga) crust (with Harrison, Humayun, McKeegan, Sharma and Trail); (5) A mission to Really Early Earth drilling project (Harrison). We have manuscripts recently published, in press or submitted for the above projects. Laboratory development is also on going as we create an Astrobiology Materials Research Center at University of Colorado.

Highlights

- Resolving the age of the oldest known sedimentary rock − We described a new isotope depth−profiling technique on zircons that resolve controversies over "inherited" ages vs. true magmatic ages for complex early Archean polymetamorphic terranes. This is important in determining the timing of the emergence of the biosphere on Earth (with Manning and Harrison).

- Mass−independent sulfur isotope anomalies in Precambrian sediments − we have unequivocally demonstrated the existence of mass−independent sulfur isotope fractionations in ancient sedimentary sulfides using a new ion microprobe multicollector technique. These signatures provide information about early terrestrial atmospheric chemistry as well as biogeochemical interactions in the sulfur cycle. This work is being extended to the Great Oxygenation Event between 1.9 and 2.4 Ga (with McKeegan, Karhu, Harrison, Coath, Greenwood, Papineau).

- Discovery of evidence for live 244Pu in pre−4 Ga zircons − This research confirms that the Earth began with chondritic Pu/U (with Harrison).

- Nitrogen in early Archean sediments − We have extended measurements to trace the origin of biological nitrogen fixation from the analysis of ammonium in metasedimentary rocks to ~3.8 Ga (with Marty, Karhu, Papineau).

- Ancient zircon quest − We have completed ion microprobe analyses on >15,000 zircons to identify candidate zircons with ages 4.0 − 4.4 Ga for inclusion mineralogy, oxygen isotopes and trace element studies (with Harrison, McKeegan, Crawford, Humayun, Sharma).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Paleoproterozoic sediments of northern Finland	
Start Date: June 11, 2002	***End Date:*** June 22, 2002
Continent: Europe	***Country:*** Finland
State/Province: Lapland (Lappi)	***Nearest City/Town:***
Latitude: N66	***Longitude:*** E24
Name of site(cave, mine, e.g.): Rantamaa	***Keywords:*** sulfur isotopes, Mass−independent isotope fractionation, Paleoproterozoic, oxygen
Description of Work: We carried out 10 days of fieldwork: mapping and sampling localities in northern Finland that span the time period 2.5 − 1.9 Ga coinciding with the Great Oxygenation Event.	
Members Involved: Stephen Mojzsis	

Field Trip Name: Paleoproterozoic sediments of southern Wyoming	
Start Date: August 1, 2003	***End Date:*** August 4, 2003
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:***
Latitude: N41	***Longitude:*** W106
Name of site(cave, mine, e.g.):	***Keywords:*** Paleoproterozoic, sulfur isotopes, oxygen, stromatolites
Description of Work: We performed sampling and mapping of localities in the Medicine Bow Mts., southern Wyoming to investigate shallow marine sediments spanning the Great Oxygenation Event	
Members Involved: Stephen Mojzsis	

Cross Team Collaborations

Team: UCLA; Collaborators: T. Mark Harrison, K.D. McKeegan, C.E. Manning

- Ongoing collaborations with the UCLA team have resulted in several publications on the Hadean zircon record of the earliest terrestrial crust and on mass−independent sulfur isotope anomalies in Precambrian sediments.

Team: Harvard; Collaborator: A.D. Anbar (University of Rochester)

- The teams collaborated on the Mission to Early Earth.

The Mission to Early Earth (MtEE) Focus Group of the NAI is one of the most successful examples of cross−team collaboration. MtEE has raised funds for an exhaustive survey of Archean sedimentary rocks from Western Australia and drill coring for non−weathered samples to be used in biogeochemical investigations. It is anticipated that the project will be fully implemented in Summer 2004.

A new effort, the Mission to Really Early Earth (MtREE) is a collaborative venture of the University of Colorado, UCLA, Australian National University and Curtin University (Perth, Western Australia) to better understand the origin and geochemistry of pre−4 Ga zircons from Western Australia.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Diversity and function of the sulfur−cycling community in hypsersaline microbial mats

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Diversity and function of the sulfur−cycling community in hypsersaline microbial mats***
NAI−NRC Postdoctoral Fellow :	***Ruth Ley***

Project Progress

Research summary:

In the past year I have conducted an intensive molecular survey of the bacterial community within hypersaline microbial mats of Guerrero Negro. The 2500 clone analysis, the largest such survey in any environment to date, has revealed unexpectedly high bacterial diversity. I have used laser confocal microscopy and fluorescent *in situ* hybridization to visualize target organisms in order to correlate the structure of the microbial community to the biogeochemical processes elucidated by our collaborators in the EcoGenomics Focus Group.

I have also participated in a study of the potential habitability of Mars' polar region soils. My contribution was to show that liquid water can exist in thin films around soil particles at below−freezing temperatures such as those predicted at periods of high obliquity. This work shows that the conditions in Mars' polar soils meet the requirements for microbial life as we know it during periods of high obliquity.

Publications:

Jakosky, B. M., K. H. Nealson, C. Bakermans, R. E. Ley, and M. T. Mellon. Sub−freezing activity of microorganisms and the potential habitability of Mars' polar regions. Astrobiology. In Press.

Spear, J.S., R. E. Ley, A. B. Berger, and N. R. Pace. The complexity of the genome pool in natural microbial ecosystems: The Guerrero Negro experience. Biological Bulletin. 168−173

1st author presentations:

Ley, R. E., J. R. Spear, K. Strain and N. R. Pace. 2003. Identification of symbionts in hypersaline microbial mats. (NASA Astrobiology Meeting, Arizona State University, AZ.)(oral)

Ley, R. E. and N. R. Pace. 2002. Microbial diversity of a hypersaline microbial mat. (National Astrobiology Institutes Executive Council Meeting, Pennsylvania State College, PA.) (oral)

Ley, R. E., J. R. Spear, and N. R. Pace. 2002. Green Non Sulfur bacteria dominate the photic zone of cyanobacterial mats at Guerrero Negro, Baja CA. Sur, Mexico. (American Society for Microbiology, Salt Lake City, UT.)

Ley, R. E., J. R. Spear, and N. R. Pace. 2002. High diversity of Bacteria in hypersaline mats at Guerrero Negro, Baja CA. Sur, Mexico. (NASA Astrobiology Meeting, NASA ARC, CA.)

Highlights

- The microbial community in hypersaline microbial mats is extremely diverse, comprised largely of unknown organisms, and dominated by an unexpected and poorly understood group: the Green Non Sulfur bacteria.
- The composition of the modern microbial mats suggests that the archaean microbial ecosystems were extremely complex and diverse systems.
- Mars' polar region soils meet the requirements for microbial life during periods of high obliquity.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities

Field Expeditions

Field Trip Name: Baja September 2002	
Start Date: 1 Sep	***End Date:*** 5 Sep
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Exportadora de Sal, Guerrero Negro	***Keywords:*** microbial mat
Description of Work: Sampling of microbial mat material for DNA extraction and microscopy	

Members Involved: David Des Marais

Cross Team Collaborations

Collaborations with other NAI teams:

NAI−Marine Biological Labs, Woods Hole, MA. PI: Mitchell Sogin.

Collaboration: I traveled to the MBL in November 2002 to use the high−throughput DNA sequencing facility run by Mitch Sogin. We generated approximately 4000 DNA sequences, which were very important contributions to this project.

NAI−NASA Ames, CA. PI: David Des Marais.
Collaboration: As a member of the EcoGenomics focus group, I participated in the field trips to the Guerrero Negro, Baja California Sur field sites in June and October of 2002. These were led by Dr. Des Marais.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Habitability of Planetary Bodies

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Habitability of Planetary Bodies***
Project Investigator:	***Owen Toon***

Project Progress

During the previous year the group led by Brian Toon and Margaret Tolbert at the University of Colorado has made progress in a number of areas. Through a combination of laboratory studies {"The condensation of carbon dioxide on water ice: Implications for the Martian atmosphere" (D. Glandorf, A. Colaprete, M. A. Tolbert, O. B. Toon), Icarus 2002).) and numerical modeling ("Carbon dioxide in an early dense Martian atmosphere", (A Colaprete, and O. B. Toon), JGR in press, (2002)} we were able to show that carbon dioxide clouds are unlikely to have provided a significant greenhouse warming in the early history of Mars. Therefore the greenhouse model to explain the ancient river valleys on Mars is seriously flawed. We were also able to use the lab data and a model to explain observed clouds on current day Mars {"Carbon dioxide snow storms during the polar night on Mars", (Anthony Colaprete, Owen B. Toon), J Geophys Res., (2002).} Building on this work, we also suggested that the Martian rivers were not formed under a more equitable climate, but rather are the results of impacts early in Mars' history. This finding means that there may never have been an extended period with warm temperatures and flowing water on Mars. Instead there may have been high temperature bursts followed by decades or centuries of rainfall interspersed with millions of years of cold temperatures such as those currently found on Mars. This is a far different environment than envisioned previously for early Mars and one that is not conducive to the origin of life at the surface.

We also made substantial progress in understanding the early atmosphere of Earth and the current atmosphere of Titan. Laboratory studies helped us understand how new particles form in Titan's atmosphere. {"Nucleation Properties of Aerosols in the Atmospheres of Mars and Titan," (D. L. Glandorf, D. B. Curtis, T. Colaprete, O. B. Toon and M. A. Tolbert), Nucleation and Atmospheric Aerosols 2000, ed. B. N. Hale and M. Kulmala, AIP vol 534, 661−664 (2000) and "Laboratory Studies of Butane Nucleation on Titan Haze Analogue, Hexane, and Acetonitrile: Application to Titan's Clouds", (D. Curtis, D. Glandorf, M. Tolbert, O. B. Toon, Mckay C, and B. Khare) Icarus, submitted.}. Further work in progress has shown us what types of particles may have formed in the early terrestrial atmosphere {Trainer, MG et al., Astrobiology yearly meeting 2003, and 2002 A. G. U. meeting.}. We are

presently writing a paper on the detailed chemistry of these particles, which is quite interesting from the point of view of sustaining atmospheres with large amounts of methane in them.

Finally we are working on a model for the hydrodynamic escape of hydrogen from early Earth. We have for the first time solved the time dependent escape equations. These should allow us to help solve the problem of the methane abundance in the early atmosphere. This work is collaborative with J. Kasting at Penn State.

Highlights

- We have produced a novel explanation for the Martian rivers, that they originated as the result of impacts. This view greatly modifies the environment that life may have originated on Mars, and suggests the only likely place is in the subsurface.

- We have for the first time created particles that may form in methane rich atmospheres also containing carbon dioxide, which may resemble that of early Earth. This work is being written up.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Odyssey	Background research
1	Cassini	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload

development, research or analysis techniques, other (specify).

Cross Team Collaborations

We have collaborated closely with C. McKay, B. Khare, A. Colaprete, and K. Zahnle at NASA Ames, and with J. Kasting in the Penn. State Program.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing: Analysis of Regions of High Spectral Variance

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing: Analysis of Regions of High Spectral Variance***
NAI−NRC Postdoctoral Fellow :	***Sara Martinez−Alonso***

Project Progress

Life on Earth thrives and may have originated in areas of hydrothermal activity, where water, energy and biogenic elements were available. Hydrothermal environments on Earth are characterized by the presence of a wide variety of mineral species. Oxides and sulfides may have acted as templates, catalysts and energy sources for the first organic reactions. Phyllosilicate minerals may have provided a substratum for the building blocks of ribonucleic acid (RNA) to assemble and grow. Minerals characteristic of hydrothermal systems (both fossil and active) can be identified through their infrared emissivity spectra by instruments such as the Thermal Emission Spectrometer (TES), onboard Mars Global Surveyor.

The large variety of mineral species characteristic of hydrothermal systems on Earth translates into a large amount of spectral variance. In order to determine what areas of Mars are more spectrally diverse, a variance index (VI) that measures the amount of spectral variance present in the TES data has been devised. A global VI map of Mars with 5−degree resolution has been produced. The spatial distribution of areas of low and high VI present a good correlation with the low and high thermal inertia regions identified from the TES data. Very low VI values dominate in vast regions of low thermal inertia, which are commonly interpreted as regions mostly covered by dust, and therefore spectrally bland. The VI maxima are located in areas characterized by high thermal inertia values, associated to surfaces dominated by rocks, susceptible of presenting a larger spectral diversity. The VI technique has been validated via a sensitivity analysis (Martinez−Alonso et al., 2003).

High VI areas are being analyzed in detail, utilizing TES data as well as higher spatial resolution data such as the Mars Global Surveyor (MGS) Mars Observer Camera (MOC) and Mars Observer Laser Altimeter (MOLA), and Mars Odyssey Themis. Areas of known mineralogical interest, as well as new

areas with previously not reported mineral occurrences, have been detected utilizing the VI method (Martinez−Alonso et al., 2002). These results show that the VI method can determine the amount of spectral variance embedded in the TES data, and therefore could be used to identify Earth−like hydrothermal systems in the surface of Mars, given that those were large enough to be detected at the TES spatial resolution.

Martínez−Alonso, S., Kindel, B.C. Mellon, M.T. (2002). Analysis of areas of high spectral variance detected in TES data [Abstract: NASA Astrobiology Institute General Meeting 2003]. Astrobiology, 2(4): 519.

Martínez−Alonso, S., Kindel, B.C., Mellon, M.T. Jakosky, B.M. (2003). Spectral variance derived from MGS−TES data as a tool to detect hydrothermal systems [Abstract]. Abstracts of Papers, 34th Lunar and Planetary Science Conference, Houston, TX. Abstract # 1805.

Highlights

- The Variance Index (VI) technique has been validated via a sensitivity analysis. This index allows the quantification of the amount of spectral information present in the MGS−TES data.

- Regions of large VI values are being analyzed: areas of known mineralogical interest, as well as new areas with previously not reported mineral occurrences, have been detected utilizing the VI method.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Data analysis Research or analysis techniques
1	Mars Odyssey	Data analysis Research or analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)

3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

In this project I am analyzing radiance data acquired by the Mars Global Surveyor TES and the Mars Odyssey Themis instruments as well as visible images acquired by the Mars Global Surveyor MOC and topography derived from Mars Global Surveyor MOLA data.

Cross Team Collaborations

This project has benefited from help provided by members of the NAI Arizona State University team. Phil Christensen organized scientific meetings for the Themis instrument. Steve Ruff, Josh Bandfield, Noel Gorelick, and Kim Murray (from the Planetary Exploration Laboratory at Arizona State University) were of great help answering questions on TES and Themis data organization.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Initiation of an RNA world

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Initiation of an RNA world***
Project Investigator:	***Michael Yarus***

Project Progress

What is the smallest useful ribonucleic acid (RNA) population? This question is a key to the accessibility of an RNA world, in that RNA is a very difficult molecule to make under primordial conditions. Therefore the fewer molecules needed to provide for the evolution of biological functions, the easier it would be to imagine their occurrence.

In the last year, we have shown theoretically in three ways (two calculations and one computer simulation) that the amount of RNA needed for evolution of an RNA cell (a ribocyte) is likely to be ten or twelve orders of ten smaller than used in all modern selection experiments. Therefore the RNA world is immensely more accessible (and its existence as a real intermediate in the evolution of life on Earth is more probable) than has been usually supposed. This previously unrealized 10^{10} to 10^{12} − fold advantage must now be tested experimentally.

Highlights

- Earlier life is more accessible than previously thought.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Molecular Survey of Microbial Diversity in Hypersaline Ecosystems, Ecogenomics

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Molecular Survey of Microbial Diversity in Hypersaline Ecosystems, Ecogenomics***
Project Investigator:	***Norman Pace***

Project Progress

Ecogenomics related activities in the Pace laboratory are focused mainly on a molecular analysis of the microbial constituents of hypersaline microbial mats, mainly at Guerrero Negro, Baja California. The goal of these studies is to understand the organismal makeup of these communities and how the individual kinds of organisms contribute to the support of this remarkable concentration of biomass. The results contribute to our knowledge of the diversity of life in extreme environments. Although substantial effort has been invested in the study of chemical aspects of the Guerrero Negro system, relatively little is known about the organisms that comprise these communities.

Most previous studies of the microbial biology of the Guerrero Negro and other hypersaline microbial mats have relied on direct microscopy or on development of cultures of microbes for laboratory studies. However, microscopy detects only morphologically conspicuous organisms, and not many microbes are culturable with standard techniques. Consequently, we are using molecular survey methods in which ribosomal ribonucleic acid (rRNA) genes are obtained directly from natural environmental deoxyribonucleic acid (DNA) by Polymerase Chain reaction and molecular cloning techniques. The studies of Guerrero Negro mats have only begun, but already promise to revolutionize our view of the makeup of such communities. Specifically, previous conclusions based on microscopy and culture have focused on cyanobacterial photosynthesis as the main source of primary productivity (conversion of carbon dioxide into biomass). We find, however, that cyanobacteria, while conspicuously present in these mats, are only one component, and generally a minor component, of the numerically dominant organisms. The generally more abundant organisms (rRNA genes) are representatives of the "Green Nonsulfur" phylogenetic division of bacteria. This was an unexpected result that changes fundamentally the way that the community needs to be modeled. The studies so far have discovered and molecularly described several hundred novel species of microorganisms.

Highlights

- We have completed a phylogenetic survey for members of the domain Eucaraya in the Guerrero Negro hypersaline mats and have found significant diversity within most kingdoms of eucaryotes present. A significant finding was the diversity in members of nematodes present and the discovery of a deeply branching, heretofore unknown, novel eucaryal kingdom of which several hundred DNA sequences were obtained.

- A phylogenetic survey for members of the domain Archaea is well underway. Several thousand clones have been sequenced and preliminary data analyses indicate that archaeal diversity is high, and that several new kinds of archaea will be identified with novel DNA sequences.

- A phylogenetic survey for members of the domain Bacteria has progressed to the point of knowing that the hypersaline microbial mats of Guerrero Negro are not dominated by members of the cyanobacteria, but surprisingly by members of the division Green Non−Sulfur. This opens up an array of questions as to how these mats form, what the mechanisms for primary productivity are, and how mats contribute to ecosystem function. At least four new candidate bacterial divisions have been discovered and are being analyzed presently.

- A separate study has revealed fascinating information about the diveristy of bacterial and archaeal life within an endoevaproite from Guerrero Negro. These gypsum/halite salt crusts have colored zones of different microbial life extending centimeters down into the crust. This study has afforded a view as to the extent of life capable of living in saturated saline conditions.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

Ruth Ley went to the Marine Biological Laboratory in Woods Hole, MA to

utilize the DNA sequencing facility of Mitchell Sogin in December 2002. She took 2800 sample clones to be sequenced for both herself and John Spear. The outcome was about 2000 good DNA sequences that are undergoing analysis in the Pace Lab here at the University of Colorado.

Both John Spear and Ruth Ley attended the "Outcomes of Genome−Genome Interactions" hosted by Mitchell Sogin and the Center for Advanced Studies in the Space Life Sciences at the Marine Biological Laboratory, Woods Hole, MA, 1−3 May 2002. The outcome was a very fruitful meeting that provided interpretation and direction to our on−going research efforts from several peers. This led to the sequencing effort described above later in the year.

Both John Spear and Norm Pace are involved with the Agouron Institute's Geobiology Program. Though not directly related to NAI, this summer course, offered at the Wrigley Marine Center on Catalina Island, trains next generation scientists and astrobiologists in all aspects of biogeochemistry. John is serving as an R.A. in the summer of 2003, Norm as a keynote speaker.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Organic and sulfur hazes in the Archean atmosphere: Climatic and photochemical consequences.

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Organic and sulfur hazes in the Archean atmosphere: Climatic and photochemical consequences.***
NAI−NRC Postdoctoral Fellow :	***Alexander Pavlov***

Project Progress

Recent discovery of the mass−independent fractionation in sulfur isotopes in the Archean sediments strongly favors extremely low atmospheric levels of oxygen in the early Earth atmosphere. Under anoxic conditions, the atmospheric lifetime of the reduced chemical species should have been dramatically longer. Therefore, anoxic Archean atmosphere was most likely rich in biologically generated CH_4 and sulfur reduced species (H_2S, SO etc.) and could have contained hydrocarbon and sulfur haze layers similar to those observed today in Titan's and Venusian's atmospheres. A substantial hydrocarbon and sulfur haze layers would have provided effective ultraviolet (UV)−shielding for the ancient biota (in the absence of ozone) and could have been an important source of "food" in the pre−photosynthetic Archean ecosystems. Also hazes would have affected Archean climate because of their "antigreenhouse effect". Lack of ancient air samples makes it hard to constrain different scenarios for the ancient world. Hazes might have produced the only "direct" imprints of the Archean atmosphere in the rock record. Therefore, the "key" questions for the Archean paleoenvironment are:

1. What were the levels of the "reduced" atmospheric gases (CH_4) in the Archean/Proterozoic atmosphere?
2. What were the "realistic" rates of hazes' production?
3. How much UV−shielding would have ancient biota gotten out of it?
4. How strong would be the climatic impact of such a haze layer and what would limit its thickness in the atmosphere?
5. What would be the elemental and isotopic composition of the haze particles?

The goal of my research is to get the quantitative answers on those questions.

Research Progress:

1. Previous photochemical simulations of the methane abundance in the Archean atmosphere (1000 ppm, Pavlov et. al., 2001) assumed diffusion limited escape of hydrogen to space. Preliminary simulations by Tian Feng show that the hydrogen escape rate in the anoxic atmosphere was several orders of magnitude smaller than the diffusion−limited escape. Therefore, abundance of methane in the Archean was most likely much higher than previously predicted and photochemical hazes should have been present throughout most of the Archean.

   Methane was expected to decrease dramatically after the Great Oxygenation Event (2.0−2.3 Gyr ago) because of the short atmospheric lifetime against oxidation. However, our recent study (Pavlov et al., 2003) shows that methane could have been still abundant (~100 ppm) even in the "moderately" oxygenated Proterozoic environment if the flux of methane from the anoxic Proterozoic ocean was ~10 times larger than the present biogenic methane flux.

2. My photochemical calculations suggest that the rate of haze formation is critically dependent on the atmospheric CH_4/CO_2 gas ratio. Melissa Trainer is simulating production of the haze particles in the laboratory experiments. She generated various types of organics under different CH_4/CO_2 ratios and indeed confirmed the cut off in haze production at CH_4/CO_2 ratio ~0.6.

There was no significant progress in 3) and 4) because the exact composition of the experimentally produced haze particles still has not been measured.

5. Recently, Ono et al. (2002) reported large positive mass−independent anomalies (D33S up to +6.9‰) in the core samples from two carbonaceous shale units (2.5 − 2.7 Ga). We proposed that the large D33S signature could be explained consistently only if the reduced sulfur aerosols (S8) were present in the anoxic Archean environment. Once formed (at ~5−6 km), the S8 aerosols would not exchange isotopes with the rest of the atmosphere and could deliver large D33S to the ground essentially intact.

Highlights

- Proterozoic atmosphere was methane−rich despite the presence of oxygen. Archean atmosphere was even more reducing because of the slow hydrogen loss from the atmosphere.

- Chemical composition of the organic aerosols depends on the atmospheric CH_4/CO_2 ratio.

- Large positive mass−independent anomalies (D33S) in the Archean shales could be the first "direct" evidence of sulfur aerosols in the Archean.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

James F. Kasting, Matthew T. Hurtgen, Michael A. Arthur, PSARC team. Our collaborative research resulted in the following paper: "Methane−rich Proterozoic atmosphere?", by Pavlov et al., 2003, Geology, v.31, p.87−90.

Douglas Rumble and Shuhei Ono, CIW NAI team. Our collaborative research resulted in the following paper: "New insights into Archean Sulfur Cycle from Mass−Independent Sulfur Isotope Records" by Ono et al. 2003, EPSL in press.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Philosophical Issues in Astrobiology

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Philosophical Issues in Astrobiology***
Project Investigator:	***Carol Cleland***

Project Progress

I have continued my work on the issue of defining 'life'. Detailed studies of the history of other scientific discoveries (e.g., the chemical composition of water, 17th century debate over whether bats are birds) reveal that defining a natural kind term (a term that designates a category of nature that is independent of human interests and concerns) in the absence of an adequately general theory does not advance scientific understanding of the phenomenon concerned and indeed may even retard the development of an adequately general theory of the phenomena. In short, logical and historical considerations demonstrate that it is a mistake to try to define 'life' in the absence of an adequately general theory of life.

I have also begun investigating the issue of how one can search for extraterrestrial life in the absence of a definition of 'life' or a general theory of living systems. The key is to have a set of reliable biosignatures for detecting terrestrial life and to use them not as definitive (as necessary and/or sufficient conditions) for life but as grounds for suspicion that life is or has been present; it is important that they not be considered definitive because there is no way of knowing in advance which ones are universal to life and which ones are unique to the peculiar circumstances (e.g., primordial conditions on the primitive Earth, contingencies of evolution) of life on Earth. This research is bringing together my earlier work on the methodology of historical science since the search for biosignatures is primarily a search for traces of past life. I am optimistic that this work will eventually yield a more effective strategy for searching for extraterrestrial life than the ones currently being employed by NASA.

Highlights

- Scientific attempts to define 'life' are misguided and counter productive; they do not advance the scientific goals of understanding the basic nature of life and finding extraterrestrial life.

- A successful search for extraterrestrial life requires neither a definition of 'life' nor a general theory of living systems.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 0.0:*** This activity does not fit one of the above categories

Cross Team Collaborations

Christopher Chyba (SETI and Stanford) and I continue to successfully work together on issues concerning attempts to define 'life'. We co−authored an article in Origins of Life and Evolution of the Biosphere ("Defining 'life'?") and have a chapter coming out in Sullivan and Baross's Planets and Life: The Emerging Science of Astrobiology.

I spent 6 months as a visiting researcher at the Centro de AstrobiologÃ-a (Madrid, Spain). I had long productive discussions with many different researchers. Perhaps the most productive of these discussions concerned the possibility that the Earth currently has a "shadow biosphere". A shadow biosphere is a microbial biosphere that is so chemically and molecularly different from life as we know it that it wouldn't be in direct competition with familiar life; familiar life couldn't metabolize it and it would occupy ecological niches that were underpopulated by familiar organisms. Such organisms might have proteins made of completely different amino acids or amino acids with the opposite chirality or it might have nucleic acids whose sugars have the opposite chirality, to name a few possibilities. I introduced the idea of a shadow biosphere to members of the Centro de Astrobiologi-a, arguing that most current theories of the origin of life hold that life is a product of chance combinations of molecular compounds and if this is so, we should expect that there must have been things such as utterly alien proteins (made of completely different amino acids), for example, and furthermore that evolutionary considerations suggest that those primitive organisms that were most different from life as we know it (e.g., had proteins containing no amino acids in common with familiar life) would have been most likely to survive competition with familiar life, yielding a shadow microbial biosphere. In response to the query "why haven't we found it?", I argued that it would be very difficult to detect with current techniques, which are based on deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) sequencing (which require the use of known enzymatic catalysts for amplification) or the ability to culture organisms (which is required for protein composition analysis). When I left, some of the researchers at CAB were intrigued enough that they were considering ways to look for my shadow biosphere!

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[July 2002 - June 2003]

Project Report: Potential habitability of Mars

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Potential habitability of Mars***
Project Investigator:	***Bruce Jakosky***

Project Progress

We are trying to understand the habitability of Mars as a way of learning about habitability of planets in general. During the past year, we have made progress on two different approaches.

First, we have been examining potential micro−environments on Mars in which liquid water could exist even at sub−zero temperatures. In particular, we are looking at the ability of thin films of liquid water to form at temperatures as high as −20°C in high−latitude ground ice or polar deposits of water ice. These temperatures can occur at moderate and high obliquity values, meaning that liquid water could have been accessible essentially at the surface as recently as a few million to a few tens of millions of years ago on Mars−−essentially at the present epoch. Organisms can survive in these environments, so it is conceivable that evidence for Martian life could be found at relatively shallow depths below the surface (e.g., centimeters to meters, rather than hundreds of meters).

Second, we are looking at the geochemical environment in which organisms might live on Mars. We have been examining in detail the ability of organisms to get energy to support metabolism from geochemical reactions in Martian hydrothermal systems. We are using geochemical models of the Gibbs energy available from redox reactions, using Martian meteorite compositions to constrain our rock composition and using a variety of reasonable assumptions about the composition of the water with which it reacts. Our results suggest that abundant energy is available, especially in potential aqueous systems that might involve relatively reduced rocks (such as olivine−rich rocks).

Results on these tasks appear in two manuscripts that are in press in the journal *Astrobiology*.

Highlights

- Liquid water can exist in thin films on Mars, where organisms could survive, and environments that can support this water can occur essentially at the present epoch.

- Abundant chemical energy exists in Martian hydrothermal systems to support microbes, if such systems exist.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	PI
1	Mars Odyssey	Co−I
2	Mars Science Laboratory	Science definition team, Co−I of planned instrument
2	Aerial Regional Environmental Survey (ARES) for Mars	Co−I on Scout study concept

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

We collaborated with Ken Nealson and Corien Bakermans (JPL/USC team), and a manuscript is in press.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Recruitment of Proteins to Serve New Functions

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Recruitment of Proteins to Serve New Functions***
Project Investigator:	***Shelley Copley***

Project Progress

A new project was begun to probe the evolution of novel enzyme activities by recruitment of pre−existing proteins. While enzymes are generally highly evolved to perform certain functions, they often have adventitious secondary activities as a consequence of the assemblage of highly reactive groups in their active sites. If these secondary activities become useful to the organism, the enzyme can be recruited to perform a new function. Subsequent mutations can then lead to improvements in that new function. This process has been profoundly important in the evolution of living organisms, providing the basis for the evolution of novel metabolic pathways that have allowed organisms to take advantage of the wide range of environmental niches available on Earth.

We have designed a new experimental system to address a fundamentally important question: from how many sources can a protein be recruited to provide a function critical for life? Some insight into this question can be gained from analysis of known proteins, but the existing repertoire of proteins reflects what did happen, rather than what could have happened. In order to define what could have happened, we plan to knock out genes required for survival in *E. coli*, and then introduce a plasmid−based library containing all of the genes in *E. coli* and ask which genes can restore viability, even at a very low level, by providing a protein that can be recruited to fill the missing function. During this first year we generated the plasmid−based library, developed the methods for recovering slow−growing strains that have recruited a new enzyme, and began to create strains in which several critical genes have been knocked out.

Highlights

- Because the project is new, we have not yet generated significant results.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

NASA ASTROBIOLOGY INSTITUTE
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[July 2002 - June 2003]

Project Report: Symbiosis and the origin of multicellularity in photosynthetic organisms

Lead Team:	***University of Colorado, Boulder***
Project Title:	***Symbiosis and the origin of multicellularity in photosynthetic organisms***
Project Investigator:	***William Friedman***

Project Progress

Symbioses, the mutually beneficial relationships between two organisms, have evolved numerous times over the course of the evolutionary history of life on Earth. Different forms of symbiosis have resulted in some of the most profound evolutionary radiations; e.g., the origin of the mitochondrion from a symbiosis of a proteobacterium with early eukaryotes, the origin of the chloroplast from a symbiosis of a cyanobacterium with an originally heterotrophic eukaryote resulting in the evolution of all photosynthetic lines of eukaryotes, and the establishment of multicellular photosynthetic organisms (plants) in terrestrial environments from a symbiosis of a fungus and a green alga.

We are characterizing the fungal symbiotic partners that may have been critical to the colonization of terrestrial environments on Earth by photosynthetic organisms. Using deoxyribonucleic acid (DNA) extraction and amplification techniques, we have begun to identify the fungal lineages that currently play a central role in the widespread symbiosis between plants and fungi (mycorrhizal association). We have chosen to work with phylogenetically basal land plant lineages so that we can reconstruct the evolutionary history of this key symbiosis. During the last year, we have discovered a complex relationship between early lineages of multicellular land plants and their fungal partners. During part of the life cycle of ancient lineages of land plants, the fungal symbiotic partner appears to supply mineral nutrients to the host plant and in return, the fungus receives fixed carbon from the plant. During another component of the plant's life cycle, the symbiosis involves an entirely different fungal partner and in this symbiosis, the plant is essentially a parasite on the fungus, receiving fixed carbon and mineral nutrients from the fungus. Thus, we are beginning to piece together a complex set of symbiotic relationships between early land plants and their fungal symbionts.

During years four and five of the currently funded NASA University of Colorado Astrobiology Program, we (Ph.D. candidate Jennifer Winther and I) began to identify (in essence, discover) some of the fungal species that grow symbiotically within the bodies of ancient lineages of plants. We have exploited

genomic small subunit ribosomal DNA (18S rDNA) and genomic ribosomal internal transcribed spacers (ITS) sequences to identify the biotypes of the fungal symbionts of early land plant lineages. Based on comparisons to databased sequences, all of the sequenced mycorrhizal fungi in ancient lineages of land plants we have studied to date belong to the genus Glomus, the same group of fungi that form symbiotic associations in most other (and recently evolved) lineages of land plants. This is the first time that mycorrhizal symbioses in early lineages of land plants have been documented on the basis of the DNA sequence identity of the fungal symbiont. Our preliminary data provide some of the first concrete molecular evidence that the extremely widespread mycorrhizal symbiosis found in extant plants may have arisen during (and potentially enabled) the earliest phases of the colonization of land by plants.

We now have evidence that approximately 75 million years after the original colonization of land by plants, and concurrent with the first increase in land plant stature from centimeters to meters, part of the life cycle of land plants became entirely subterranean (and strictly heterotrophic). This extreme alteration in the ecology of early plants appears to have been accomplished through an alteration of the symbiotic relationship of plants to their fungal partners. In essence, the flow of organic carbon from the plant to the fungus was reversed, and the plant became a parasite upon the fungus and its carbon (ultimately derived from fungal connections with other plants that are photosynthesizing). This type of subterranean habitat during a major portion of the life cycle of plants still exists today and is widely found in ancient lineages of plants. In these lineages of extant plants, the entirely subterranean heterotrophic phase of the life cycle may be as long as 15 years.

Highlights

- We are beginning to understand one of the most important symbioses in the evolutionary history of life on Earth, the mycorrhizal (plant−fungus) association in early land plant lineages.

- We are analyzing whether plants radiated into terrestrial environments or whether fungi in association with plants were the key to the single (in the 4 billion year history of life on Earth) colonization of land by photosynthetic organisms.

- We have made the first DNA sequence−based identification of a fungal partner (symbiont) in one of the most ancient lineages of land plants.

- We are beginning to piece together an unusual but important shift in the life cycle of plants: the transition to prolonged subterranean and heterotrophic phases during the upper Silurian (roughly 420 million years ago).

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in

microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Queensland Australia to collect ancient lineages of land plants and their fungal symbionts	
Start Date: 10−5−03	***End Date:*** 10−25−03
Continent: Australasia	***Country:*** Australia
State/Province: Queensland	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collected target taxa within the ancient land plant lineages of Psilotales and Ophioglossalesa from the tropical rainforests in Queensland. Collected plants were processed for molecular and developmental studies of their fungal symbionts.	
Members Involved: Jennifer Winther	

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Project Report: The Formation of Planets Around Young Stars

Lead Team:	***University of Colorado, Boulder***
Project Title:	***The Formation of Planets Around Young Stars***
Project Investigator:	***John Bally***

Project Progress

I used the Keck Observatory 10 meter telescopes to study young stars in the Orion nebula during two separate runs (in collaboration with M. Morris and R. Shuping at UCLA). In November 2002, we used Adaptive Optics (AO) and a near−infrared spectrograph (NIRSPEC) to obtain new images an spectra of low−mass protostars and their disks in the immediate vicinity of the massive stars in Orion. We measured the disk mass−loss rates, discovered new jets, and produced images as sharp as those generated by the Hubble Space Telescope. In December, we used the 10−20 micrometer wavelength camera to obtain images of the still highly embedded young stars forming in the cloud core know as OMC1 lying immediately behind the Orion Nebula.

In March, we completed a deep narrow−band imaging survey (covering nearly 10 square degrees of sky) of the Carina Nebula, a region 100 times as hostile as Orion to the survival of circumstellar proto−planetary disks. Nevertheless, we found evidence for such disks. Indeed, the Carina nebula appears host to the largest population of such "proplyds" outside the Orion Nebula.

We continue to analyze velocity−resolved Farby−Perot data cubes of the Orion nebula in our continuing investigation of the impact of clustering and radiation fields on the survival of proto−planetary disks in the type of environment in which most stars in the sky form.

I served as the curator for several astrobiology−related exhibits at the Denver Museum of Nature and Science which was opening in June 2003 as part of the museum's "Space Odyssey" exhibit. My work includes providing scientific oversight of the new Europa planetarium show slated to open in late 2003.

I taught the "Extra−terrestrial Life" course during the Spring 2003 semester. This is our flagship Astrobiology Course for undergraduates.

Highlights

- The Carina nebula appears to host the largest population of

proto−planetary disks outside the Orion Nebula.

- Most low−mass stars are born in the immediate vicinity of highly destructive massive stars. Thus, planet formation must either be very rapid, or exo−planets will be relatively rare (~3 to 10% of stars).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Terrestrial Planet Finder	Planning support, background research
2	Galactic Exoplanet Survey Telescope	Science Team member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Most stars are born in OB assocaitions along with massive stars. If the "standard model" of planet formation is the only viable path to exoplanets (e.g. if gravitational disk instability does not work), then planets will be relavively rare, and TPF will have to search to greater distances than previously thought. Furthermroe, this research is deomnstrating that several types of planetary systems not yet found may exist. For example, systems which contain close−in rocky planets but no gas giants such as Jupiter (such systems can form if only standard model works, and produces meter−scale rocky bodies in abundance by the time volatiles (H, He, etc.) are removed by photo−ablation.

Cross Team Collaborations

Mark Morris is a collaborator with the UCLA Astrobiology team.

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Fellowships: University of Colorado, Boulder

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Ruth Ley
Project Title: Diversity and function of the sulfur−cycling community in hypsersaline microbial mats
Advisor: Norman Pace, Project Investigator
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: August 2002

Recipient: Sara Martinez−Alonso
Project Title: Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing: Analysis of Regions of High Spectral Variance
Advisor: Bruce Jakosky, Advisor
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: September 2002

Recipient: Alexander Pavlov
Project Title: Organic and sulfur hazes in the Archean atmosphere: Climatic and photochemical consequences.
Advisor: Owen Toon, Advisor
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: February 19, 2002

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EPO: University of Colorado, Boulder

These are the Education and Public Outreach activities for the University of Colorado, Boulder.

Astrobiology Seminar Series

In both the fall and spring semesters of the school year, the Center for Astrobiology partners with an affiliated department on campus to bring in speakers for Astrobiology−related seminars. This year, our center partnered with the Department of Geology in the fall semester for the following talks:

September 18, 2002: Dr. Munir Humayun, The University of Chicago: "Life in an Antarctic Meteorite?"

October 16, 2002: Dr. Ariel Anbar, University of Rochester, "Fe Isotopes in Nature."

November 20, 2002: Prof. A. Jay Kaufman, University of Maryland, "Proterozoic Snowball Earths."

In the spring, we partnered with the Laboratory for Atmospheric and Space Physics (LASP) for the following talks:

February 20, 2003 − Dr. Allan Treiman, Lunar and Planetary Institute, "Martian Meteorites."

April 3, 2003 − Dr. John Grant, National Air Space Museum, "Mars Rover Landing Site Selection"

April 24, 2003 − Dr. Everett Shock, Arizona State University, "Life in Hydrothermal Environments."

Public and invited speaking engagements

The Center for Astrobiology has very active lecture and seminar participation. The public talks given by our Co−Investigators and Principal Investigator follow:

Bruce Jakosky:

− 11 Sep 02, "Mars Odyssey results in the context of Mars exploration",

(Lockheed Martin Astronautics, Denver).

− 17 Sep 02, "Life on Earth−−and Elsewhere?" (public symposium on astrobiology at CU)

− 17 Sep 02, "Life on other planets?" (presentation at "Life on Earthâ??and Elsewhere?" public symposium)

− Advisory Committee, AAAS Program on Dialogue on Science, Ethics, and Religion.

− 27 Mar 03, "Life elsewhere? Astrobiology, science, and society" (AAAS, DOSER public lecture series).

− 10 Apr 03, "Life elsewhere in our solar system?" (Astrobiology public symposium at Ft. Lewis College)

− Convener and session chair, "Frontiers of Mars Exploration: Geology, climate, and life", (AAAS meeting, Denver, Feb. 15, 2003).

− 19 Feb 03, participant in NASA Headquarters Space Science Update (press conference) on Mars snow, water, and gullies.

− Numerous interviews with print, radio, and TV media

Stephen Mojzsis:

− "Mass−independent sulfur isotopes in the Precambrian" (Geological Sciences Seminar, University of Helsinki, June 2002, Helsinki, Finland).

−Participation in 2−part series produced for NOVA on the early Earth (airs August 2003).

−Participation in numerous public lectures, newspaper and magazine interviews regarding topics in Astrobiology.

−"Mass−independent sulfur isotopes in Archean sediments" (Geophysical Sciences Colloquium, University of Chicago, November 2002, Chicago, Illinois).

−"The oldest known sediments and what they mean" (LASP seminar October 3, 2002).

−"Mission to Very Early Earth: When did conditions suitable for life emerge?" 100th anniversary celebration, CU Geological Sciences, 25 October 2002.

William Friedman:

− "The history of life on Earth: the impact of rare events" (Denver Museum of Nature and Science) with approximately 200 people from the general public in attendance.

Norman Pace:

− "The Nature and Extent of the Tree of Life" (The Episcopal Diocese of Denver, 15−17 May 2003)

− "The Search for the Tree of Life." (Invited Talk, University of Texas−−Southwestern Medical School and UT−Austin, 15−18 April 2003.)

− "The Search for the Tree of Life." (Invited Talk, University of Washington, 2−3 April 2003.)

Life on Earth − And Elsewhere?

This symposium was the 4th annual Center for Astrobiology Public Symposium. The title this year is "Life on Earth − And Elsewhere?" The speakers follow:

− Norm Pace, "Origin and Diversity of Life on Earth"

− William Friedman, "History of Life on Earth and the Impact of Rare Events"

− Bruce Jakosky, "Potential for Life on Other Planets"

− John Bally, "Extrasolar Planets"

Each speaker gave a 20−minute presentation; the last 20 minutes of the symposium were a QAsession for the audience.

Astrobiology Traveling Show

Colorado University (CU) is piloting a new program of extramural public symposia (informally called our "traveling show") to visit places that generally are not able on their own to support this type of activity. We target 2− and 4−year colleges and universities that generally do not have sufficient resources to support visits by leading researchers, and schools that serve historically underrepresented populations, and expose them to cutting edge research and the excitement of astrobiology. In this instance, we visited Ft. Lewis College in Durango, Colorado. We visited at our expense, presented an evening public symposium for their faculty, students, and the local community and visited in small groups with students and faculty.

Ft. Lewis College is a 4−year undergraduate school that historically caters to Native American students. This first symposium will involve our Co−Is William Friedman (talking about the origin and evolution of life on Earth), Bruce

Jakosky (on the possibility of life in the rest of our solar system), and John Bally (on planets and life outside of our solar system).

Discovery Science: A Program for 6th Grade Girls: Lab Tour and Experimental Support

The Boulder Valley Public Schools participated last summer in a project to expose elementary school−aged girls to active science laboratories as part of an initiative to interest girls in pursuing the sciences. Dr. Norm Pace and Dr. John Spear participated on the CU campus, taking the students on a tour of the Pace lab and demonstrating for them how to perform various lab tasks, including electrophoresis gels and other miscellaneous lab activities.

International Geobiology Course: Tour of Yellowstone National Park

Dr. John Spear and J.J. Walker, from the Pace Lab, participated in the International Geobiology Course, sponsored by USC/Agouron Institute this summer. The course consists of 20 students, 10 men and 10 women, 10 American and 10 International in some combination. The course is held at the Wrigley Marine Center on Catalina Island; the participants are then flown to another site for a field trip. John Spear and J.J. Walker conducted the course field trip tour of Yellowstone National Park.

The Microbiology of Fast Food

Spear, J.R. 2003. The Microbiology of Fast Food. Advisor to Anthony Van Haverbeke, Broomfield Parochial Schools,

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Publications: University of Colorado, Boulder

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
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Members: University of Colorado, Boulder

Team Members sorted by current team.

Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Name:	John Bally
Email:	bally@casa.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Julia Barzyk
Email:	jgmurphy@uchicago.edu
Institution:	University of Chicago
Name:	Alicia Berger
Email:	bergera@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Carol Cleland
Email:	cleland@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Christopher Coath
Email:	Chris.Coath@Bristol.ac.uk
Institution:	University of Bristol
Name:	Emily Cobabe−Ammann
Institution:	University of Colorado, Boulder
Name:	Shelley Copley
Email:	copley@cires.Colorado.edu

Institution:	University of Colorado, Boulder
Name:	Zane Crawford
Email:	Zane.Crawford@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Dan Curtis
Email:	daniel.curtis@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Andrew Dalby
Email:	andrew.dalby@colorado.edu
Institution:	University of Colorado, Boulder
Name:	John Daspit
Email:	john.daspit@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Ico de Zwart
Email:	icodezwart@bigfoot.com
Institution:	University of Colorado, Boulder
Name:	Jasvinder Dhillon
Email:	jasvin@cires.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Gamelyn Dykstra
Email:	dykstrag@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Kat Eason
Email:	astrobio@argyre.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Attila Elteto
Email:	Attila.Elteto@Colorado.EDU

Institution:	University of Colorado, Boulder
Name:	William Friedman
Email:	ned@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Megan Greening
Email:	megan.greening@colorado.edu
Institution:	University of Colorado, Boulder
Name:	James Greenwood
Email:	jmaes.greewood@yale.edu
Institution:	Yale University
Name:	J. Harris
Email:	jjharris@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Mark Harrison
Email:	Mark.Harrison@anu.edu.au
Institution:	Australian National University
Name:	Munir Humayun
Email:	hum8@midway.uchicago.edu
Institution:	University of Chicago
Name:	Bruce Jakosky
Email:	jakosky@argyre.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Juha Karhu
Email:	Juha.Karhu@helsinki.fi
Institution:	University of Helsinki
Name:	Bruce Kindel
Email:	kindel@cses.colorado.edu

Institution:	University of Colorado, Boulder
Name:	Robin Knight
Email:	Rob.knight@Colorado.edu
Institution:	University of Colorado, Boulder
Name:	Michal Legiewicz
Email:	Michal.legiewicz@Colorado.edu
Institution:	University of Colorado, Boulder
Name:	Ruth Ley
Email:	Ley@samiam.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Craig Manning
Email:	manning@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Sara Martinez−Alonso
Email:	sara.martinez@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Bernard Marty
Email:	bmarty@crpg.cnrs−nancy.fr
Institution:	CRPG−CNRS
Name:	Tom McCollom
Email:	tom.mccollom@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Kevin McKeegan
Email:	kdm@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Melanie McKinney
Email:	melanie.mckinney@lasp.colorado.edu

Institution:	University of Colorado, Boulder
Name:	Michael Mellon
Email:	mellon@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Nick Moeckel
Email:	nickolas.moeckel@casa.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Stephen Mojzsis
Email:	mojzsis@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Dan Nickerson
Email:	Daniel.Nickerson@Colorado.edu
Institution:	University of Colorado, Boulder
Name:	Norman Pace
Email:	nrpace@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Ben Pageler
Email:	Ben.Pageler@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Dominic Papineau
Email:	dominic.papineau@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Alexander Pavlov
Email:	pavlov@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Teresa Segura
Email:	segurat@colorado.edu

Institution:	University of Colorado, Boulder
Name:	Mukul Sharma
Email:	Mukul.Sharma@Dartmouth.EDU
Institution:	Dartmouth College
Name:	Heather Sickels
Email:	Heather.Sickels@colorado.edu
Institution:	University of Colorado, Boulder
Name:	John Spear
Email:	spearj@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Feng Tian
Email:	tian@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Margaret Tolbert
Email:	tolbert@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Owen Toon
Email:	btoon@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Dustin Trail
Email:	Dustin.Trail@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Melissa Trainer
Email:	trainer@ucsub.colorado.edu
Institution:	University of Colorado, Boulder
Name:	Stacy Varnes Farrar
Email:	varnes@argyre.colorado.edu

Institution:	University of Colorado, Boulder
Name:	Jeffrey Walker
Email:	Jeffrey.walker@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Kaj Williams
Email:	kaj.williams@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Joseph Williams
Email:	Joe.Williams@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Jennifer Winther
Email:	Jennifer.winther@colorado.edu
Institution:	University of Colorado, Boulder
Name:	Michael Yarus
Email:	yarus@buffmail.colorado.edu
Institution:	University of Colorado, Boulder

University of Rhode Island
Executive Summary
Principal Investigator: Steven D'Hondt

The University of Rhode Island (URI) team of the NASA Astrobiology Institute (NAI) works to gain a fundamental understanding of Earth's subsurface life. The team's research is principally, but not exclusively, focused on study of life in deeply buried marine sediments. Earth's deep biosphere is a critical component of Earth's biogeochemical cycles and serves as a model for possible life on other planets. Consequently, the team's objectives are to understand the subsurface microbial ecosystems of marine sediments, their role in Earth's biogeochemical cycles, and their relevance to the search for life on other planets.

Environments of special interest for our team include: 1) old, deeply buried sediments where life exists despite extremely low concentrations of electron donors and key nutrients, and 2) hot, deeply buried anoxic sediments where life may exist independently of the photosynthesis−based ecosystem at Earth's surface. The ecosystems of these subsurface habitats are potentially representative of the ecosystems that may exist on other planets.

The team's investigators are based at the University of Rhode Island, Woods Hole Oceanographic Institution, and the University of North Carolina at Chapel Hill. To effectively accomplish their objectives, URI team researchers collaborate with each other and with scientists at other institutions throughout the world. For example, over the last year, team members have collaborated closely with scientists at the Massachusetts Institute of Technology, the Max Planck Institute for Marine Microbiology (Germany), the NASA Ames Research Center, Pennsylvania State University, the University of Aarhus (Denmark), and the University of Miami. To gain access to subsurface environments, URI team members participate in international expeditions through the Ocean Drilling Program (ODP).

Over the last decade and a half, scientists throughout the world have documented the widespread occurrence of life deep beneath Earth's surface. However, fundamental questions about Earth's subsurface life have yet to be answered. The URI team is actively addressing many of these questions: What categories of organisms live beneath Earth's surface? How are they related to surface organisms? How closely related are subsurface organisms in geographically distant but similar environments? How much living biomass inhabits Earth's subsurface environments? What do subsurface organisms do for a living? How active is subsurface life? What is its effect on the surface

world?

To explore the taxonomic composition of subseafloor ecosystems, URI team members recently finished a 16S ribosomal ribonucleic acid (rRNA) survey of bacteria and archaea in subseafloor sediments of the Nankai Trough (Kormas et al., 2003) and are working on genetic studies of subseafloor sediments from ODP Leg 201 (in the Peru Margin and the eastern equatorial Pacific). Karen Lloyd, Mark Lever and Andreas Teske are working to isolate, polymerase chain reaction (PCR) amplify, clone and sequence diagnostic key genes for methanogens and sulfate reducers from Leg 201 samples. Antje Lauer, Ketil Soerenson and Teske are developing deoxyribonucleic acid (DNA) isolation procedures and documenting bacterial and archaeal 16S rRNA profiles from the Leg 201 samples, using Denaturing Gradient Gel Electrophoresis (DGGE).

Our genetic studies to date have revealed high diversity in subseafloor prokaryotic communities e.g., Kormas et al, 2003). They have also shown that distinct communities occur at different subseafloor depths. Our studies of bacterial nucleic acids demonstrate that several unique bacterial lineages occur repeatedly in deep subseafloor sediments, suggesting that deep subseafloor sediments constitute a unique environment (Kormas et al, 2003). These unique lineages are candidates for sharing physiological characteristics that predispose them to a subsurface mode of life. Our studies have also identified a specific archaeal phylotype (within the genus Thermococcus) with a trans−Pacific distribution pattern (Figure 1) (Kormas et al., 2003). This archaeal distribution and the repeated occurrence of bacterial lineages mentioned above demonstrate the "connectedness" of life across great distances in deep subseafloor sediments.

URI team members have also made significant headway toward documenting biogeochemical signatures of present and past microbial processes. Kai−Uwe Hinrichs, Helen Sturt, Kristin Smith and Roger Summons' analyses of intact polar lipids from microbial isolates demonstrate great potential to distinguish microbial phylotypes in natural samples on a species level. John Hayes, Hinrichs and Laura Hmelo are actively developing protocols for isotopic analysis of volatile fatty acids in subseafloor pore waters. Hinrichs, Wolfgang Bach, Hmelo and Sturt are undertaking mechanistic studies of biological hydrocarbon formation in the deep subsurface (Hinrichs et al., 2003).

These Year−5 biosignature studies have led to several interesting results. For example, one line of our biosignature study showed that concentrations of intact polar lipids in the deep subsurface are generally orders of magnitude lower than in surface sediments, reflective of significantly lower densities of microbial populations. Another line of study suggests that ethane and propane are biologically created by hydrogenation of small carbon−bearing organic and inorganic molecules in a variety of deep subseafloor sedimentary environments. Finally, a third line of biosignature study demonstrated that adsorption of biologically produced hydrocarbons is an important process in subseafloor environments. By removing these hydrocarbons, this adsorption enhances free energy yields and allows biological production of the hydrocarbons to continue in subseafloor environments (Hinrichs et al., 2003).

URI team members are also advancing understanding of subseafloor microbial activity and its effects on Earth's biogeochemical cycles. To assess relationships between cell counts and community activity, David C. Smith, Beverly Chen and Andrew Staroscik developed protocols for adenosine triphosphate (ATP) analysis of subseafloor sediments and completed ATP analyses of ODP Site 1230. Scott Rutherford, Steven D'Hondt and Arthur J. Spivack mapped global patterns of subseafloor sulfate reduction (Figure 2) and estimated their effect on the global sulfur cycle (Rutherford et al., 2003). Guizhi Wang, Rutherford, D'Hondt and Spivack are using chemical data and biogeochemical flux models to estimate net rates of several metabolic processes in subseafloor sediments (D'Hondt et al., 2003; Wang et al., 2003).

The early results of our ATP studies suggest that the active subseafloor biomass is substantially smaller than estimates of subseafloor biomass based on cell counts. This finding suggests that the living subsurface biomass may be substantially lower than generally estimated (the dead may greatly outnumber the quick in subseafloor body counts). Despite this low estimate of living biomass, our studies of subseafloor sulfur fluxes indicate that prokaryotes in deeply buried marine sediments play an important role in the global sulfur cycle; our global flux calculations indicate that subseafloor activities permanently remove about 50% of the sulfur that enters the ocean each year (Rutherford et al., 2003).

Graduate, undergraduate and post−doctoral education and research are integral parts of the URI team's mission. During the Year−5 report interval, our active research team included four post−doctoral scholars (Lauer, Soerenson, Sturt and Rutherford), three graduate students (Lever, Lloyd, and Wang) and five undergraduate students. All of these individuals played vital roles in our ongoing program. To introduce astrobiology to young scientists with particularly strong potential, this year the URI team initiated nationally competed summer research fellowships for upper−class (junior or senior) students to work with URI investigators on projects of astrobiological significance. Two summer fellows (Uri Manor and Beverly Chen) were selected from 16 applicants in this year's competition. Chen is working on the ATP studies mentioned above. Manor is working with Rutherford, Wang and D'Hondt to develop an inverse−modeling program for estimating net rates of microbial activity from deep subsurface biogeochemical data. Both students are expected to complete their fellowships in the Year−5 report period.

To build a deeper institutional base of astrobiology awareness among undergraduate and graduate scientists and engineers, URI astrobiologists expanded the academic programs of their home institutions by integrating astrobiological themes into existing microbiology courses, as well as by offering a new URI graduate course, "Subsurface Life" (Autumn, 2002), and an upper−class undergraduate URI engineering and science course, "Exploring the Ocean of Europa" (Spring, 2003). To introduce our work and the field of astrobiology to the broader public, URI team investigators gave public presentations and lectures at a variety of universities and other venues. To disseminate our work and its relevance more broadly, in the Year−5 interval the team also completed and now maintains a website on URI astrobiology efforts in research and education (http://www.gso.uri.edu/astrobiology).

In short, research, education and outreach by the NAI URI Team and its collaborators are steadily advancing knowledge and awareness of life deep beneath Earth's surface, its role in Earth's surface processes, and its relevance to the search for life on other planets.

Figure 1. Archaeal 16S rRNA tree of deep subsurface archaeal populations in Nankai Trough sediments, based on ca. 900 sequence positions (Kormas et al., 2003). The subsurface Thermococcus species in Nankai are related to Thermococcus spp. from vent effluents at the Juan de Fuca vents offshore Washington, indicating a trans−Pacific occurrence of closely related strains.

Figure 2. Map of sulfate flux to subseafloor predicted from regression of porewater data against distance from shore and chlorophyll concentration in surface waters (Rutherford et al., 2003)

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NASA ASTROBIOLOGY INSTITUTE
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Project Report: Subsurface Biospheres

Lead Team:	***University of Rhode Island***
Project Title:	***Subsurface Biospheres***
Project Investigators:	***Steven D'Hondt , Andreas Teske , Kai−Uwe Hinrichs , David Smith , Arthur Spivack , John Hayes***

Project Progress

To explore the taxonomic composition of subseafloor ecosystems, URI team members finished a 16S ribosomal ribonucleic acid (rRNA) sequencing survey for bacteria and archaea in subseafloor sediments of the Nankai Trough (Kormas et al., 2003) and are working on genetic studies of subseafloor sediments from the Ocean Drilling Program (ODP) Leg 201 (in the Peru Margin and the eastern equatorial Pacific). Lloyd, Lever and Teske are working to isolate, polymerase chain reaction (PCR) amplify, clone and sequence diagnostic key genes for methanogens and sulfate reducers from Leg 201 samples. Lauer, Soerenson and Teske are developing deoxyribonucleic acid (DNA) isolation procedures and documenting bacterial and archaeal 16S rRNA profiles from the Leg 201 samples, using Denaturing Gradient Gel Electrophoresis (DGGE). Initial results of the DGGE analyses show distinct archaeal community differences with depth at the two organic−poor sites we have focused on, ODP Sites 1225 and 1231.

URI team members have also made significant headway toward documenting signatures of present and past microbial processes. Hinrichs, Sturt, K. Smith and Summons' analyses of intact polar lipids from microbial isolates demonstrate great potential to distinguish microbial phylotypes in natural samples on a species level. Additionally, their studies of Leg 201 samples show that concentrations of intact polar lipids in the deep subsurface are generally orders of magnitude lower than in surface sediments, reflective of significantly lower densities of microbial populations. Hayes, Hinrichs and Hmelo are actively developing protocols for isotopic analysis of volatile fatty acids in subseafloor pore waters. Hinrichs, Bach, Hmelo and Sturt are undertaking mechanistic studies of biological hydrocarbon formation in the deep subsurface (Hinrichs et al., 2003).

URI team members are also advancing understanding of subseafloor microbial activity and its effect on Earth's biogeochemical cycles. To assess relationships between cell counts and community activity, D. Smith, Chen and Staroscik developed protocols for adenosine triphosphate (ATP) analysis of

subseafloor sediments and completed ATP analyses of ODP Site 1230. Rutherford, D'Hondt and Spivack mapped global patterns of subseafloor sulfate reduction and estimated their effect on the global sulfur cycle (Rutherford et al., 2003). Wang, Rutherford, D'Hondt and Spivack are using chemical data and biogeochemical flux models to estimate net rates of several metabolic processes in subseafloor sediments (D'Hondt et al., 2003; Wang et al., 2003).

Some results of these Year 4 studies are provided in the "Highlights" section of this report.

Highlights

- Our genetic analyses have revealed high diversity in subseafloor prokaryotic communities. These analyses also show that several unique bacterial lineages occur repeatedly in deep subseafloor sediments, suggesting that deep subseafloor sediments constitute a unique environment (Kormas et al, 2003). These unique lineages are candidates for sharing physiological characteristics that predispose them to a subsurface mode of life.

- Our genetic studies have also identified a specific archaeal phylotyope (within the genus Thermococcus) with a trans−Pacific distribution pattern (Kormas et al., 2003). This archaeal distribution and the repeated occurrence of bacterial lineages mentioned above demonstrate the "connectedness" of life across great distances in deep subseafloor sediments.

- The early results of our ATP studies suggest that the active subseafloor biomass is substantially smaller than estimates of subseafloor biomass based on cell counts (D. Smith, Chen and Staroscik, unpublished). This finding suggests that the living subsurface biomass may be substantially lower than generally estimated.

- Our biogeochemical studies suggest that ethane and propane are biologically created by hydrogenation of small carbon−bearing organic and inorganic molecules in a variety of deep subseafloor sedimentary environments (Hinrichs and coworkers, unpublished).

- Our biogeochemical studies also demonstrate that adsorption of biologically produced hydrocarbons is an important process in subseafloor environments. By removing these hydrocarbons, this adsorption enhances free energy yields and allows biological production of the hydrocarbons to continue in subseafloor environments (Hinrichs et al., 2003).

- Our studies of global biogeochemical fluxes indicate that prokaryotes in deeply buried marine sediments play an important role in the global sulfur cycle by removing about 50% of the sulfur that enters the ocean (Rutherford et al., 2003).

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Jupiter Icy Moons Orbiter (JIMO)	Participation in a NASA−sponsored community forum (June 2003) to help define potential scientific direction for the mission.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project develops concepts and approaches that are relevant to the search for subsurface life and subsurface habitability of Earth, Mars, the icy moons of Jupiter, and other planetary bodies.

Field Expeditions

Field Trip Name: Ocean Drilling Program Leg 207	
Start Date: 11−Jan−2003	***End Date:*** : 6−Mar−2003
Continent:	***Country:*** International waters
State/Province:	***Nearest City/Town:***
Latitude: 55W	***Longitude:*** 10N
Name of site(cave, mine, e.g.): Demerara Rise	***Keywords:*** Organic−rich Cretaceous black shales
Description of Work: Dr. Sturt sailed as a shipboard microbiologist on the JOIDES Resolution for Leg 207. She collected sediment samples to be used	

for down core profiling of intact polar lipids, phylogenetic analyses, and studies of adsorbed hydrocarbon gases.

Members Involved: Helen Sturt

Fellowships: University of Rhode Island

There are no Postdoctoral Fellowships for this team.

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EPO: University of Rhode Island

These are the Education and Public Outreach activities for the University of Rhode Island.

NAI Yr−5 E/PO Report for Subsurface Biospheres Project

To build a deeper institutional base of astrobiology awareness among under graduate and graduate scientists and engineers, URI astrobiologists expanded the academic programs of their home institutions by integrating astrobiological themes into existing microbiology courses, as well as by offering a new URI graduate course, "Subsurface Life" (Autumn, 2002), and an upper−class undergraduate URI engineering and science course, "Exploring the Ocean of Europa" (Spring, 2003). To introduce astrobiology to young scientists with particularly strong potential, this year the URI team initiated nationally competed summer research fellowships for upper−class (junior or senior) students to work with URI investigators on projects of astrobiological significance. To introduce our work and the field of astrobiology to the broader public, URI team investigators gave public presentations and lectures at a variety of universities and public venues.

To disseminate our work and its relevance more broadly, in the Year−5 interval the team also completed and now maintains a website on URI astrobiology efforts in research and education (http://www.gso.uri.edu/astrobiology).

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Members: University of Rhode Island

Team Members sorted by current team.

Name:	Wolfgang Bach
Email:	wbach@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Beverly Chen
Email:	brchen@artsci.wustl.edu
Institution:	University of Rhode Island
Name:	Steven D'Hondt
Email:	dhondt@gso.uri.edu
Institution:	University of Rhode Island
Name:	John Hayes
Email:	jhayes@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Kai−Uwe Hinrichs
Email:	khinrichs@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Laura Hmelo
Email:	lhmelo@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Christopher House
Email:	chouse@geosc.psu.edu
Institution:	Pennsylvania State University
Name:	Konstantinos Kormas

Email:	kkormas@cc.uoa.gr
Institution:	Woods Hole Oceanographic Institution
Name:	Antje Lauer
Email:	alauer@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Mark Lever
Email:	lever77@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Karen Lloyd
Email:	klloyd@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Uri Manor
Email:	manoru@SLU.EDU
Institution:	University Rhode Island
Name:	James Miller
Email:	miller@egr.uri.edu
Institution:	University of Rhode Island
Name:	Victoria Orphan
Email:	vorphan@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	April Pariseault
Email:	april@gso.uri.edu
Institution:	University of Rhode Island
Name:	Edward Roggenstein
Email:	Roggenstein@gso.uri.edu
Institution:	University of Rhode Island
Name:	Scott Rutherford

Email:	srutherford@gso.uri.edu
Institution:	University of Rhode Island
Name:	Robert Sand
Email:	sand@gso.uri.edu
Institution:	University of Rhode Island
Name:	David Smith
Email:	dcsmith@gso.uri.edu
Institution:	University of Rhode Island
Name:	Kristin Smith
Email:	Ksmith@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Bruno Soffientino
Email:	bruno@gso.uri.edu
Institution:	University of Rhode Island
Name:	Ketil Sorensen
Email:	Sorensek@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Arthur Spivack
Email:	spivack@gso.uri.edu
Institution:	University of Rhode Island
Name:	Andrew Staroscik
Email:	amstar@gso.uri.edu
Institution:	University of Rhode Island
Name:	Helen Sturt
Email:	hsturt@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Roger Summons

Email:	roger.summons@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Ben Swanson
Email:	JaminBenswa@aol.com
Institution:	University of Rhode Island
Name:	Sean Sylva
Email:	ssylva@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Name:	Andreas Teske
Email:	teske@email.unc.edu
Institution:	University of North Carolina − Chapel Hill
Name:	Guizhi Wang
Email:	gzhwang@gso.uri.edu
Institution:	University of Rhode Island

University of Washington
Executive Summary
Principal Investigator: Peter Ward

Our research at the University of Washington has centered on three important astrobiological questions: What are the characteristics of planets that can evolve complex organisms? Where might such planets occur? How does biological complexity evolve on a planet, and how might it end?

We are beginning the third year of research into these questions. Below, our results and progress is summarized based on specific research problems defined in our original proposal.

How often, where, and under which conditions do habitable planets form and persist? We define a habitable planet as a solid body capable of supporting life as we know it. The study of extra−solar habitable planets involves a broad interdisciplinary approach that extends from understanding how planets are formed to understanding the conditions that allow such life to originate, survive, and evolve. During the past year (2002−2003), Lucio Mayer and Tom Quinn Mayer and Quinn have continued performing simulations of giant planet formation by fragmentation of a gaseous disk, and have published their results in Science. They are extending previous work by considering the effect of different equations of state on the outcome, and by continuing the calculation for longer periods of time. Lufkin and Quinn have started simulations of giant planet migration in gaseous disks, while Barnes and Quinn in collaboration with Lissauer (Ames) continue their simulations of planetesimal accretion in the terrestrial region. They have made progress in speeding up this computationally challenging calculation. The aim is to determine the mass spectrum of planetesimals coming out of the middle stage of planet formation as a function of distance from the Sun. The information to date suggests that the gravitational instability model appears to be viable, and therefore giant planets should be common. Secondly, planet migration appears to be a chaotic process.

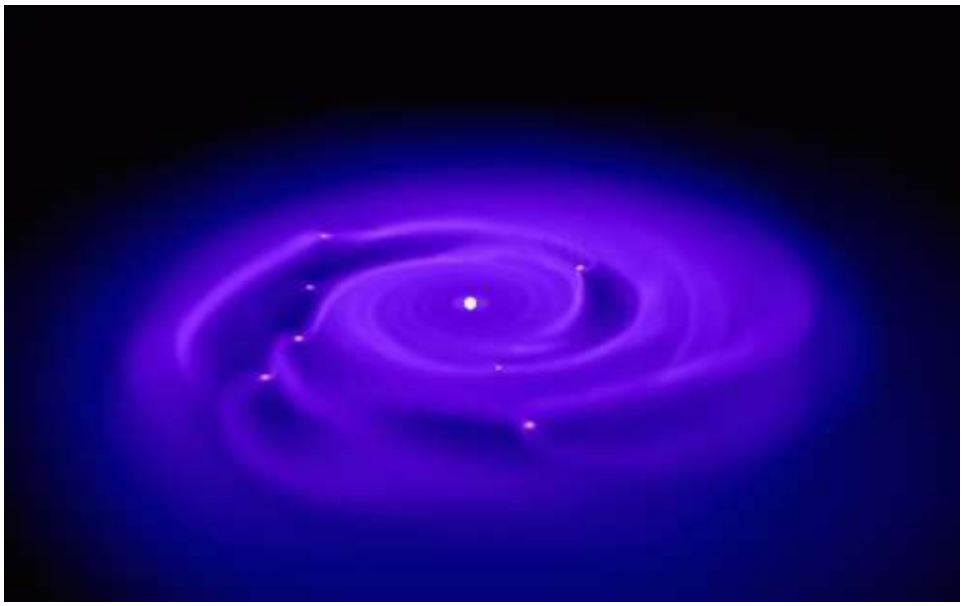

Figure 1. *Gasdynamical simulations of planet formation show that giant planets can be formed in hundreds of years. Mayer et al, 2002,* Science.

Our team is also examining metallicity gradients in nearby stars. These new observations of recently announced stars with planets continue to confirm their previously reported high metallicities relative to otherwise similar field stars. We have also uncovered preliminary evidence that giant planets being discovered by the Doppler method are less common around K and M dwarfs than they are around G dwarfs.

What caused the Delivery and retention of organics and volatiles through Earth History? The volatile and organic composition of impacting bodies is a key factor in the evolution of habitable planets. What are the relative roles of large comet and asteroid fragments and interplanetary dust particles (IDPs) in bringing these materials to a planet? In collaboration with George Cody of Carnegie NAI lead team, Brownlee and Kress have found that organic material found in bulk meteorites can be released into the gas phase when subjected to atmospheric entry conditions (flash−heating at a rate ~500 K/sec and peak temperature of 1000 K for a few seconds). These compounds may have played important roles in the atmospheric chemistry of early Earth, during a time when the flux of micrometeorites was much higher than today. In particular, all of the compounds named above are greenhouse gases. We also found numerous small polycyclic aromatic hydrocarbons, which would have been excellent absorbers of ultraviolet (UV) radiation during a time when no ozone layer existed. Over 250 200µm diameter unmelted micrometeorites were identified and extracted from sediments recovered from the unique South Pole Water Well sample provided by collaborator Susan Taylor from CRREL in Hannover. Graciela Matrajt (an astrobio−supported Post Doc visiting from France) extracted the particles, crushed them and treated them with HF. AIB was discovered in these samples, the first amino acid detection in micrometeorites. We are studying all three of these processes and their effects on prebiotic evolution.

How do mass extinctions and impacts affect the evolution and survival of complex organisms, i.e., the long−term habitability of planets? Mass extinctions are short−term events that kill off a significant proportion of a planet's biota, and on Earth have been of greatest consequence to more complex organisms such as metazoans. Surface life is vulnerable to major planetary catastrophes, for example, impact of a large comet or asteroid, radiation and particles from a nearby supernova, or catastrophic climate changes such as intense intervals of greenhouse heating or Snowball−Earth type episodes. It is now known that at least one of the major mass extinctions was caused by large body impact, and we would very much like to know if others as well are related to this. The major line of study involves the study of impact craters and their history. Impact cratering involves evaluation of projectiles, which to first order is a measure of the asteroids and comets passing in near Earth space. More broadly it involves the origin of those objects, the orbital evolution of the time of their existence, and at least in the case of asteroids, a series of collision and fragmentation processes that occurred in the asteroid belt. Once the materials are in near Earth space, it involves the evaluation of the material passing through atmospheres of various densities (and in some cases not passing through the atmosphere, and then the mechanism of the hypervelocity impart event itself. The physics of the impact include the explosive release of the kinetic energy, which produces the vaporization and melting of rocks and excavation of material not only as an eject blanket in the immediate vicinity of the crater, but in the case of large impact events (which can be biologically significant) the ejection of debris through the atmosphere into space where it can then envelope the entire planet. The biological consequence for the sudden release of this energy can occur on many scales from affecting individuals to the death of species and even removal of entire ecosystems or biota. The mechanics, biological and geological consequences of impact cratered is an enormous field in the very sweep of its questions. During the past year, two major mass extinction boundaries were studied: the Permian−Triassic (P/T) boundary in Africa and Canada, and the Triassic−Jurassic (T/J) boundary in the Queen Charlotte Islands, Nevada, Italy, and the Newark Basin. Isotopic and paleontological results from these sites are now either in progress or are finished. Our new work suggests that neither the P/T nor T/J mass extinctions were caused by large body impact

Figure 2. *Co−I David Kring on the Triassic/Jurassic boundary, New York Canyon, Nevada. Photo by Peter Ward*

What can we learn from the geological and fossil record about the evolution of eukaryotes and metazoans? Though we can extrapolate back from existing organisms or build theoretical biogeochemical models, the only robust empirical data that show how early life on Earth evolved and interacted with its environment comes from the study of early Precambrian rocks. Despite popular misconceptions, globally there is in fact a moderate abundance of well−preserved Archaean (>2.5 Ga) and Paleoproterozoic (2.5−1.6 Ga) rocks, which can serve as our clearest windows on the events that occurred shortly after life's origin. Further research was performed in 2003 on Archean hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. Also, new research was initiated in the areas of metamorphism of Archean biosignatures, Archean paleobarometry, and on the age and origin of controversial "microfossils" putatively of Archean age from the Pilbara Craton, Australia. Field−work was conducted on Hadean supracrustal rocks from Isua, Greenland, the early Archean Apex Basalt near Marble Bar, Australia, and the late Archean Fortescue Group near Tom Price, Australia. This research has shown that cyanobacterial and eukaryotic lipids are present in rocks half a billion years before other fossils of these groups appear in the geologic record and that molecular fossils can survive for much longer under higher thermal regimes than previously expected.

Also, we discovered that microbial sulfate reduction existed in ~3.5 billion year old oceans and this reduction shows that peripherally branching bacterial phyla had already evolved. Finally, and perhaps most significantly, the work of our group, based on mapping of the ~3.5 billion year old Apex Basalt, indicates that the "microfossils" previously reported from this unit are not as

old as the surrounding rocks.

What can we learn from the physiology and molecular characteristics of extant life about the evolutionary pathways by which microbes and their communities evolve, and by which complex organisms originate? The 0.5 Byr period prior to 3.5 Ga probably experienced extensive evolutionary experimentation and very limited physiological diversity. Recent evidence also points to lateral gene transfer between Bacteria and Archaea as the main mechanism involved in the formation of eukaryotes. Subsequently, symbioses between specific kinds of bacteria and eukaryotes contributed to the rise of oxygen−respiring and oxygen−producing multicellular biota. Today, both lateral gene transfer and interdependence of different species living in communities are ancient processes that continue in the microbial world.

The invention of multicellularity was a major biological innovation contributing to new states of biocomplexity. This was preceded, however, by the invention of eukaryotic cellular organization. The genome sequences from Bacteria have yielded many surprises, including the presence of genes thought only to be present in eukaryotes. We have found genes for tubulin in four species of Prosthecobacter, a genus of the bacterial division, Verrucomicrobia. The discovery of tubulin in bacteria raises questions as to their origin. They could have been transferred horizontally from a eukaryotic organism to these bacteria or vice versa. The goal of our current research is to better understand the origin of the bacterial tubulin genes that are very distantly related to those from eukaryotes, indicating that the transfer, if it occurred, must have happened a long time ago. Based upon partial genome sequences that are available, we are currently trying to determine which of the three hypotheses seems most reasonable. The most readily tested hypothesis is the last one. If it is correct, then we would expect that a substantial number of eukaryotic genes would be found in the genomes of the Verrucomicrobia. Preliminary results based upon Blast searches of genes of the Verrucomicrobia indicate, however, that fewer other eukaryotic genes have been found in the Prosthecobacter genome than expected based on the simplest variant of this model, that the Verrucomicrobia are the founding member of the Eucarya.

What was the nature of early Earth communities? A second way to examine the ancient Earth is through study of microbial communities that likely resemble those of the Precambrian. These communities include those found in (a) anaerobic and photosynthetic microbial mats and biofilms, (b) the sub−seafloor associated with deep−sea hydrothermal vents, and (c) water ice. It is possible that hidden in the presently unknown diversity of these ecosystems there exist organisms with metabolic pathways that are relics of common metabolisms of the past. We participated in one Early Microbial Ecosystem Research Group (EMERG) field trip in 9/2002 to the Guerrero Negro evaporation ponds to study microbial mat populations in these ponds. These mat populations are visually homogeneous over kilometers of extent and display steep geochemical gradients (e.g. light, oxygen) with depth. We are assessing bacterial diversity using Terminal Restriction Fragment Length Polymorphism (TRFLP), a rapid method for determining total community structure and composition. We have assessed diversity over two scales: horizontally, at varying spatial scales over a kilometer distance, and vertically,

using cores sliced at submillimetric scales with depth. Results indicate that these bacterial communities are remarkably stable across even large spatial scales (~1 km); however some variation even at fine scales (cm) was detected. Highly significant differences have been seen with depth in the mat over the upper 9 mm of the mat and significant differences between day and night samples were detected, suggesting significant migration of microorganisms may be occurring.

The second project is investigating a specific functional assemblage of microorganisms, the sulfate−respiring prokaryotes (SRP). High levels of activity for this group have been measured in this site. A wide diversity of SRP has been identified and significant differences in SRP community composition with depth were revealed. Significant correlations of SRP community structure with geochemical gradients were detected.

What is organismal metabolism in extreme environments? Another approach to understanding the habitability of planets is to consider the range of extreme environmental conditions on Earth that support life. For example, the detection of water ice and/or submarine hydrothermal vent systems on another planetary body would satisfy some of the key criteria for habitability. Laboratory observations of bacterial motility and field observations of bacterial attachment led to the testable hypothesis that a temperature threshold exists in ice formations (−10°C in sea ice), below which bacteria cease moving as a means to locate optimal resources and conditions and instead become attached to a surface (first−stage biofilm formation), allowing for continued activity down to −20°C (lowest temperature tested yet). We have also introduced a new aspect to first−stage biofilm formation in the cold: the role of bacterial viruses in altering bacterial behavior and possibly triggering attachment. Building on our finding of considerable morphological diversity of bacteriophage in subzero Arctic seawater and on field work last fall (CASES 2002 expedition), novel phage−host systems were established in the laboratory, using the obligately psychrophilic (cold−loving) bacterium, Colwellia psychrerythraea strain 34H (whole genome sequence available), as the host. Initial experiments have revealed a potential link between phage infection of a bacterium and its production of exopolymers that promote attachment.

Project Report: A Study of Marine and Terrestrial Stable Isotopic Geochemistry During the End−Permian and End−Triassic Mass Extinction Events

Lead Team:	***University of Washington***
Project Title:	***A Study of Marine and Terrestrial Stable Isotopic Geochemistry During the End−Permian and End−Triassic Mass Extinction Events***
NAI−NRC Postdoctoral Fellow :	***Geoff Garrison***

Project Progress

Proposed Research

I have proposed to examine geologic records of the Permian−Triassic (P−Tr, 251 Ma) and Jurassic−Triassic (200 Ma) extinction events in two locations: the Karoo Basin of South Africa (terrestrial deposits), and the Queen Charlotte Islands of British Columbia (marine deposits). This work is intended to address three questions:

1. What was the timing of events across the P−Tr and Tr−J horizons? Did terrestrial extinctions precede (and perhaps give rise to) or follow the extinctions seen in marine records?
2. How fast did these events occur? Millennia or millions of years?
3. What caused the mass extinctions? Were they similar events or totally unrelated with the same result?

The balance of nitrogen, carbon, oxygen, and sulfur isotopes within different sedimentary materials (e.g. sedimentary organic matter, carbonate minerals) will shift in response to changes in the physical and biogeochemical nature of the Earth system. As such, identifying such shifts in the geologic record across mass extinction events will enable us to better understand how such planetary sterilizations occurred.

Progress

Since January, 2003, I have been involved in establishing the new Cooperative Facility for Isotopic Research at the University of Washington (http://depts.washington.edu/cfir/). We have successfully installed an EA−CF−IRMS system (elemental analyzer−continuous flow−isotope ratio mass spectrometer), and are currently working on installing a second system. I

am now analyzing the backlog of samples collected over the past 10 years. In addition to my originally proposed research, I have added a third field area in Alberta, which has only recently been identified as having marine shales deposited during the P−Tr extinction event. In addition to stable isotope analyses, I am also planning to analyze samples from this area for platinum group elements in order to study the chemical redox state of the Panthalassia ocean during this time in Earth history.

Highlights

- We have established the new Cooperative Facility for Isotopic Research within the University of Washington Astrobiology Program (UWAB; http://depts.washington.edu/cfir/), including a new EA−CF−IRMS system (elemental analyzer−continuous flow−istotope ratio mass spectrometer) calibrated for analyzing C,H,N,S isotopic ratios in geologic materials.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Visit to the Permian−Triassic Seafloor	
Start Date: November 2, 2002	***End Date:*** November 5, 2002
Continent: North America	***Country:*** Canada
State/Province: Alberta	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Opal Creek	***Keywords:***
Description of Work: field site reconasissance, sample collection for stable isotope analyses and trace metal analysis	
Members Involved: Geoff Garrison	

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Building a habitable planet: the geological record

Lead Team:	***University of Washington***
Project Title:	***Building a habitable planet: the geological record***
Project Investigator:	***Roger Buick***

Project Progress

Further research was performed on Archean hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. New research was initiated in the areas of metamorphism of Archean biosignatures, Archean paleobarometry, and on the age and origin of controversial "microfossils" putatively of Archean age from the Pilbara Craton, Australia. Field−work was conducted on Hadean supracrustal rocks from Isua, Greenland, the early Archean Apex Basalt near Marble Bar, Australia, and the late Archean Fortescue Group near Tom Price, Australia.

Principal outcomes were:

1. Microthermometric analysis of Paleoproterozoic oil−methane−carbon dioxide−water fluid inclusions from ~2.4 billion year old rocks from Elliott Lake, Canada, showed that the hydrocarbons were trapped early at high temperatures and demonstrated the survival of complex hydrocarbon molecules for billions of years under closed−system and high−pressure conditions, thus establishing a base−line for preservation of such biosignatures on other planets.
2. A major study of hydrocarbon biomarker molecules in late Archean sediments from the Hamersley Basin showed that cyanobacterial and eukaryotic lipids are present in rocks half a billion years before other fossils of these groups appear in the geologic record and that molecular fossils can survive for much longer under high thermal regimes than previously expected.
3. A thorough review of the Archean sulfur cycle and constraints upon sulfur isotopic fractionation confirmed the existence of microbial sulfate reduction in ~3.5 billion year old oceans and showed that peripherally branching bacterial phyla had already evolved.
4. Mapping of a newly discovered outcrop of clastic metasediments ~3.8 billion years old confirmed the existence of turbidites in the Isua greenstone belt and demonstrated the occurrence of large low−strain domains within the world's oldest supracrustal succession.

5. Mapping of the ~3.5 billion year old Apex Basalt indicated that the "microfossils" previously reported from this unit are not as old as the surrounding rocks.

Highlights

- Hydrocarbon−bearing fluid inclusions from Elliot Lake, Canada, show that complex organic molecules can survive greenschist facies metamorphic conditions in closed systems at high pressures for ~2.4 billion years, potentially providing a minimum temporal stability limit for molecular bio−signatures on other terrestrial planets.

- Complex organic and biomarker molecules are preserved in kerogenous sediments up to 2.72 billion years old, allowing reconstruction of diverse Archean biotas and showing that bio−signatures indicative of metabolic status can be preserved under adverse conditions for temporal intervals relevant to early solar system habitability.

- Sulfur isotopic fractionations in ~3.5 billion year old evaporitic sediments from North Pole, Australia, show that microbial sulfate reduction, a complex metabolic process, evolved very early in Earth's history and thus could have been significant on other briefly habitable planets.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Isua	
Start Date: 15 July, 2002	***End Date:*** 1 August, 2002
Continent:	***Country:*** Greenland
State/Province:	***Nearest City/Town:***
Latitude: 65N	***Longitude:*** 50W
Name of site(cave, mine, e.g.): Isua	***Keywords:***
Description of Work: mapping low−strain metasediments in the world's oldest greenstone belt	
Members Involved: Roger Buick	

Field Trip Name: Warrawoona

Start Date: 4 August, 2002	***End Date:*** 19 August, 2002
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:***
Latitude: 21S	***Longitude:*** 119E
Name of site(cave, mine, e.g.): Warrawoona Group	***Keywords:***
Description of Work: mapping the Apex Basalt around the Chinaman Creek "microfossil" site	
Members Involved: Roger Buick	

Field Trip Name: Fortescue	
Start Date: 20 August 2002	***End Date:*** 7 September 2002
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:***
Latitude: 23S	***Longitude:*** 117E
Name of site(cave, mine, e.g.): Fortescue Group	***Keywords:***
Description of Work: identifying suitable rocks for paleobarometry studies	
Members Involved: Roger Buick	

Cross Team Collaborations

- Roger Summons, Harvard, Archean hydrocarbon biomarker study, 4 publications
- Jochen Brocks, Harvard, Archean hydrocarbon biomarker study, 4 publications
- Yanan Shen, Harvard, Archean sulfur isotope study, 1 publication

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Causes of Mass Extinction: Isotopic and paleontological constraints

Lead Team:	***University of Washington***
Project Title:	***Causes of Mass Extinction: Isotopic and paleontological constraints***
Project Investigator:	***Peter Ward***

Project Progress

During the grant period data gathering trips were conducted in Italy, (Triassic−Jurassic boundary site), with co−I Ken Farely; to the Permian /Triassic boundary in Alberta with National Research Council (NRC) post Doc Geoff Garrison, and to the New York Canyon region of Nevada, with co−I David Kring. Paleontological, isotopic, and chemical studies of all three sites are either underway in our labs or now completed. Geochemical analyses of last year's sampling at the Kennecott Point section (Triassic/Jurassic) have now been completed, while geochem from last year's trip to the Karoo of South Africa is now completed and is ready for publication. At the University of Arizona we have been preparing and analyzing samples collected from the Queen Charlotte Islands for petrologic studies using thin−sections. Mineral separations are also underway, so that we can examine the samples for evidence of impact−induced shock metamorphism.

The Triassic−Jurassic (T/J) boundary is a particularly interesting target for our work because an impact event, and possibly multiple impact events, may be associated with this major extinction boundary. The occurrence of multiple impact events over a short period is suggestive of a comet shower. In previous work (our Year 1) we analyzed T/J samples from the Queen Charlotte Islands, and found no evidence for extraterrestrial 3He. However we are concerned that the Queen Charlotte samples were sufficiently heated by burial to release the extraterrestrial ^{3}He from its carrier minerals, so we have analyzed samples from several other localities. In the summer of 2002 we collected about 100 limestone samples for extraterrestrial ^{3}He analysis from two important T/J sections in northwestern Italy. Our analyses of these rocks reveal only a very small extraterrestrial ^{3}He signal. While there appears to be elevated extraterrestrial ^{3}He levels in two of the shocked−quartz bearing shales, the effect is small and may result solely from changes in accumulation rate. These data provide no new evidence for a comet shower. Taken together these observations provide no evidence at all for an extraterrestrial impact at the T/J boundary.

Perhaps the strongest recent evidence for a role of impacts at major extinction boundaries is the work of Becker et al. reporting extraterrestrial fullerenes, with encapsulated extraterrestrial noble gases, at both the Cretaceous−Tertiary boundary and Permian−Triassic (P/T) boundary. The latter is especially important because it is among the few clues to the cause of the biggest extinction event in Earth history. We previously reported our inability to reproduce the Permian−Triassic results. In the last year we developed a new technique by which to evaluate the key question of fullerene He retentivity. He bearing fullerenes were made either by synthesizing them in a He atmosphere, or by subjecting fullerenes to high He pressures at elevated temperatures. We took He−bearing fullerenes and measured the He release as a function of temperature from about 50 to 250°C. Our hope was to obtain a linear Arrhenius relation from which we could estimate the release rate under natural conditions. We found that the release pattern does not obey a linear Arrhenius relation, making extrapolation impossible. Instead it appears that a major change in behavior occurs as the sample is heated. Based on reports in the literature we believe this pattern arises from traces of organic solvents used in the purification of the fullerenes, which degrade the fullerenes at elevated temperatures.

Highlights

- Based on a variety of evidence, the UW team has found that both the P/T and T/J mass extinction events appear not to be consistent with the record and evidence of large−body impact extinction that is apparent at K/T boundary.

- We have found that the fossil record at the P/T boundary shows a terrestrial extinction phase that appears to pre−date the marine phase.

- We have recovered data for the T/J extinction suggesting that it occurred in two steps, one at the end of the Norian Stage, and one at the end of the Rhaetian Stage.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Italy	
Start Date: August 26, 2002	***End Date:*** September 1, 2002
Continent: Europe	***Country:*** International waters
State/Province: Florence Region	***Nearest City/Town:***
Latitude:	***Longitude:***

Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Geological sample collection	
Members Involved:	

Field Trip Name: Nevada	
Start Date: April 8	***End Date:*** April 11
Continent: North America	***Country:*** USA
State/Province: Nevada	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): New York Canyon	***Keywords:***
Description of Work: Geological sample collection	
Members Involved: Peter Ward	

Field Trip Name: Alberta	
Start Date: November 2	***End Date:*** November 5
Continent: North America	***Country:*** Canada
State/Province: Alberta	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Opal Creek	***Keywords:***
Description of Work:	
Members Involved: Peter Ward	

Cross Team Collaborations

During this period we collaborated with Harvard/MIT (Sam Bowring); and JPL (Joe Kirschvink). Bowring is currently analyzing samples for age determination for Triassic samples. Kirschvink is studying samples for paleomagnetism from Permian−aged strata.

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Causes of mass extinctions: testing impact models

Lead Team:	***University of Washington***
Project Title:	***Causes of mass extinctions: testing impact models***
Project Investigators:	***Peter Ward , Roger Buick***

Project Progress

A manuscript was completed on a carbon isotopic, palynological and carbon−cycle modeling study of a non−marine Permian−Triassic boundary section in the Sydney Basin, Australia, showing that multiple isotopic excursions separate two mass−extinction horizons. The data are incompatible with a single impact event causing carbon−cycle perturbation and concomitant mass−extinction, as well as with most other proposed kill mechanisms for the Permian−Triassic. Modeling supports an oceanographic explanation for the isotopic excursions and the mass extinction(s).

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Cross Team Collaborations

NASA Ames team: David Catling, carbon cycle calculations for Permian−Triassic boundary isotopic excursions.

Project Report: Delivery of Organics to Earth and Earthlike Planets − Brownlee and Kress

Lead Team:	***University of Washington***
Project Title:	***Delivery of Organics to Earth and Earthlike Planets − Brownlee and Kress***
Project Investigators:	***Donald Brownlee , Monika Kress***

Project Progress

In collaboration with George Cody of Carnegie NAI lead team, Brownlee and Kress have found that organic material found in bulk meteorites (Murchison was the one used in this study) can be released into the gas phase when subjected to atmospheric entry conditions (flash−heating at a rate ~ 500 K/sec and peak temperature of 1000 K for a few seconds). Many of the more refractory organics found in Murchison are released without major chemical modification; other organics found in our experiments are apparently heat−modified daughter products of other compounds. Also released were significant amounts of CO_2, H_2O, CH_4, SO_2, H_2S and other light gases, and a variety of light hydrocarbons. These compounds may have played important roles in the atmospheric chemistry of early Earth, during a time when the flux of micrometeorites was much higher than today. In particular, all of the compounds named above are greenhouse gases. We also found numerous small polycyclic aromatic hydrocarbons, which would have been excellent absorbers of ultraviolet (UV) radiation during a time when no ozone layer existed.

Over 250 200µm diameter unmelted micrometeorites were identified and extracted from sediments recovered from the unique South Pole Water Well sample provided by collaborator Susan Taylor from CRREL in Hannover. Graciela Matrajt (an astrobio−supported Post Doc visiting from France) extracted the particles, crushed them and treated them with HF. Extreme efforts were used to limit and understand contamination. The samples were analyzed for amino acids at ASU by collaborator Sandra Pizzarello. AIB was discovered in these samples, the first amino acid detection in micrometeorites. The data are being studied to estimate the amount of amino acids and other organic materials delivered to the pre−biotic Earth at the time of the origin of life. The analyzed particles studied are believed to be representative of the organic−rich outer planetary system materials that seed all habitable zone planets with carbonaceous matter. The 200 micron size range is at the peak of the mass distribution where most of the 30,000 tons of extraterrestrial material is annually delivered to Earth. Some of the organic components of these small

particles are retained inside the particles, others are destroyed by atmospheric entry heating and others are liberated into the atmosphere. We are studying all three of these processes and their effects on prebiotic evolution

Highlights

- This study found the first detection of alpha−AIB extraterrestrial amino acid in micrometeorites.
- Micrometeorites could have been an important source of greenhouse gases on prebiotic Earth.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Stardust	Brownlee is the PI of this mission background research on pristine organics
2	TPF	background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Our work on thestudy of micrometeorites and their pyrolysis products relates to the understand of the development of the atmospheres ofterrestrial planets. We are studying the composition of these particles, in order to put constraints on the amounts of types of organics being delivered to young terrestrial planets, before modification by atmospheric entry. Stardust (Brownlee, PI) is a mission to return the most pristine, unaltered extraterrestrial samples ever collected. We are also determining what happens to extraterrestrial material when it undergoes atmospheric entry. In the large fluxes expected to be typical

of young planetary systems, this material may alter the atmospheric sectral features of an earthlike planet, so we are trying to get an understanding of molecular signatures of heavy exogenous flux which should not be confused with a biosignature. This will be in support to TPF science.

Field Expeditions

Field Trip Name: Ram River Valley Meteorite Search	
Start Date: 8/24/02	***End Date:*** 8/27/02
Continent: North America	***Country:*** Canada
State/Province: Calgary, Alberta	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Ram River Valley	***Keywords:***
Description of Work: Meteorite search	
Members Involved: Monika Kress	

Cross Team Collaborations

We are collaborating with George Cody (Carnegie) to identify organic products released from meteoritic material under atmospheric entry conditions. This has been a very fruitful collaboration because Cody has the lab facilities to do the experiments, while Kress Brownlee provided the meteorite sample and helped design the experiment, and assisted in the analysis of the results.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Delivery of organic materials to planets

Lead Team:	***University of Washington***
Project Title:	***Delivery of organic materials to planets***
Project Investigators:	***Thomas Quinn , Jonathan Lunine***

Project Progress

In collaboration with Jonathan Lunine, Quinn and Raymond have performed integrations of planetary embryos as they form the terrestrial planets. They have explored the dependence of the chemical composition of the resulting terrestrial planets on the properties of the planet formation scenario. Properties they have examined include the mass, orbital parameters and formation time of Jupiter, and the position of the snow line with respect to the habitable zone. They find that moving Jupiter in or out with respect to the snowline tends to decrease the amount of volatiles delivered to planets in the habitable zone. They also find that the amount of volatiles that a planet receives is a very stochastic process, varying greatly from one simulation to the next. These results are being written up in a paper that is in preparation.

Quinn and Raymond have also explored techniques for connecting the current population of Near Earth Asteroids with the Main belt population.

Highlights

- Having a Jupiter at 4 AU or 7 AU results in significantly drier terrestrial planets than a Jupiter at 5.2 AU.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission	***Mission Name (for class 1 or***	***Type of Involvement****

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Delivery of organic materials to planets

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Mission Involvement

Mission	***Mission Name (for class 1 or***	***Type of Involvement****

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Dynamics of comets, asteroids, and planets

Lead Team:	***University of Washington***
Project Title:	***Dynamics of comets, asteroids, and planets***
Project Investigator:	

Project Progress

Mayer and Quinn have continued performing simulations of giant planet formation by fragmentation of a gaseous disk, and have published their results in Science. They are extending previous work by considering the effect of different equations of state on the outcome, and by continuing the calculation for longer periods of time.

Lufkin and Quinn have started simulations of giant planet migration in gaseous disks. In a paper submitted to Monthly Notices, they have mapped out the possible migration/formation scenarios as a function of disk mass and planet mass. They demonstrate that the standard picture of a smooth migration inward is probably incorrect, and that the process is a rather chaotic one that involves close encounters and collisions of giant planets.

Barnes and Quinn in collaboration with Lissauer (Ames) continue their simulations of planetesimal accretion in the terrestrial region. They have made progress in speeding up this computationally challenging calculation. The aim is to determine the mass spectrum of planetesimals coming out of the middle stage of planet formation as a function of distance from the Sun.

Barnes and Quinn continue to investigate the stability of extra−solar planetary systems as they are being discovered. They continue to find that most planetary systems, including our own, are on the edge of being unstable. This has implications for the efficiency of planet formation.

Highlights

- The gravitational instability model for planet formation appears to be viable in a variety of conditions. This implies that Giant Planets should be a common phenomenon.

- Planet migration is a chaotic process, involving planet−planet scatterings and mergers.

- The formation process tends to produce planets in orbits with much larger eccentricities and inclinations than observed in our own Solar System.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Kepler	Background research
1	SIM	Background research
2	TPF	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Fundamental theoretical research on planet formation is needed both for mission planning, particularly in the case of TPF, and in interpreting mission results.

Cross Team Collaborations

The research on terrestrial planet formation involves collaboration with Jack Lissauer, a member of the Ames Lead Team. The expertise of the Ames planetary scientists is helping to formulate the best computational experiments to perform.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Dynamics of comets, asteroids, and planets

Lead Team:	***University of Washington***
Project Title:	***Dynamics of comets, asteroids, and planets***
Project Investigator:	***Thomas Quinn***

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: First−Stage Biofilm Formation Under Extreme Conditions in Ice

Lead Team:	***University of Washington***
Project Title:	***First−Stage Biofilm Formation Under Extreme Conditions in Ice***
Project Investigators:	***Jody Deming , Hajo Eicken***

Project Progress

Laboratory observations of bacterial motility and field observations of bacterial attachment led to the testable hypothesis that a temperature threshold exists in ice formations (−10°C in sea ice), below which bacteria cease moving as a means to locate optimal resources and conditions and instead become attached to a surface (first−stage biofilm formation), which allows for continued activity down to −20°C (lowest temperature tested yet). The relevant observations and hypothesis have been published (Junge et al., 2003) or submitted for publication (Junge et al., Submitted, 2003) and further experimental tests are underway. We have also introduced a new aspect to first−stage biofilm formation in the cold: the role of bacterial viruses in altering bacterial behavior and possibly triggering attachment. Building on our finding of considerable morphological diversity of bacteriophage in subzero Arctic seawater (Wells and Deming, Submitted, 2003) and on field work last fall (CASES 2002 expedition), novel phage−host systems were established in the laboratory, using the obligately psychrophilic (cold−loving) bacterium, *Colwellia psychrerythraea* strain 34H (whole genome sequence available), as the host. Initial experiments have revealed a potential link between phage infection of a bacterium and its production of exopolymers that promote attachment (Wells and Deming, unpublished). Our overall habitat focus remains on sea ice, after having demonstrated microscopically and non−destructively (Junge et al., Submitted, 2003) that freshwater (lake) ice formations are more space−limited (contain more constricted volumes of inhabitable liquid) than ice formed from seawater. Interactions with co−I Steve Warren on polar snow as another possible, but unlikely, medium for microbial activity has further convinced us to stay with sea ice. This continued focus also recognizes the special role of salts in constraining the inhabitable space within an ice matrix (Eicken et al., 2002; Eicken, 2003; Deming and Eicken, In Preparation, 2003) in triggering specific microbial responses (largely hypothetical at this stage; Deming, 2002, 2003), and in conceivably enabling the presence of microbial biosignatures on Europa (Eicken et al., 2003). Although tangential to our low temperature research but relevant to first−stage biofilm formation under extreme conditions in general, we also completed this year our work on a new sampler for conducting in situ

experiments on the seafloor using very hot fluids from active hydrothermal vents (Phillips et al., In Press, 2003).

Highlights

- Rapid bacterial motility at −10°C expands the number of habitats that can be actively colonized by microorganisms to include very cold ice formations (Junge et al., 2003).

- Bacterial attachment to surfaces, including ice crystals and very likely salt crystals, enables metabolic activity in the liquid brines of sea ice at temperatures from −2 to −20°C (Junge et al., Submitted, 2003).

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	JIMO (Jupiter Icy Moons Orbiter)	Deming and Eicken are Europa Focus Group members, developing background research and life−detection concepts; Eicken is also a member of the JIMO Science Definition Team.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Field Expeditions

Field Trip Name: Arctic 2002 (NOAA Office of Ocean Exploration aboard the Canadian Coast Guard icebreaker Louis S. St. Laurent)	
Start Date: August 14, 2002	***End Date:*** September 8, 2002
Continent:	***Country:*** Canada and USA
State/Province: Alaska, USA, and Northwest Territories, CA	***Nearest City/Town:*** (Nearest City/Town: Barrow, AK, and Tuktoyaktuk, NW Territories)
Latitude: 70−76°N	***Longitude:*** 132−160°W
Name of site(cave, mine, e.g.): Arctic Ocean, Beaufort Sea and Canada Basin	***Keywords:*** Arctic seawater, sea ice, extremophiles
Description of Work: The funded work (by NOAA Office of Ocean Exploration), targeting subzero Arctic waters and sea ice, involved bringing into culture potentially novel microorganisms, especially extremophiles able to function at low temperatures, high salt concentrations, and/or high hydrostatic pressures. Some of the resulting organisms provide useful laboratory models for NAI research.	
Members Involved: David Allen	

Field Trip Name: CASES 2002 (Canadian Arctic Shelf Exchange Study aboard the Canadian Coast Guard icebreaker Pierre Radisson)	
Start Date: September 18, 2002	***End Date:*** October 26, 2002
Continent:	***Country:*** Canadian waters
State/Province: Northwest Territories (Nearest City/Town: Tuktoyaktuk)	***Nearest City/Town:***
Latitude: 70−72°N	***Longitude:*** 124−134°W
Name of site(cave, mine, e.g.):	***Keywords:*** Arctic seawater, sea ice, extremophiles
Description of Work: The funded work (by NOAA Office of Ocean Exploration), targeting subzero Arctic waters and sea ice, involved bringing into culture potentially novel microorganisms, especially extremophiles able to functional at low temperatures, to produce cold−active extracellular enzymes and exopolymers, and/or to host cold−active viruses. Some of the resulting organisms and viruses provide useful laboratory models for NAI research.	

Members Involved: Jody Deming

Cross Team Collaborations

Deming and Michael Thomashow (co−I at Michigan State; both elected to the National Academy of Sciences in April 2003) interacted over production of a workshop report, entitled Frontiers in Polar Biology in the Genomics Era, by the National Academies Press. The report includes connections between Polar Biology and Astrobiology. Deming and Jean Brenchley (co−I at Penn State) have interacted on the role of cold−adapted enzymes in microbial survival under extreme conditions and the co−advising of former UW Doctoral Student (and UW Astrobiology Program Affiliate Student), Adrienne Huston, in the preparation of a three−year postdoctoral fellowship proposal to NSF, which has been funded in full. Huston will join the Brenchley lab as a postdoctoral associate in 2004, after completing work at the University of Liege, Belgium, in 2003−2004. Co−I Hajo Eicken (and Deming) interact regularly with other NAI members of Europa Focus Group; Eicken interacts regularly with other NAI members of the JIMO Science Definition Team

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Galactic Chemical Evolution and Extrasolar Planets

Lead Team:	***University of Washington***
Project Title:	***Galactic Chemical Evolution and Extrasolar Planets***
Project Investigator:	***Guillermo Gonzalez***

Project Progress

Laws continued to acquire high−resolution spectra of planet−hosting stars, proper motion pairs, and M67 turnoff stars with the echelle spectrograph at Apache Point Observatory. A collaborator, N .B. Suntzeff, obtained spectra of several southern targets in April 2001 with the echelle spectrograph on the Cerro Tololo 4−m Blanco telescope. Another collaborator, B. E. Reddy, observed additional southern targets in June 2002. Laws and Gonzalez are in the process of reducing and analyzing these data. The data acquisition part of this project is effectively complete.

Our paper reporting on the metallicities and masses of planet−hosting candidates observed by us through March 2002 was published in May 2003; a summary of the findings was reported by Laws at the Winter 2003 American Astronomical Society (AAS) meeting. The results of this study continue to confirm the findings of our previous studies that stars hosting giant planets have a higher mean metallicity than the overall nearby star population. We also report for the first time a statistically suggestive deficit of giant planets around low mass stars.

We are presently preparing our next paper (Paper VIII) in our series on the abundances of stars hosting giant planets, in which we will report on the non−Fe elemental abundances of the stars from our previous paper. We are additionally in the process of reducing and analyzing spectra of proper motion pairs and M67 turnoff stars; each of these topics will be addressed in a separate paper.

In Spring 2003 we completed a study of the unusual star, J37, an A star in the young cluster NGC 6633. No single known process can account for the elemental abundance pattern of J37. We find evidence suggestive of accretion of material similar in composition to the Earth. The paper has been accepted for publication in the Astrophysical Journal.

Highlights

- Observations of recently announced stars with planets continue to confirm their previously reported high metallicities relative to otherwise similar field stars.

- We have uncovered preliminary evidence that giant planets being discovered by the Doppler method are less common around K and M dwarfs than they are around G dwarfs.

- We have found an abundance pattern in the star J37 in NGC 6633 that strongly suggests the accretion of circumstellar material of Earth−like composition.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Microbial Mat Communities

Lead Team:	***University of Washington***
Project Title:	***Microbial Mat Communities***
Project Investigators:	***David Stahl , Jesse Dillon***

Project Progress

We participated in one Early Microbial Ecosystem Research Group (EMERG) field trip in 9/2002 to the Guerrero Negro evaporation ponds. This collaborative project involves geochemical and molecular biological analysis of the microbial mat populations in these ponds. These mat populations are visually homogeneous over kilometers of extent and display steep geochemical gradients (e.g. light, oxygen) with depth. Core samples of microbial mats were frozen and returned for molecular analysis. Deoxyribonucleic acid (DNA) was subsequently extracted from these samples and in combination with past years' extracts was used in two main projects investigating microbial diversity in these samples.

In the first, we are measuring the distribution and diversity of bacteria in these microbial mat samples. We used standard polymerase chain reaction (PCR) techniques to amplify the conserved bacterial 16S ribosomal ribonucleic acid (rRNA) gene. We are assessing bacterial diversity using Terminal Restriction Fragment Length Polymorphism (TRFLP), a rapid method for determining total community structure and composition. We have assessed diversity over two scales: horizontally, at varying spatial scales over a kilometer distance, and vertically, using cores sliced at submillimetric scales with depth. Results indicate that these bacterial communities are remarkably stable across even large spatial scales (~1 km); however some variation even at fine scales (cm) was detected. Highly significant differences have been seen with depth in the mat over the upper 9 mm of the mat and significant differences between day and night samples were detected, suggesting significant migration of microorganisms may be occurring. The second project is investigating a specific functional assemblage of microorganisms, the sulfate−respiring prokaryotes (SRP). High levels of activity for this group have been measured in this site. In collaboration with Dr. Mitchell Sogin at Woods Hole MBL, we are determining the DNA sequence diversity of genes specific to this group with depth in the microbial mat samples. A wide diversity of SRP has been identified, and significant differences in SRP community composition with depth were revealed. Significant correlations of SRP community structure with geochemical gradients were detected.

Highlights

- Diverse communities of sulfate−reducing bacteria that vary across a redox gradient are found in hypersaline microbial mats.

- Differences in bacterial community profiles indicate that microbial mat community structure varies greatly across a redox boundary and over a diel cycle.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Field Expeditions

Field Trip Name: Ecogenomics Microbial Mat Field Trip	
Start Date: 9/8/02	***End Date:*** 9/11/02
Continent: North America	***Country:*** Mexico
State/Province: Baja California S.	***Nearest City/Town:***
Latitude: 27â??41'N	***Longitude:*** 113â??55'W
Name of site(cave, mine, e.g.): hypersaline ponds	***Keywords:*** microbial mat
Description of Work: Field Sampling in Hypersaline ponds	
Members Involved: Jesse Dillon	

Cross Team Collaborations

Collaborative work with the Ecogenomics EMERG group (Headed by David Des Marais, NASA Ames) included field sampling in hypersaline ponds in Guerrero Negro, Baja CA, MX. Data gathering and collaborative analysis are ongoing and will soon lead to the submission of collaborative publications.

We collaborated with Ashita Dhillon and Mitchell Sogin of the MBL NAI group. We provided DNA sequence data and alignments for the dsrAB gene to Dr. Dhillon, who analyzed DNA sequences samples from her site in Guaymas Basin. The work was recently published in Applied and Environmental

Microbiology. See the publications record in the workbook.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Origin of the eukaryotic cell: implications from bacterial tubulin in the Division Verrucomicrobia

Lead Team:	***University of Washington***
Project Title:	***Origin of the eukaryotic cell: implications from bacterial tubulin in the Division Verrucomicrobia***
Project Investigator:	***James Staley***

Project Progress

Bacterial homologs for alpha− and beta−tubulin genes have been found in Prosthecobacter species that are members of the Division Verrucomicrobia. The genes that we have named, btuba and btubb, occur in an operon along with a light chain kinesin homolog. radiative transfer polymerase chain reaction (RT−PCR) indicates the genes are being expressed. Phylogenetically, the deduced amino acid sequences indicate these proteins are 30 to 35% related to eukaryotic tubulins. The results of this work were published in PNAS (Jenkins et al., 2002). We are now working on resolving the various possibilities that could explain the origin of these genes. Two hypotheses involve horizontal gene transfer (HGT) either from the Eucarya to the Verrucomicrobia or vice versa. An alternative hypothesis is that a member of the Verrucomicrobia or a closely related group evolved to become the founding ancestors of the Eucarya. Based upon partial genome sequences that are available, we are currently trying to determine which of the three hypotheses seems most reasonable. The most readily tested hypothesis is the last one. If it is correct, then we would expect that a substantial number of eukaryotic genes would be found in the genomes of the Verrucomicrobia. Preliminary results based upon BLAST searches of genes of the Verrucomicrobia indicate, however, that fewer other eukaryotic genes have been found in the Prosthecobacter genome than expected based on the simplest variant of this model. However, it may be possible to consider the last hypothesis in the framework of the Pre−Darwinian world model developed by Carl Woese. His model of early cellular evolution involves a Pre−Darwinian period, dominated by rampant HGT, which preceded the Darwinian world of vertical or hereditary evolution. We are analyzing this scenario to determine whether it might help explain the origin of the Eucarya from this early period.

Reference:

Jenkins, C., R. Samudrala, I. Anderson, B. P. Hedlund, G. Petroni, N. Michailova, N. Pinel, R. Overbeek,, G. Rosati and J. T. Staley. 2002. Genes

for the cytoskeletal protein tubulin in the bacterial genus *Prosthecobacter*. *PNAS* 99:17049−17054.

Highlights

- We have discovered tubulin genes in bacteria. Tubulin is found in all eukaryotic organisms, but has never before been found in any of the Bacteria or Archaea, raising the issue of where they may have originated.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.2:*** Foundations of complex life

Cross Team Collaborations

We are collaborating with Mitchell Sogin's group at Woods Hole in another project on desert varnish formation. Using molecular approaches, we are identifying the types of Bacteria, Archaea and Eucarya that live in desert varnish.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Fellowships: University of Washington

The NAI−NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Geoff Garrison
Project Title: A Study of Marine and Terrestrial Stable Isotopic Geochemistry During the End−Permian and End−Triassic Mass Extinction Events
Advisor: Peter Ward, Advisor
NAI Lead Team: University of Washington
Fellowship Began In: January 2003

NASA ASTROBIOLOGY INSTITUTE
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EPO: University of Washington

These are the Education and Public Outreach activities for the University of Washington.

Project AstroBio: Year−Long Program of Science/Teacher Partnerships in Puget Sound Schools

Project AstroBio has expanded on the success of Project ASTRO/Seattle, a science education and public outreach program administered by the UW Department of Astronomy since 1997. Project ASTRO created over 100 partnerships (and has sustained 65 of those) between teachers of grades 3 − 12 and professional and amateur astronomer and Earth and space scientists in the Puget Sound region of Washington. This year is our second as Project AstroBio. We began last summer with the training workshop for teacher and science partners who would work together in the 2002−2003 school year. Now that we are fully functioning as Project AstroBio, we will be training a new cadre of 22 teacher/scientist partnerships for the 2003−2004 school year and beyond. The partnerships will work together in the classroom, providing resource expertise and hands−on science activities as an adjunct to the regular teaching schedule. In each Project AstroBio partnership, students are guided through inquiry−based, hands−on activities in topics relevant to Astrobiology. Project AstroBio activities are rigorously designed to meet national and state education standards.

In 2002−2003 astrobiology researchers and graduate students Jesse Dillon, Jeremy Dodsworth, Monika Kress, John Leigh, and Steve Vance joined Project AstroBio as new science partners. Project AstroBio Director Woody Sullivan continues to visit an elementary school classroom, having begun as an astronomer partner with the original Project ASTRO in 1997. They each visited "their" classroom between five and seven times, thus having a direct impact on the science education of nearly 200 K−12 students.

In May 2003, Coordinator Linda Khandro, and Director Woody Sullivan hosted a Follow−up Activity for teachers and science partners at which time a new classroom activity was conducted: A Scale Model of Geologic Time Scale and Evolution of Life.

Project AstroBio: Annual Training Workshop for Teachers and Science Partners

Project AstroBio workshop: This two day mandatory training session brings the new Project AstroBio partners together for the first time. Partners work

together to learn strategies for effective communication between scientists and teachers, and between scientists and students, as well as take part in actual hands−on activities of the sort that they will be conducting with students. Each member of the partnership receives two volumes of activities in astronomy and related sciences, in addition to custom−made and classroom−tested activities in astrobiology. Various additional materials for classroom activities are also supplied.

In July 2002, astrobiology researchers and graduate students Jesse Dillon, Jeremy Dodsworth, Monika Kress, John Leigh, and Steve Vance joined Project AstroBio as new science partners, at which time a total of 22 new partnerships were formed.

Astrobiology Public Lecture Series at UW

The goal of the lecture series is to present current astrobiological research results to the broader community. The lectures are presented by participating faculty and distinguished visitors, carefully chosen for their ability to communicate well with the public. The lectures cover the many aspects of Astrobiology and occur each autumn and spring academic quarter. Astrobiologist and SETI astronomer Seth Shostak, who was enthusiastically received by a standing−room only audience of over 600, gave our October 2002 public lecture. In spring 2003, Mars expert Jack Farmer spoke to over 300 people. The lecture series is also intended to interest middle and high school students, thus we announce the series to Puget Sound science teachers and our Project AstroBio teacher partners.

Center for Astrobiology and Early Evolution Newsletter

Center for Astrobiology and Early Evolution (CABEE) Newsletters: the CABEE Newsletter, titled "Planets Life", is published each autumn and spring academic quarter, and disseminated to an interested public via mailing lists, lectures, workshops, and among our astrobiology community on campus. Each issue (five to date) includes astrobiology research news and news of the UW astrobiology community. Newsletters will soon be available online via our Website. A listing of the articles submitted by the UW Astrobiology team to date include:

Issue # 1, June 2001
Life on the Rocks: Geomicrobiology at deep−sea hydrothermal vents, Matthew Schrenk (graduate student, Oceanography),
Mars Evolution: Understanding planetary climate change, John Armstrong (graduate student, Astronomy).

Issue # 2, November 2001
Life in the Cold: Sea−ice Microbiology, Karen Junge (graduate student, Oceanography),
Collapse of Simple Life Forms Linked to Mass Extinction 200 Million Years Ago, Peter Ward (professor, Earth and Space Sciences).

Issue # 3, May 2002
How the Ingredients for Life Came to Earth: Clues from Antarctic Micrometeorites, Monika Kress (post doc, Astronomy),
The Earliest Earth: An Analog for a Lively Mars? Roger Buick (professor, Earth and Space Sciences).

Issue # 4, October 2002
Complex Organisms and the Breath of Life, David Catling (professor, Atmospheric Sciences),
Microbial Mats: Analogs of Earth's Earliest Communities? Jesse Dillon (post doc, Microbiology/Civil Engineering).

Issue # 5, April 2003
A New Kind of Hot Spring in the Abyss: The Lost City Hydrothermal Field, Deborah Kelley (researcher, Oceanography),
Signs of Liquid Water: Life on Jupiter's Moon Europa? Steve Vance (graduate student, Earth and Space Sciences).

Astrobiology on the School Front: Interning and Mentoring

Many UW astrobiologists dedicate time and resources to assisting interested students of all ages. The contributions that Kress, Dillon, Dodsworth, Leigh, Sullivan and Vance have made to Project AstroBio are reported elsewhere.

While aboard a second NOAA−supported icebreaking expedition in September−October 2002, Oceanographer Jody Deming interacted with several native Inuit high school students from Inuit (Northwest Territories, Canada) who had been brought aboard to learn from and work with scientists on the icebreaker. Deming has also been asked to serve as Chief Scientist aboard the Canadian research icebreaker for a six−week leg of a yearlong over wintering expedition in the Arctic Ocean (again, for CASES, on the Mackenzie Continental Shelf near the entrance to the Northwest Passage, Canadian Archipelago). As part of her charge, she will oversee activities of a program called "Schools on Board," whereby a group of twelve high school students and their teachers, as well as three media representatives for documentary filming, will be brought aboard the ship by charter flight for one week to experience directly the life, activities and discoveries of research scientists working under extreme conditions in the Arctic winter. Astrobiology research goals and concepts will receive particular attention.

Throughout the year Astronomer and Science Historian Woody Sullivan worked with Minority Institutions Astrobiology Collaborative (MIAC) at Goddard Space Flight Center, Maryland, to help bring astrobiology to historically black colleges.

Developing an Astrobiology Curriculum

In addition to working directly with students and teachers, UW astrobiologists are also developing curricula and curriculum materials, and UW astrobiology graduate students are now assisting these courses as Teaching Assistants (TAs). Jeremy Dodsworth and Steve Vance have each TA'd the pilot undergraduate Astrobiology 101 course in Fall 2002, and Steve Vance presented a lecture on Astrobiology to a college astronomy class at Seattle University.

Astronomer Woody Sullivan and oceanographer John Baross secured a contract with Cambridge University Press for a graduate−level textbook on Astrobiology (eds. Baross Sullivan), with chapters contributed by both UW and non−UW NAI researchers. The text is loosely based on the Crystal Mountain conference on Astrobiology hosted by the UW in August 2001. Chapters are now mostly submitted and editing has begun. The text is expected to be complete late in 2004.

Public Access: Astrobiology Lectures and Presentations

Public presentations and lectures are an important component of UW's astrobiology education/public outreach efforts, and many investigators have been active in a variety of communities.

Astrophysicist Monika Kress presented talks in astrobiology to the National Space Society, Seattle; the American Association of Women in Science, Seattle Chapter; The American Museum of Natural History, New York City; Lawrence Livermore National Laboratory, Institute for Geophysics and Planetary Physics; Seattle University; and Horizon House, Seattle.

Astronomer Don Brownlee gave public talks on Astrobiology related to his book, Life and Death of Planet Earth to the University of Washington Geology, Oceanography, and Astronomy Departments; the University of Colorado; California Institute of Technology; Oregon Mensa Society; Powel's Book Store, Portland, Oregon; Denver Museum of Nature and Science; and the Smithsonian Air and Space Museum.

Paleontologist Peter Ward gave public lectures to the Boston Museum of Science; The Denver Museum; The Rose Center and Hayden Planetarium, New York City; the Rimini Conference, Italy; the Skeptic Society, Pasadena, CA; and the University Book Store, Seattle.

Astronomer and Science Historian Woody Sullivan participated in (and led a one−hour session) at the Mars Exploration workshop held at Kennedy Space Center, Florida; talked about Mars to the public at the UW Astronomy Day Open House; gave presentations on Project AstroBio and on Mars to the Boeing Employees Astronomical Society, Seattle; gave a talk on the Mars sundial to the National Science Teachers' Association as part of a Planetary Society−sponsored session, Philadelphia; presented the "Project AstroBio" poster paper at the February NAI meeting at ASU (co−authored with Khandro); and gave a talk on "Astrobiology Education" to the founding workshop of the Minority Institutions Astrobiology Collaborative (MIAC).

The Media Front: UW Astrobiologists Are Interviewed

UW astrobiologists are frequently asked to provide interviews to the print and broadcast media. They also produce articles for popular and lay−science publications, for example, the most recent (July−August 2003) issue of Mercury, a publication of the Astronomical Society of the Pacific, features an article by Astrophysicist Monika Kress, titled, "Why Mars Will Be So Close to Earth".

In 2002−2003, meteorologist and glaciologist Stephen Warren conducted a video interview about "Snowball Earth" for ABI's Education and Public Outreach Program.

Paleontologist Roger Buick was an interviewee on astrobiology topics to BBC World Service, Associated Press radio; Science journal; Scientific American and Discover magazines, and the Seattle Times newspaper.

Astronomer Don Brownlee and paleontologist Peter Ward, authors of the popular book, Rare Earth, and its recently released sequel, The Ends of the Earth, were frequent guests on local and national TV and film productions, including NPR Science Friday, Book TV C−SPAN, CNN with Paula Zahn, and dozens more radio and TV interviews. The July−August 2003 issue of Mercury includes a book review by Gregory Laughlin on The Ends of the Earth.

Microbiologist Jim Staley provided an article for Current Opinion in Biotechnology, titled, Astrobiology, the transcendent science: the promise of astrobiology as an integrative approach for science and engineering education and research.

National Geographic Magazine is preparing a lead article on the National Oceanic and Atmospheric Administration (NOAA)−supported expedition to the Canada Basin in August−September of 2002 (see fieldwork section). This article will feature Oceanographer Jody Deming's program (among others), the goals of which were to bring potentially novel microorganisms of the extremophile variety into laboratory culture, some of which are now available as model strains for NAI−supported research. In April 2003, Deming attended

the Official Announcement Ceremony for the funding of a Canadian research icebreaker and its first international scientific mission in Quebec City, at the invitation of The Honorable Allan Rock, Minister of Industry, Canada. At that public international event, she was featured in a short film describing the astrobiological significance of research that can be accomplished from this new platform in the high Arctic under extreme conditions. This short film is being used throughout Canada to educate the public on the importance of the Arctic realm in the research enterprise.

In April 2003, as part of the recruitment efforts for Project AstroBio, a local radio station program, Celestial North, featured Project AstroBio and its opportunities for teachers and school children.

NASA Mission EPO

Throughout the year Astronomer and Science Historian Woody Sullivan worked on EPO for the Mars Exploration Rover missions, centered on the Mars sundial, but involving all aspects of the missions, including astrobiology.

Contributions to Planning Meeting for Cosmic Origins Exhibit

Dr. Cherilynn Morrow and Dr. James Harold are contributing to the design and planning for the Cosmic Origins exhibit project, a $2.4 million dollar, 3,000 square foot traveling exhibit in development at the Space Science Institute in Boulder, CO. Primary funding for the exhibit comes from the National Science Foundation (NSF) with collaborative contributions from NASA and other partners. In November 2002, the Space Science Institute (SSI) hosted a planning meeting to refine project goals and develop learning goals and interactive experiences for each exhibit area. Exhibit visitors will explore the birth of stars, the formation and detection of planets around other stars, and the search for life beyond Earth.

Twenty−five participants attended the planning meeting, including research scientists, an exhibit designer, an exhibit text writer, and educators such as the E/PO managers of the NASA Astrobiology Institute, the SETI Institute, and several other NASA missions. NAI supported travel for Krisstina Wilmoth to participate in the planning meeting. Morrow and Harold are using their planning time on the Cosmic Origins project to identify how to include an interactive device or computer kiosk related to the science of the Virtual Planetary Laboratory Astrobiology Team at the Jet Propulsion Laboratory. This science explores how we might use remote sensing of an extrasolar planet's atmosphere to detect evidence of life on that planet.

In addition to the traveling exhibition, the Cosmic Origins project includes a comprehensive education program for host−site museum educators and docents, classroom teachers, and the web−browsing public. We anticipate many other fruitful connections between NAI Central and several other NAI

E/PO Teams as the Cosmic Origins project unfolds.

Public Talks on Astrobiology: The Virtual Planetary Laboratory

The public arena is one of the most comprehensive forms of broadcasting scientific information. The members of the Virtual Planetary Laboratory were privileged to have been invited to share their knowledge and contribute to the next generation of scientists on a number of occasions this year.

Professor Jim Kasting was invited to speak for the National High School Science Teachers Annual Meeting at the University of California, San Diego.

Dr. Victoria Meadows was invited to talk at the First Annual NASA week at Bennett College in North Carolina. We consider this quite an honor as Dr. Meadows was the only speaker there representing Jet Propulsion Laboratory and/or California Institute of Technology. She was also invited to present talks at the Adler Planetarium, Pasadena History Museum's: The History of Astronomy in Pasadena, and the Australian Museum in Sydney, Australia.

Dr. Chris Parkinson contributed a talk on astrobiology to Gardena Middle School in Los Angeles, California. He was also invited to talk at York University in Toronto, Canada.

Reviewing Education and Public Outreach Products: The Virtual Planetary Laboratory

Dr. Victoria Meadows reviewed a Web−based game on understanding planetary spectra for JPL's Planetquest Website. Dr. Meadows also reviewed a popular article for Jet Propulsion Lab's Spotlight Series, "Creating Planets in Cyberspace."

Publications: University of Washington

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Members: University of Washington

Team Members sorted by current team.

Name:	David Allen
Email:	dallen@usgcrp.gov
Institution:	US Climate Change Science Program
Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Name:	Rory Barnes
Email:	rory@astro.washington.edu
Institution:	University of Washington
Name:	Steven Benner
Email:	benner@chem.ufl.edu
Institution:	University of Florida
Name:	Tim Blake
Email:	timblake@iinet.net.au
Institution:	University of Western Australia
Name:	Heather Bouzek
Email:	bouzek@u.washington.edu
Institution:	University of Washington
Name:	Jochen Brocks
Email:	brocks@oeb.harvard.edu
Institution:	Harvard University
Name:	Donald Brownlee

Email:	brownlee@astro.washington.edu
Institution:	University of Washington
Name:	Roger Buick
Email:	buick@ess.washington.edu
Institution:	University of Washington
Name:	Shelly Carpenter
Email:	seashell@u.Washington.edu
Institution:	University of Washington
Name:	David Catling
Email:	davidc@atmos.washington.edu
Institution:	University of Washington
Name:	Mark Claire
Email:	mclaire@astro.washington.edu
Institution:	University of Washington
Name:	George Cody
Email:	g.cody@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Name:	Jody Deming
Email:	jdeming@u.washington.edu
Institution:	University of Washington
Name:	Jesse Dillon
Email:	jdillon@u.Washington.edu
Institution:	University of Washington
Name:	Jeremy Dodsworth
Email:	jadodswo@u.washington.edu
Institution:	University of Washington
Name:	Adriana Dutkiewicz

Email:	adriana@es.usyd.edu.au
Institution:	University of Sydney
Name:	Hajo Eicken
Email:	hajo.eicken@gi.alaska.edu
Institution:	University of Alaska
Name:	Ken Farley
Email:	farley@mail.gps.caltech.edu
Institution:	California Institute of Technology
Name:	Geoff Garrison
Email:	garrison@u.washington.edu
Institution:	University of Washington
Name:	Guillermo Gonzalez
Email:	gonzog@iastate.edu
Institution:	Iowa State University
Name:	Jelte Harnmeijer
Email:	jelte@u.washington.edu
Institution:	University of Washington
Name:	Erik Hendrickson
Email:	elh@u.washington.edu
Institution:	University of Washington
Name:	Michael Hughes
Email:	michaelh@mail.usyd.edu.au
Institution:	University of Sydney
Name:	Cheryl Jenkins
Email:	toast@u.washington.edu
Institution:	University of Washington
Name:	Karen Junge

Email:	kjunge@ocean.washington.edu
Institution:	University of Washington
Name:	Linda Khandro
Email:	lindak@astro.washington.edu
Institution:	University of Washington
Name:	Joseph Kirschvink
Email:	kirschvink@caltech.edu
Institution:	California Institute of Technology
Name:	Monika Kress
Email:	kress@astro.washington.edu
Institution:	University of Washington
Name:	David Kring
Email:	kring@LPL.Arizona.Edu
Institution:	University of Arizona
Name:	Chris Laws
Email:	laws@astro.washington.edu
Institution:	University of Washington
Name:	John Leigh
Email:	leighj@u.washington.edu
Institution:	University of Washington
Name:	Graham Logan
Email:	Graham.Logan@ga.gov.au
Institution:	Geoscience Australia
Name:	Graeme Lufkin
Email:	gwl@astro.washington.edu
Institution:	University of Washington
Name:	Jonathan Lunine

Email:	jlunine@lpl.arizona.edu
Institution:	University of Arizona
Name:	Graciela Matrajit
Email:	Graciela.matrajt@ias.u−psud.fr
Institution:	Universite Paris−Sud
Name:	Lucio Mayer
Email:	mayer@astro.washington.edu
Institution:	University of Washington
Name:	Karen McKenzie
Email:	Karen.MacKenzie@ga.gov.au
Institution:	Geoscience Australia
Name:	James Nicol
Email:	James.Nicol@jdsu.com
Institution:	University of Sydney
Name:	Maynard Olson
Email:	mvo@u.washington.edu
Institution:	University of Washington
Name:	Thomas Quinn
Email:	trq@astro.washington.edu
Institution:	University of Washington
Name:	Birger Rasmussen
Email:	brasmuss@geol.uwa.edu.au
Institution:	University of Western Australia
Name:	Sean Raymond
Email:	raymond@astro.washington.edu
Institution:	University of Washington
Name:	John Ridley

Email:	jridley@laurel.ocs.mq.edu.au
Institution:	Macquarie University
Name:	Yanan Shen
Email:	yshen@oeb.harvard.edu
Institution:	Harvard University
Name:	David Stahl
Email:	dastahl@u.washington.edu
Institution:	University of Washington
Name:	James Staley
Email:	jtstaley@u.washington.edu
Institution:	University of Washington
Name:	Woodruff Sullivan
Email:	woody@astro.washington.edu
Institution:	University of Washington
Name:	Roger Summons
Email:	roger.summons@mit.edu
Institution:	Massachusetts Institute of Technology
Name:	Peter Ward
Email:	argo@u.washington.edu
Institution:	University of Washington
Name:	Stephen Warren
Email:	warren@u.washington.edu
Institution:	University of Washington
Name:	Lori Watson
Email:	bibber77@hotmail.com
Institution:	University of Sydney
Name:	Llyd Wells

Email:	chimera1@ocean.washington.edu
Institution:	University of Washington

Virtual Planetary Laboratory
Executive Summary
Principal Investigator: Victoria Meadows

Towards Characterization of Extrasolar Terrestrial Planets

> "There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non−luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth."
>
> −GIORDANO BRUNO (1584)

Are we alone? The richness and enormous vastness of our universe makes our solitariness seem almost unthinkable, and so this ancient musing has remained one of the most fundamental of human questions. Yet while the medieval monk Giordano Bruno could only speculate on the prevalence of other planetary systems that could harbor life, in the last decade we have been fortunate enough to see the search for other worlds evolve beyond the realms of heresy and science fiction, into science theory, and finally, into science fact.

As this report is being written, we now know of 107 planets outside our own solar system. These planets have been discovered using existing ground−based telescopes. However, in the coming decades NASA and the European Space Agency (ESA) will design, build and fly space−borne observatories to expand our knowledge of the number and distribution of planets in our Galaxy, and to determine whether or not these planets might support life. These missions, such as NASA's Kepler, Terrestrial Planet Finder (TPF), and Life Finder will specifically search for habitable terrestrial worlds, that is, Earth−sized rocky worlds that can maintain liquid water on their surfaces for extended periods of time. TPF, planned for launch in 2015, will be designed to directly detect Earth−sized worlds around nearby stars, and to determine whether or not these sister planets are habitable, like our own Earth, and will initiate the search for the global signs of non−technologically advanced life. The most ambitious of these planned missions, Life Finder, is envisioned to build upon the discoveries of TPF, to provide a more detailed spectroscopic search for non−technologically advanced life on planets in our Solar neighborhood.

To optimize the designs and search strategies for these NASA missions, and to ultimately interpret the data that they return, we must expand our ability to recognize worlds that might have habitable conditions, and to discriminate between planets with and without life, based only on remote−sensing observations.

Characterizing Extrasolar Terrestrial Planets

Methods for characterizing terrestrial planets in our solar system have been refined for decades by planetary and Earth−observing scientists. Some of these techniques can be adapted for use in the characterization of terrestrial planets around other stars. Examples include time−resolved whole−disk photometry, spectroscopic remote sensing for the detection and retrieval of atmospheric and surface composition and physical parameters, and time−resolved spectroscopy of spectral features to look for diurnal or seasonal variations in surface albedo or atmospheric composition. However, since existing observing techniques are not yet sensitive enough to directly detect and gather information on Earth−sized planets around other stars, our principal means of advancing our understanding of these planets is via theoretical modeling studies. So, to improve our understanding of the potential range of environmental and spectroscopic characteristics for terrestrial planets in our galaxy, our team is developing a suite of innovative modeling tools to simulate the environments and spectra of a range of plausible extrasolar planets and for the early Earth.

These modeling tools comprise a Virtual Planetary Laboratory (VPL). This tool will incorporate models to couple the radiative fluxes, climate, geology and biology of a terrestrial planet to produce a self−consistent state for a broad range of candidate planetary environments. Self−consistency between a planet's chemical, physical, and biological properties state is particularly important when trying to understand the detectability of biosignatures in the spectrum of the planet's atmosphere and surface. This effort is strongly interdisciplinary, calling upon the expertise of planetary scientists, astronomers, biologists, geologists, chemists, mathematicians, computer scientists and statisticians to all work together towards a focused common goal. This effort therefore exemplifies the science of astrobiology, an interdisciplinary approach to understanding life in our universe.

The Virtual Planetary Laboratory

The core of the VPL is a coupled radiative transfer/climate/chemistry model, which is being assembled from existing models that have already been validated individually and used to address many key scientific problems in planetary and Earth sciences. This coupled−climate−chemistry model is being augmented by interchangeable modules currently under development. These modules consist of geological, exogenic, atmospheric escape, and life process models that will be used to characterize fluxes of heat and trace species at the upper and lower boundaries of a planetary atmosphere.

The VPL will be validated using data derived from terrestrial planets in our own solar system. It will then be used to explore the plausible range of atmospheric

compositions and thermal structures, and to generate disk−averaged spectra for extrasolar planets and for early Earth. These models will be run with and without biological processes to improve our understanding of the effects of life on a planet's atmospheric composition and spectrum. They will also be used to create a spectral catalog that can be used as a statistical sample space to explore the optimum wavelength range, spectral resolution, and instrument sensitivity required to characterize extrasolar terrestrial planets.

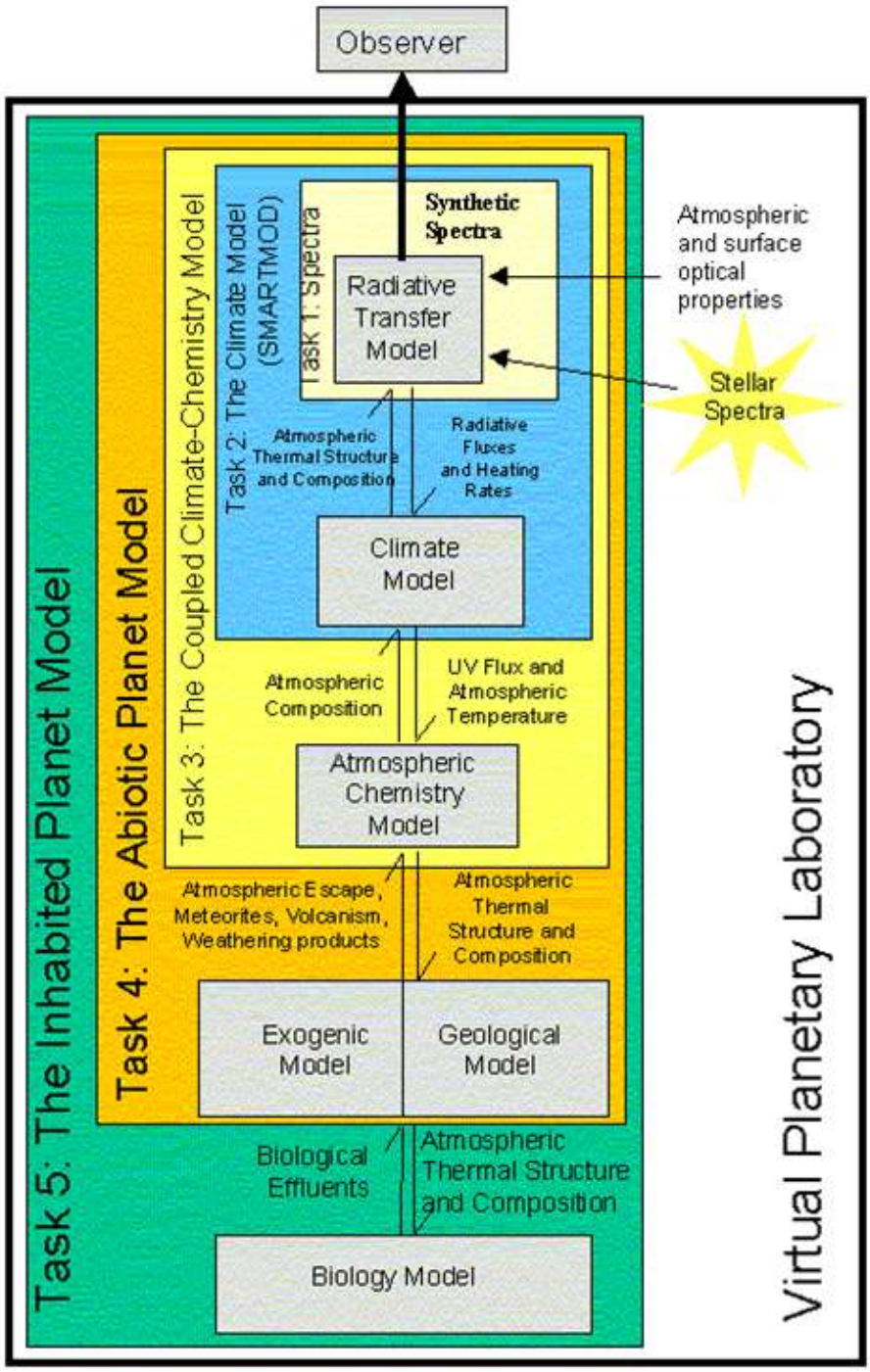

Figure 1. *The suite of radiative transfer, climate, chemical, geological, and*

biological component models are shown as boxes,and their interactions with each other are shown as arrows. The information transferred between these component models is labeled at each interface. The order in which these component models are coupled to each other during the course of building the VPL is specified by the Task number. The radiative transfer, climate and atmospheric chemistry models already exist, and the remaining models are under development by our team. At each task development stage the model can be used to generate synthetic spectra to derive required capabilities for astronomical instrumentation.

Progress This Year

Assembling the Virtual Planetary Laboratory

In the second year of this program, we continued our long−term efforts to develop the suite of VPL models. Focusing initially on the architecture of the integration, we defined the basic structure and communication modes for the integrated model. This included defining the requirements for the model−to−model translators and the nature and content of the common database that will hold initialization information, model input and output, and control status flags. Integration of the radiative transfer and climate models is completed, with the climate and chemistry models to follow. The geological, exogenic and biological processes will initially be specified as "state vectors" in the common database, to allow testing on the larger model, and later will be replaced with the full analytical or numerical models.

We have updated our one−dimensional (1−D) radiative−convective equilibrium (RCE) climate model to better support interaction with the geological and life components of the planet. We upgraded the RCE model to incorporate our line−by−line, multiple scattering radiative transfer model in place of simpler band modeling and 2−stream methods. A mixing length approach has been implemented to provide a self−consistent description of the vertical transport of heat and volatiles throughout the environment. Both these new features enhance the model's ability to provide climate constraints needed for the geological and life processes. We also added a simple cloud model for formation and dissipation of clouds, which will later include precipitation.

Work has also proceeded on defining the "boundary layer" geology and atmospheric escape models. We have planned a series of 1−D reactive transport models to characterize biogeochemical cycling in different environments, which will couple to the atmosphere and lithosphere via flux terms fed through the database. This design draws upon team work performed this year on modeling to analyze Archean paleosol isotopic measurements. This work has improved understanding of elemental cycling on ancient Earth and will provide empirical constraints for VPL models of the Archean Earth.

This year, team members also worked on geology models that link the planetary boundary layer with the planet's mantle and core. This included the development of physical models to reconcile geochemical observations, and to understand the link between plate tectonics, thermal evolution and degassing for the Earth throughout its history. Team members have also explored the link

between planetary thermal evolution and the generation of the planetary magnetic fields that can strongly affect long−term planetary habitability.

Looking to the upper planetary boundary layer, we have developed a new technique to model hydrodynamic loss processes from planetary atmospheres that overcomes previous difficulties and instabilities in modeling supersonic outflow. We have validated a preliminary model, which will be incorporated as an upper boundary module for the VPL. This model can be applied to both terrestrial planets and extrasolar gas giant planets.

To support the VPL life modules, we have conducted both field work and modelling studies. We have continued our field assessments of life in high−pH aquifers and springs associated with ultramafic rocks, an environment analagous to early Earth's, or an undifferentiated water−rich terrestrial planet. Our objectives are to understand how microbial communities may have fared in primordial environments without prior chemical weathering, to understand nutrient limitations, and to look for biosignatures associated with these communities. Several organisms have been isolated, and a baseline for annual and seasonal variations in geochemical conditions is emerging.

We have also been developing an anaerobic early Archean ecosystem model to understand biological productivity and methane production prior to the origin of oxygenic photosynthesis. The model explicitly accounts for cycling of hydrogen and carbon through primary production by hydrogen utilizing methanogens, fermentation, methanogenesis and photolysis. The ecosystem model has been run in conjunction with an atmospheric chemistry model. Initial results indicate that for a volcanic flux of hydrogen at the modern rate, the atmosphere could contain up to ~350 ppmv of methane if hydrogen utilizing methanogens were the primary producers. This level of methane would produce a strong signature in the spectrum of the planet.

We have also initiated a dynamical model of a microbial ecosystem, which includes interaction with the external environment, including the stellar flux. In this multicomponent model, individual microbial species interact with each other, and their growth is governed by available energy and chemical resources, and limited by space. We continue to explore the stability of these equations, for both the autonomous and environment−coupled system. We are also working on expansion of the model to include stellar−driven photosynthetic life.

In addition to development of the architecture and individual models, we are also gathering spectroscopic information required as input for extrasolar planet models. Both as ongoing support to the planetary modeling efforts, and as part of independent research to explore the concept of the "G star analog" we have combined astronomical observations and photospheric models to create high−resolution, full−wavelength range spectra for stars of different spectral type. Team members have also collated an ongoing, yet already comprehensive, database of spectral line lists and absorption cross−sections for 45 molecules required by planetary atmosphere models.

In addition to initiating the assembly of the VPL itself, our team has also

worked on two related proof−of−concept or precursor projects, both of which use component models of the VPL to explore the detectability of biosignatures via remote−sensing techniques. These modeling efforts and results are described below.

Spatially Resolved Planetary Models

The first such project uses the VPL's radiative transfer model to produce spatially resolved spectral models of planets in our own solar system. The 3−D "datacube" of synthetic spectra that is generated for each planet is being used to determine the effects of spatial and spectral averaging and temporal variability on the detectability of biosignatures, and other spectral features that provide important constraints on a planet's physical and chemical state, and its potential for habitability. These models are also being created as a validation standard to test progressive development of the larger VPL model. This year, we completed the Mars model, producing disk−averaged synthetic spectra and lightcurves, and used this model and TPF instrument models to understand our ability to detect the CO_2 ice cap in the disk−averaged spectrum of a successively more frozen planetary surface. We are currently working on the comparable Earth model. As an experimental validation component for this project, our collaborators at the Australian Center for Astrobiology (Bailey and Chamberlain) continue to acquire and analyze high−resolution full−disk spectra of Mars and Venus using ground−based telescopes.

Earths Around Other Stars

In collaboration with the Penn State NAI team, we have explored the environments and detectability of biosignatures from extrasolar terrestrial planets similar to the Earth. Using a coupled 1−D radiative−convective climate model, we have determined atmospheric compositions for Earth−like planets with oxygen levels from the present atmospheric level (PAL), down to 1/100,000th PAL, around stars hotter and cooler than our own Sun. We have also run self−consistent models for atmospheric conditions during the Earth's early Proterozoic. We have the used the VPL radiative transfer model, and the detailed spectrum of the parent star, to generate high−resolution synthetic spectra for these atmospheres, which we have analyzed for detectability using TPF instrument simulator models. These spectra are the first steps in building a spectral library of terrestrial planets for use in TPF mission planning and data analysis.

Significant results included an improved understanding of the behaviour and detectability of ozone and other atmospheric constituents for an Earth−like atmosphere at different oxygen levels. These simulations have also provided significant insight into the combined effects of temperature and trace gas distributions on the detectability of biosignatures, especially around stars of different spectral type, and the results are directly relevant to the Terrestrial Planet Finder mission. As part of this project, we also calculated surface ultraviolet (UV) fluxes and UV dose rates for erythema and deoxyribonucleic acid (DNA) damage. We find that planetary UV surface fluxes are low for high−oxygen planets orbiting the high−UV output F stars, because of the creation of a protective "super" ozone layer. These results will help us to

further understand what effects stellar type and planetary atmospheric composition might have on planetary habitability and biological evolution.

Extrasolar Hot Jupiters

We have developed a 1−D chemical model for extrasolar "hot Jupiters" for which the formation of hydrocarbons, oxygen chemistry, and hydrodynamical loss are significantly enhanced because of their environment. Significant results include an improved understanding of the chemical mechanism for H and H_2 production in these unusual planets. The modifications to the chemical model to incorporate new chemistry, database modeling, and to couple it to a hydrodynamic escape code are directly applicable to modifications required for the VPL terrestrial planet models.

Education and Public Outreach

Our EPO team this year has participated in planning meetings for the Cosmic Origins travelling museum exhibit and is developing a framework for a family guide on Life Elsewhere. The EPO team has also run workshops on astrobiology and astronomy at several conferences. Scientific team members have participated in or contributed to many courses, presentations, talks and media interviews, including 7 university courses, 19 university seminars, a talk to middle school students, 7 talks at museums or observatories, and 6 interactions with the media, including interviews for public television. Team scientists have also participated in preparing and reviewing EPO material for the web. Further information about the VPL can be found on our public website, which was launched this year: http://vpl.ipac.caltech.edu.

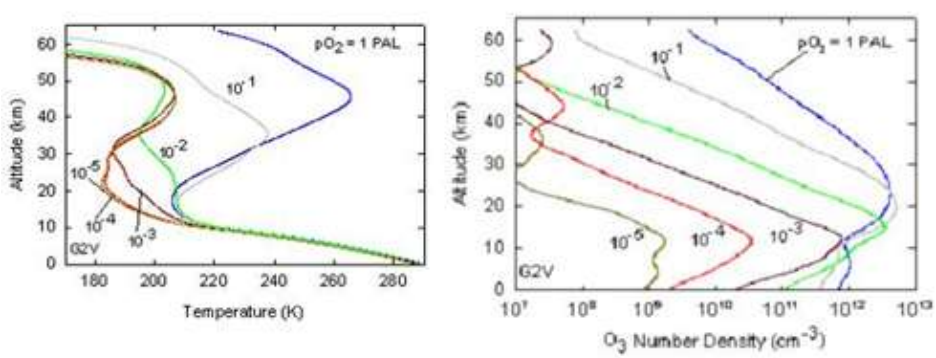

Figure 2. *Plots showing a) atmospheric temperature and b) ozone mixing ratio, as function of altitude for Earth−like planets with successively lower abundances of oxygen in their atmospheres. The blue line shows results for an atmosphere with the present atmospheric level of O_2, and the other lines are labeled with the factor of 10 reduction in oxygen abundance from the present level. These plots show the gradual cooling of the stratosphere, and the descent of the peak concentration of ozone in the atmosphere as a function of the decreasing atmospheric O_2 abundance.*

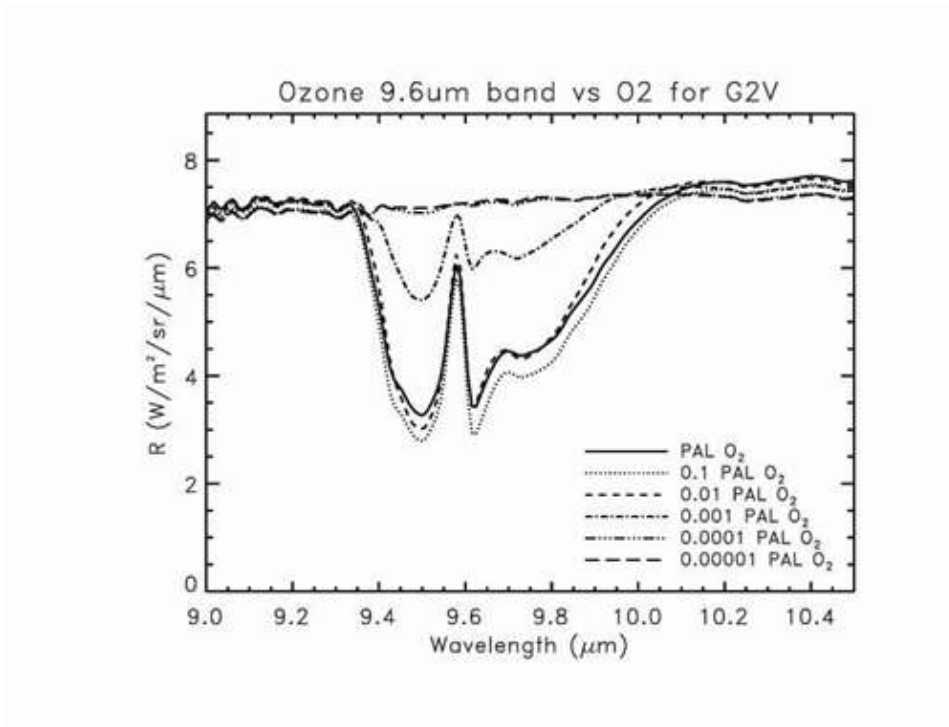

Figure 3. *This plot shows the ozone band as a function of atmospheric oxygen abundance for a planet around a G2V star. The ozone column decreases, but remains appreciable down to O_2 levels of 0.01 PAL, but the 9.6um ozone band retains almost the same strength down to this O_2 level because the lower ozone column is offset by enhanced absorption due to the greater temperature difference between the stratosphere and the warm, emitting planetary surface.*

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Characterization of Terrestrial Planets From Disk−Averaged Spectra: Spatially and Spectrally Resolved Planetary Models

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***Characterization of Terrestrial Planets From Disk−Averaged Spectra: Spatially and Spectrally Resolved Planetary Models***
Project Investigator:	***Victoria Meadows***

Project Progress

This project uses spatially resolved spectral models of planets in our own solar system to determine the instrument sensitivity and spectral resolution required to detect signs of habitability or life in disk−averaged astronomical spectra of extrasolar planets at visible and infrared wavelengths.

This year, we completed the Mars model by using a spectrum resolving (line−by−line) atmospheric/surface radiative transfer model (Spectral Mapping Atmospheric Radiative Transfer (SMART), D. Crisp), and Martian surface albedos (from Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES)) and atmospheric data derived from the Ames Mars General Circulation Model (MGCM) simulations to generate a database of spatially resolved synthetic spectra for a range of illumination conditions (phase angles) and viewing geometries. These results were then processed with a model that resamples the spatially resolved spectra to create a synthetic, disk−averaged view of the planet from a specific viewing geometry. These results were validated via comparison with the Mars Global Surveyor Thermal Emission Spectrometer (MGS TES). The three−dimensional (3−D) "datacube" of synthetic spectra generated by the model was used to determine the effects of spatial and spectral averaging, and temporal variability on the detectability of surface features, and its potential for habitability. The results include disk−averaged synthetic spectra or images, and lightcurves showing variability at visible and MIR wavelengths as a function of viewing angle. We also explored the ability to detect the CO_2 ice cap in the disk−averaged spectra, using TPF instrument models. We have determined that the ice cap must cover down to 50 degrees latitude before a low−resolution, pole−on disk averaged spectrum would show detectable spectral features of CO_2 ice. Currently we are working on the comparable Earth model, having acquired the relevant satellite data to start the radiative transfer modeling.

Figure 1a, 1b. *Disk−averaged spectra at visible (a) and mid−IR wavelengths (b) for increasing extension of the southern polar−cap area to 0 (black curve), 20 (violet curve), 40 (light−blue curve), 50 (gree n curve), 60 (yellow curve), 70 (red curve), 80 (grey curve), 90 (black curve) degrees from the pole. For larger planet ice coverage, the CO_2 ice feature is seen at wavelengths between 11 and 13.5 microns (G. Tinetti).*

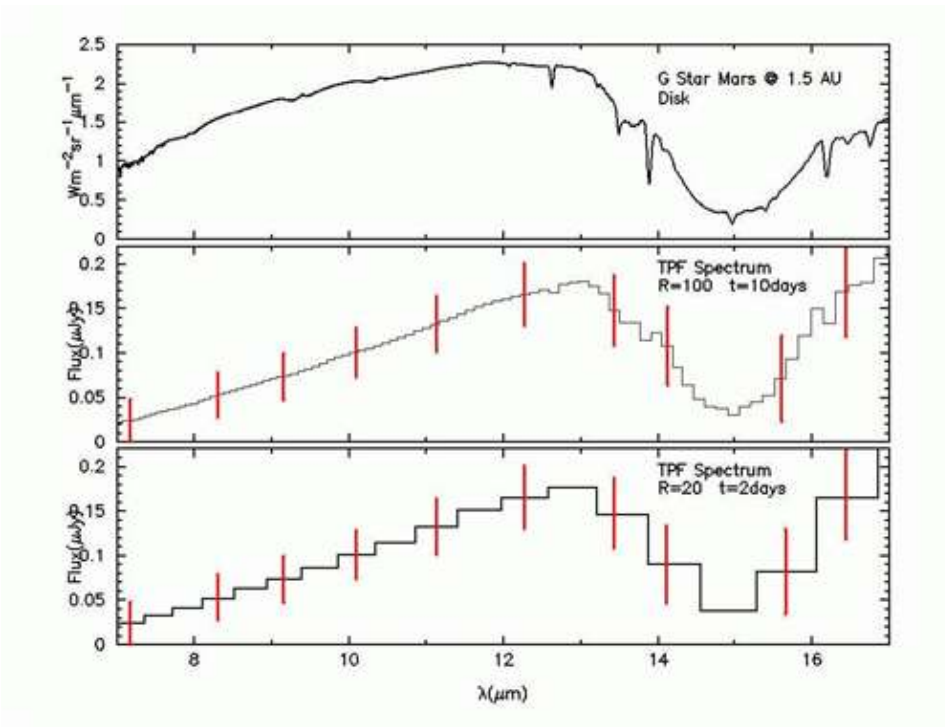

Figure 2. *Simulation of TPF spectral observation of a disk averaged spectrum of Mars. The TPF book design interferometer model was used (T. Velusamy) i.e. four 4m telescopes on a 75m baseline. The upper panel shows a full resolution spectrum of Mars at its usual distance from the Sun. The middle and lowest panels show the TPF spectrum for this planet, at the same distance from its parent star, around a star 10pc distant. The spectrum has been modified by the instrument to spectral resolutions of R=100 and 20, respectively with corresponding TPF integration times of 2 10 days. The error bars (in red) indicate 1 sigma sensitivities. (T. Velusamy)*

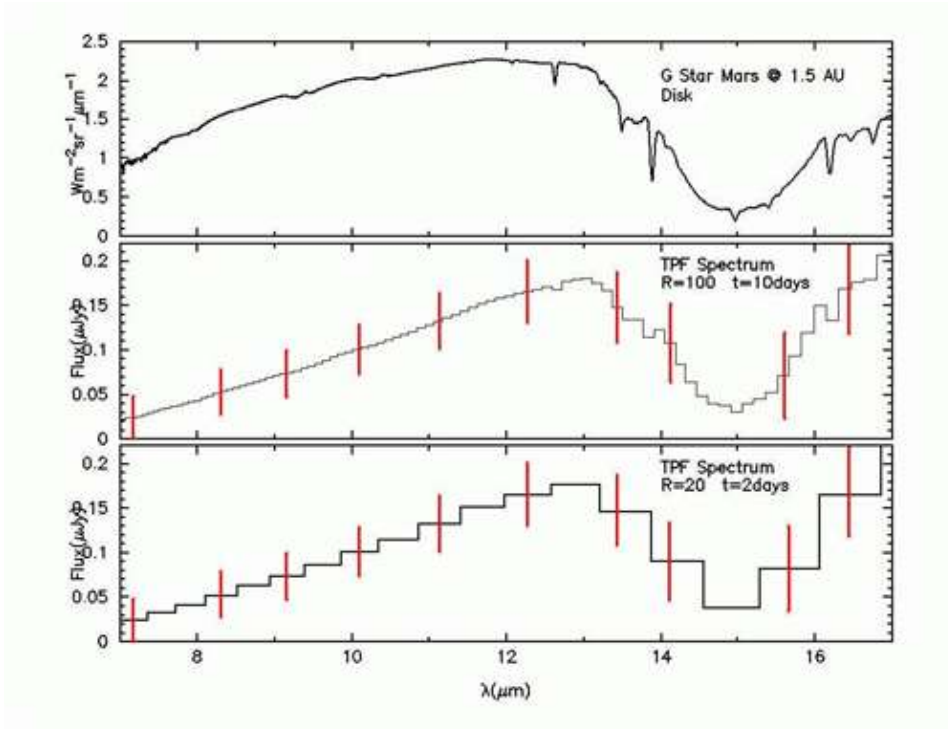

Figure 3. *Simulation of a TPF spectrum of an entirely CO_2 ice−covered Mars (based on the North polar−cap spectrum). Model parameters and figure panels as described for Figure 2. With longer integration times and adequate S/N, the CO_2 ice feature would be relativley easy to detect in the R=100 case, but far more difficult for R=20. (T. Velusamy).*

As an experimental validation component for this project, our collaborators at the Australian Center for Astrobiology (Bailey and Chamberlain) continue to acquire and analyze high−resolution full−disk spectra of Mars and Venus using ground−based telescopes.

Highlights

- We have completed modeling two fully spatially and spectrally resolved days on Mars, one close to the summer solstice (Ls = 105) and another corresponding to (Ls = 211.6). We have been able to use the results from these two days and seasons to constrain variability at visible and MIR wavelengths as a function of viewing angle, and to provide disk−averaged synthetic spectra for comparison with observational data.

- Interesting first results from the model include the simulation of an increasingly frozen Mars, as a tool for studying the detectability of surface type from TPF for disk−averaged spectra. Using the Mars model combined with a model for a TPF interferometeric design, we have determined that surface CO2 ice can be spectrally identified in a TPF MIR spectrum of a disk−averaged Mars, even at low resolution, if the ice covers down to at least 50 degrees latitude from the pole, although higher integration times are required for the icy planet, over a

similar sized rocky planet.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	TPF	V. Meadows is member of the TPF Science Working Group, planning support, research or analysis techniques
3	Life Finder	planning support, background research
3	Earth Observing Pathfinder: Orbiting Carbon Observatory	D. Crisp, PI
3	Solar System Exploration Decadal Review: Venus Panel	D. Crisp (chair), V. Meadow (participant), planning support, background research.
2	ESA Venus Express	D. Crisp co−I, planning support
3	ESA ExoMars	D. Crisp co−I, planning support.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The spatially and spectrally resolved planetary models under development in this project are specifically designed to explore the detectability of planetary characteristics for a range of possible instrument spectral resolutions and sensitivities. As such they provide an important tool for the planning and requirements for missions such as TPF, and its higher−spectral resolution successor, Life Finder. Meadows has also served this year as a member of the

Terrestrial Planet Finder Science Working Group, advising the Precursor Science, Science Requirements, Inteferometer Instrumentation and Education and Public Outreach task groups.

Our work on understanding and modelling the appearance of terrestrial planets in our own solar system underpins our interest in these planets as our only current examples of the potential family of terrestrial planets in our galaxy. Scientists working on this task have also served on panels and NASA missions where in addition to leading mission roles they have been able to bring their astrobiology perspective to bear on strategy and science planning for terrestrial planet missions. Notably, D. Crisp is the Principal Investigator of the Earth System Science Pathfinder Orbiting Carbon Observatory (OCO). This mission will make the first space−based remote sensing measuremetns of Earth's atmospheric CO_2 with the spatial and temporal resolution and precision needed to characterize surface sources and sinks of this important greenhouse gas. These observations will improve our understanding of the Earth's carbon cycle, and facilitate improved predictions of future atmospheric CO_2 concentrations and their effect on the Earth's climate. D. Crisp is also a member of the Prospector Science Team, an instrument proposed in response to the ESA ExoMars Anouncement of Opportunity. As a member of that team, he is responsible for characterizing the near−surface radiative and thermal environment at the Martian surface. The radiative transfer modeling being developed under this task is directly relevant to this activity. D. Crisp is a also a member of the PFS and VMC science teams for the ESA Venus Express. In those roles, he is responsible for remote sensing retrieval and thermal balance studies of the Venus atmosphere. While serving on the Venus Community Open Panel for the Solar System Exploration Decadal Review, D. Crisp (chair) and V. Meadows (participant) provided astrobiologically relevant science goals for Venus exploration to the final report from that panel.

Field Expeditions

Field Trip Name: AAT/UCLES and ANU/CASPIR Observations of Oxygen on Venus	
Start Date: 20 Sept 2002	***End Date:*** 26 Sept 2002
Continent: Australasia	***Country:*** Australia
State/Province: NSW	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Spring Observatory	***Keywords:*** Astronomical Observations
Description of Work: David Crisp obtained ultra−high resolution Anglo−Australian Telescope/University College London Echelle Spectrograph (AAT/UCLES) spectra of the Venus nightside, and Jeremy Bailey and Sarah Chamberlain of the Australian Center for Astrobiology obtained simultaneous images of the Venus nightside at 1.27microns using	

the CASPIR infrared camera/spectrograph on the Australian National University 2.3m telescope. These simultaneous observations were designed to search for visible and near−IR airglow emission from oxygen in the Venus atmosphere. These observations were designed to explore oxygen abundance and chemistry in a CO_2 dominated terrestrial atmosphere as a means of providing better models and constraints on abiotic O_2 abundance on terrestrial planets. Although the UCLES observations were disappointing, the CASPIR 1.27um observations obtained the first complete set of observations of oxygen airglow appearance, dispersal and reappearance on the Venus nightside, providing a valuable piece of evidence required for understanding the generation and nature of this emission.

Members Involved:

Cross Team Collaborations

Postdoc Giovanna Tinetti, of Ken Nealson's JPL/USC group, has been collaborating extensively with our team on this project. With summer students William Fong and Heather Snively, Dr. Tinetti is principally responsible for the development and construction of the Mars model, and the running of subsequent experiments with the completed model.

We are currently also collaborating with the Australian Center for Astrobiology team members, Jeremy Bailey and Sarah Chamberlain, who provide ground−based spectroscopic data for terrestrial planets as a validation to our models.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Characterization of Terrestrial Planets From Disk−Averaged Spectra: Spectroscopic Studies to Understand Detectability and Habitability.

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***Characterization of Terrestrial Planets From Disk−Averaged Spectra: Spectroscopic Studies to Understand Detectability and Habitability.***
Project Investigators:	***Victoria Meadows , Thangasamy Velusamy , James Kasting***

Project Progress

In this project we focus on understanding what we can learn about an extrasolar terrestrial planet from remotely sensed, disk−averaged spectra, as a function of spectral resolution and instrument sensitivity. With these spectroscopic studies we will build a spectral library of terrestrial planets for use in Terrestrial Planet Finder (TPF) mission planning and data analysis, and better understand the wavelength−dependent surface ultraviolet (UV) fluxes, to determine what constraints these might provide on planetary habitability and biological evolution.

We have used a range of Earth−like, self−consistent planetary atmospheres with different oxygen abundances around F2V, G2V and K2V stars (Krelove, Segura and Kasting) as the basis for this study. Using a spectrum resolving (line−by−line) atmospheric/surface radiative transfer model (Crisp) and a detailed spectra description of the parent star (Cohen), we have generated synthetic spectra of these planetary atmospheres, from the UV to the far−infrared (IR) (Meadows). These spectra clearly show the delectability of biosignatures such as O_2, O_3, CH_4 and N_2O, and also atmospheric CO_2. Figure 1 shows our results on ozone as a function of atmospheric oxygen abundance for a planet around a G2V star and Figure 2 shows the spectrum for as "Earth" around stars of different spectral type and the differences in detectability of atmospheric features. To further explore planetary habitability, and planetary conditions for life, Kasting, Segura and Sommerlatt have computed surface UV fluxes and UV dose rates for erythema and deoxyribonucleic acid (DNA) damage. Interestingly, planetary UV surface fluxes are low for high−oxygen planets orbiting the high−UV output F stars, because of the creation of a protective "super" ozone layer.

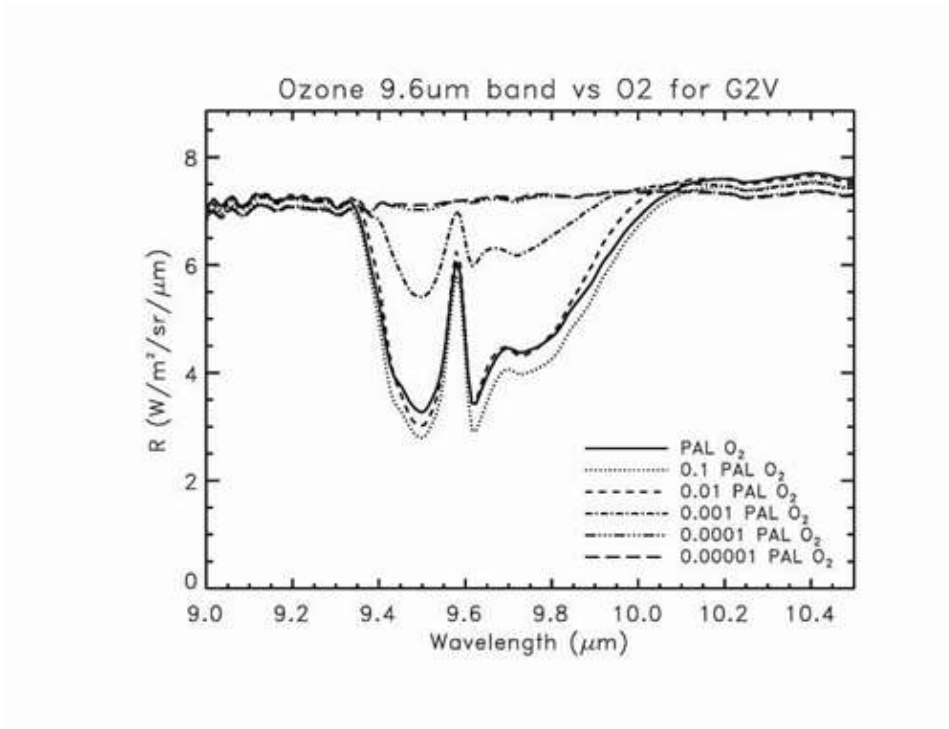

Figure 1. *This plot shows ozone as a function of atmospheric oxygen abundance for a planet around a G2V star. The ozone column decreases, but remains appreciable down to O_2 levels of 0.01 PAL, but the 9.6um ozone band retains almost the same strength down to this O_2 level because the lower ozone column is offset by enhanced absorption due to the greater temperature difference between the stratosphere and the warm, emitting planetary surface (Segura, Krelove, Kasting)*

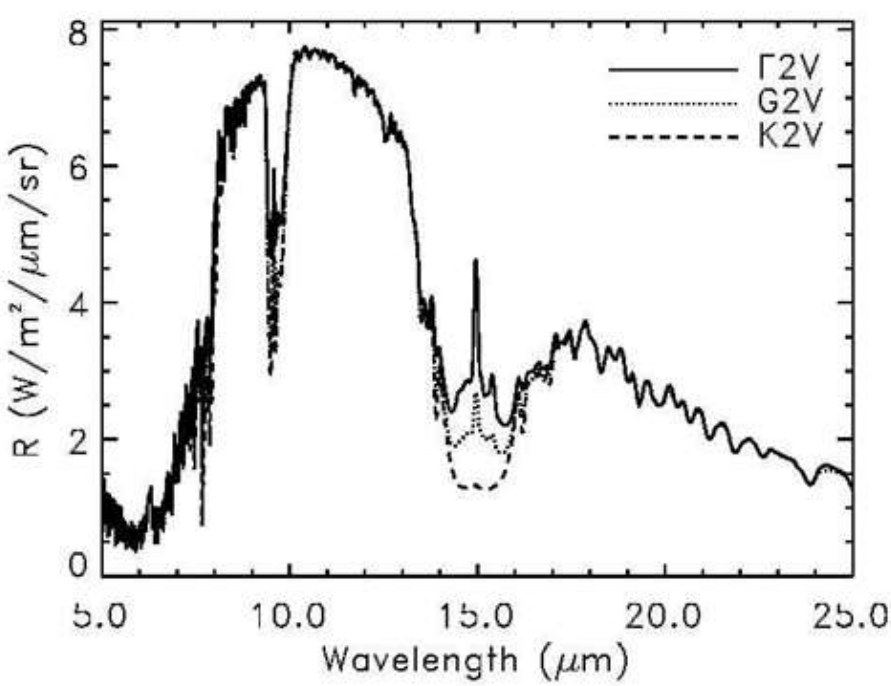

Figure 2. *The spectrum for as "Earth" around stars of different spectral type. Marked differences are seen in the detectability of features such as ozone and carbon dioxide, as a result of the atmospheric temperature and abundance changes driven by the spectral energy distribution of the parent star.(Meadows and Crisp)*

In addition, Velusamy ran the spectra generated by this project through a TPF instrument simulator for one possible design configuration (an interferometer with 4 x 3.5m mirrors on a fixed boom) to look at required spectral resolution and detectability for these features. Figure 3 shows an example of the simulated spectrum for an Earth around a G2V star at 10pc, as observed by this instrument simulator. Expanding on this project, Velusamy has also examined the design and use of a small space−borne Bracewell nulling interferometer for observations of Jovian and terrestrial planets in the 4−12um spectral region. Such an instrument would have the sensitivity and resolution at 5 microns to detect Jupiters in the young clusters, over a wide range of ages and distances, from 8 Myr (Eta Cam at 100pc) to 650 Myr (Hyades at 45pc).

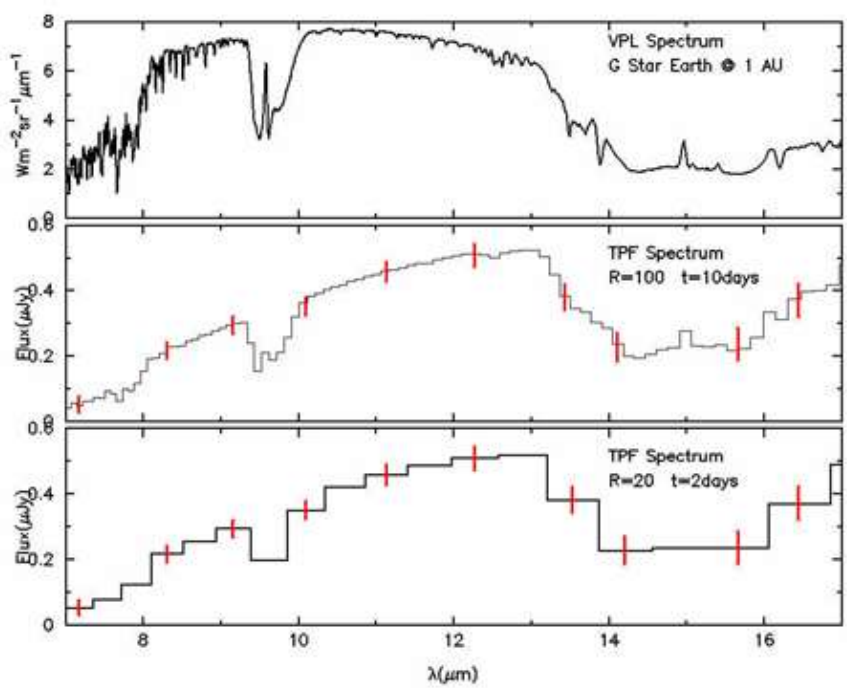

Figure 3. *Simulation of TPF spectral observation of a Earth around a Sun−like star. The TPF book design interferometer model was used i.e. four 4m telescopes on a 75m baseline. The upper panel shows a full resolution spectrum of Earth at its usual distance from the Sun. The middle and lowest panels show the TPF spectrum for this planet, at the same distance from its parent star, around a star 10pc distant. The spectrum has been modified by the instrument to spectral resolutions of R=100 and 20, respectively with corresponding TPF integration times of 2 10 days. The error bars (in red) indicate 1 sigma sensitivities. (Velusamy)*

Highlights

- We have begun our exploration of potential biomarkers in extrasolar planet atmospheres, producing spectra from the UV to the far−IR from radiatively and chemically self−consistent atmospheres to assess the detectability of atmospheric and surface features for Earth−like planets around stars of different spectral type.

- We have shown that ozone and methane might be observed simultaneously in a Mid−Proterozoic−type terrestrial planet atmosphere. The simultaneous presence of O_2 (or O_3) and reduced gases is considered the firmest remote evidence for extraterrestrial life.

- We have computed surface UV fluxes and UV dose rates for erythema and DNA damage, and we came to the surprising conclusion that planets with oxygen−rich atmospheres around stars with high UV flux may be able to greatly reduce surface UV flux via the creation of a "super−ozone" layer.

- All the above results have been written up in Segure et al., 2003, to be submitted to Astrobiology by July 2003.

- We have run several of our computed spectra for Earth−like planets through an instrument simulator for a possible TPF design to understand detectability of specific atmospheric constituents as a function of spectral resolution and sensitivity.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	TPF Science Working Group Member, planning support, data analysis.
3	Life Finder	planning support, data analysis.

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa,

biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The spectroscopic analysis described here is directly related to the principal goals of the TPF mission, which is to detect and characterize terrestrial planets in the habitable zones of neraby stars, and supports mission planning and future data analysis. The detailed, higer spectral resolution results being determined here will also inform the Life Finder mission.

This year, VPL team lead Vikki Meadows also served as member in TPF Science Working Group, representing astrobiological interests in this mission, and advising the Precursor Science, Science Requirements, Inteferometer Instrumentation and Education and Public Outreach task groups.

This year VPL team member Velusamy served in the TPF Interferometer Science team at JPL, analyzing the imaging capabilities of the TPF designs. He also participated in the NASA's TPF related program for Extra−solar Planets Advanced Mission Concepts, proposing a "Self−Luminous Planet Finder" to study Jovian planets in young star systems

Cross Team Collaborations

This research benefits greatly from an extremely strong collaboration with Jim Kasting and his postdocs and students in the Penn State NAI Lead Team. Jim and his group pioneered the coupled climate−photochemical modeling that produces the planetary atmospheres we have used to explore the detectability of planetary characteristics. By using these atmospheres as inputs to our radiative−transfer models, and using the stellar spectra and molecular line lists provided by VPL team members Cohen, Brown and Butler (work described in an associated report), we are able to generate synthetic spectra of these model atmospheres over very large wavelength ranges, and use these spectra for detectability analyses.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Chemistry Models for Extrasolar Planets

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***Chemistry Models for Extrasolar Planets***
Project Investigators:	***James Kasting , Chris Parkinson***

Project Progress

This year, we have worked on both a coupled photochemical−climate model for Earth−like planets, which is an end−to−end test case for the larger VPL atmosphere model, and chemistry models for extrasolar giant planets.

The Photochemical−Climate Model for Earth−Like Planets: This model (J. Kasting) has been used to model chemically and radiatively self−consistent atmospheres for Earth−like planets around other stars. Experiments were run (Kasting, Krelove, Segura) for an "Earth" with oxygen levels from the present atmospheric level (PAL), down to 1/100,000th PAL. This time−stepping model was also run to equilibrium to derive atmospheres for the planets around F2V, G2V and K2V stars, and to understand atmospheric conditions during the Earth's Proterozoic. Figure 1 shows vertical profiles of ozone and temperature for Earth at different oxygen levels. We found that as atmospheric oxygen is removed, the ozone layer descends, and the stratospheric temperature bulge is reduced (via reduced heating from solar ultraviolet (UV) absorption by ozone). However, the ozone column remains appreciable down to 0.01 PAL of oxygen. We also modelled Earth−like planets orbiting K2V and F2V stars. The model atmospheres were also used as input to generate synthetic planetary spectra as described in an associated report.

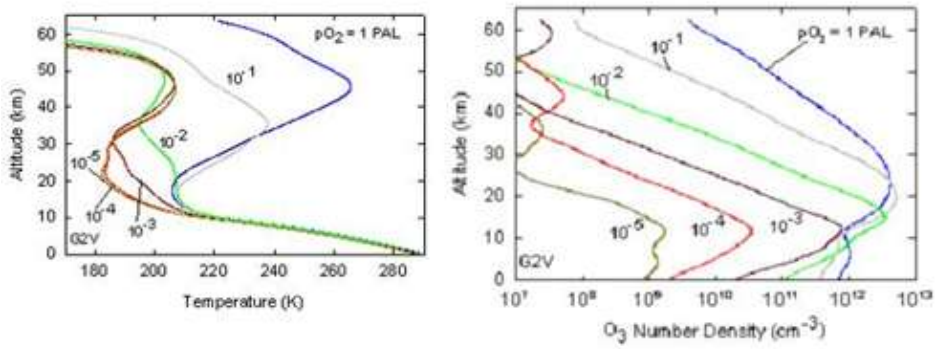

Figure 1. *Plots showing a) atmospheric temperature and b) ozone mixing ratio, as function of altitude for Earth−like planets with successively lower abundances of oxygen in their atmospheres. The blue line shows results for an atmosphere with the present atmospheric level of O_2, and the other lines are labeled with the factor of 10 reduction in oxygen abundance from the present level. These plots show the gradual cooling of the stratosphere, and the descent of the peak concentration of ozone in the atmosphere as a function of the decreasing atmospheric O_2 abundance.*

Extrasolar Jovian Planet Chemistry Models: Atmospheric escape rates are extremely important for understanding a planet's evolution, and escape rates from young terrestrial planets are believed to be much higher than observed present−day rates. To validate the VPL hydrodynamic escape module for younger planets, we are using observations of "hot Jupiters" as a model validation for high escape rates. For this work, we have developed a one−dimensional (1−D) chemical model for Jovian planets that are extremely close to their parent star (Parkinson). In this environment, they experience high temperatures and UV fluxes, which modify the chemical reactions normally seen in Solar System Jovian planets. For extrasolar hot Jupiters, the formation of hydrocarbons, oxygen chemistry, and hydrodynamical loss is significantly enhanced because of their environment. Because of enhanced photolysis of higher order hydrocarbon species, our model is based only on H_2, CO, H_2O and CH_4. Our two main results are that (a) H is produced largely in the atmosphere through the reactions of OH radicals, and H_2 is not sensitive to the exact abundance of CO, H_2O, and CH_4 and (b) H_2O acts as a catalyst and can be produced via the reactions of CO and H_2. The modifications to the chemical model to incorporate new chemistry, database modeling, and to couple it to a hydrodynamic escape code are directly applicable to

modifications required for the VPL terrestrial planet models.

Highlights

- Kasting, Krelove and Segura have self−consistently modeled the atmospheres of Earth−like planets with varying abundances of oxygen, for planets around stars of different spectral type. These model results are the basis for studies of planetary characterization from remote−sensing spectroscopy (Segura et al., 2003).

- Parkinson and Yung have completed research a) detailing the chemistry of extrasolar "hot Jupiters" and b) delineating the methodology and validation of the planetary atmospheric hydrodynamic escape model and its coupling to the chemistry model for the VPL (M. Liang et al., 2003; Parkinson et al., 2003).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars Volcanic Emission and Life Scout (MARVEL)	Mission Principal Investigator
2	TPF	Planning support, data analysis
2	Life Finder	Planning support, data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Relevance to the TPF/PS Program

1. MARVEL

   MARVEL is a Mars Exploration program 2007 mission concept. Project Team member Mark Allen serves as the PI for this mission concept, which focuses searching for atmospheric markers of extant volcanism and life.

2. TPF and Life Finder (general)

   The chemistry model(s) under development here are a crucial component of the combined VPL model, which will allow us to model plausible extrasolar planet environments,and ultimately, their appearance from space. This information will be important for TPF and Life Finder mission planning and data analysis. The extrasolar hot Jupiter research will enhance our understanding of Jovian planets close to their parent star, and could be used to interpret more detailed spectroscopic observations of these planets by instruments as sensitive as TPF.

Cross Team Collaborations

Carnegie Institute of Washington team member Sara Seager contributed to the chemistry paper on extrasolar "hot Jupiters" (M. Liang et al., 2003).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Climate Model For Extrasolar Terrestrial Planets

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***Climate Model For Extrasolar Terrestrial Planets***
Project Investigator:	***David Crisp***

Project Progress

As the first step in our efforts to simulate the environments of extrasolar terrestrial planets, a simple 1−dimensional radiative convective equilibrium (RCE) model (c.f. Crisp, 1986; 1989) will be used to study the globally averaged, thermal structures of their atmospheres and surfaces. An existing RCE model (Crisp 1990; Gerstell, Crisp, and Crisp, 1995) is being upgraded to simulate a broad range of plausible environments. This model originally combined band modeling methods with a 2−stream multiple scattering algorithm to estimate radiative heating rates. This approach produced reliable results in some cases, but could produce significant errors in atmospheres where both multiple scattering and line absorption by gases contributed to the radiation field. Second, unlike most climate models, which use a simple convective adjustment to simulate the effects of vertical convection, the RCE model adopted here uses mixing length theory to simulate convection. This approach produces much more realistic temperature profiles near planetary surfaces. However, even though this approach could also provide a self−consistent method for transporting water vapor and other volatiles from the surface to other atmospheric layers, the existing model did not include this capability.

The RCE model upgrades implemented this year address both of these issues. The Spectral Mapping Atmospheric Radiative Transfer (SMART) algorithm has been installed in place of the simpler band modeling and 2−stream methods. The mixing length approach was also extended to transport volatiles as well as heat, and a simple, non−precipitating cloud model was added, so that clouds could form and dissipate as the atmospheric thermal structure evolved toward equilibrium.

Preliminary tests of this model show that additional modifications will be needed to improve its capability, stability, and ease of use. The mixing length scheme is currently being upgraded by adopting the vertical transport scheme from the University of Helsinki 1−dimensional planetary boundary layer model (Savijarvi 1995; 1999). The cloud model is being upgraded to include precipitation as well as condensation and evaporation of clouds.

Highlights

- The radiative transfer model that forms the heart of the climate model was successfully ported from an obsolete workstation to a 32−CPU beowulf cluster. This should reduce the computation time for this module by about a factor of 100.

- The first version of the climate model came on line this year. Even though this code has thus far served more as a learning experience than a useful research tool, it still constitutes a significant step forward.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning support, data analysis
3	Lifefinder	Planning support and data analysis
2	ESSP Orbiting Carbon Observatory	Mission Principal Investigator
2	ExoMars	Member of the Prosector Science Team, responsible for surface radiation budget studies
2	Venus Express	Member of the Science Teams for the Venus Monitoring Camera (VMC) and Planetary Fourier−transform Spectrometer (PFS)

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

TPF and Life Finder: The climate model under development here is a crucial component of the combined VPL model, which will allow us to model plausible extrasolar planet environments,and ultimately, their appearance from space. This information will be important for TPF and Life Finder mission planning and data analysis.

Orbiting Carbon Observatory (OCO): D. Crisp is the Principal Investigator of the Earth System Science Pathfinder Orbiting Carbon Observatory (OCO). This mission will make the first space−based remote sensing measuremetns of atmospheric CO_2 with the spatial and temporal resolution and precision needed to characterize surface sources and sinks of this important greenhouse gas. These observations will improve our understanding of the Earth's carbon cycle, and facilitate improved predictions of future atmospheric CO_2 concentrations and their effect on the Earth's climate. There is strong synergy between the NAI VPL radiative transfer and climate modeling activities and the analysis tools being developed for OCO.

ExoMars: D. Crisp is a member of the Prospector Science Team, an instrument proposed in response to the ESA ExoMars Anouncement of Opportunity. As a member of that team, he is responsible for characterizing the near−surface radiative and thermal environment at the Martian surface. The radiative transfer modeling and surface boundary layer algorithms being developed under the NAI VPL climate modeling task are directly relevant to this activity.

Venus Express: D. Crisp is a member of the PFS and VMC science teams. In those roles, he is responsible for remote sening retrieval and thermal balance studies of the Venus atmosphere. The tools being developed as part of the VPL climate modeling task will be used in those investigations.

Cross Team Collaborations

Dr. Giovanna Tinetti, of Dr. Ken Nealson's team from the University of Southern California, has collaborated extensively with us on this project. She is currently responsible for the convective modeling module for the climate model code.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Spectroscopic Databases to Support Extrasolar Planet Modeling

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***Spectroscopic Databases to Support Extrasolar Planet Modeling***
Project Investigators:	***Martin Cohen , Linda Brown***

Project Progress

In this project, we have concentrated on gathering and providing spectroscopic information required for modeling extrasolar planets. The two current components of this effort are 1) providing high−resolution, full−wavelength range spectra for stars of different spectral type, and 2) collating and providing a comprehensive database of the spectral line lists and wavelength−dependent surface albedos required by the VPL radiative transfer models to produce synthetic spectra of planetary atmospheres and surfaces.

Stellar Spectra: Cohen has worked to provide broad−wavelength spectra for stars of different spectral type, and to look at the range of ultraviolet (UV) properties of G star "solar analogs". We have extracted short− and long−wavelength UV spectra of 18 G−dwarf stars, and the K2V star epsilon Eri from NASA's International Ultraviolet Explorer (IUE) Final Archive and have recalibrated them. To these UV spectra we have appended Kurucz photospheric spectra covering the visible and infrared (IR). These full−wavelength range spectra were used by VPL team members (led by Kasting) to model the atmospheres and appearance of Earth−like planets around stars of different spectral type.

To explore G star UV properties and their effects on habitability, Cohen compared the empirical UV and modeled−photospheric spectra for two solar−analog G0V stars, HD206860 (active) and HD 114710 (inactive) and also compared them to the Sun. From this analysis we conclude that the solar−analog assumption based on classification by spectral type alone is a poor way to establish stars with potentially habitable planets, as both the active and inactive G0V stars are far more UV−luminous than the Sun, and provide very different UV fluxes incident on an associated planet.

Line List Database: Brown and Butler have worked to collect line lists and absorption cross−sections for 45 molecules of interest to planetary modelers. These data have been collated and can be "ordered" by the team via a web−page interface that provides spectra of the line−list data in both

wavenumbers and microns. Each molecule in the database may have available data from several different sources, including infrared absorption cross−sections from Pacific Northwest National Lab (PNNL), infrared line lists from the HITRAN database, UV cross−sections from personal collections of VPL personnel, or journal articles. Although the database is currently only accessible by VPL members, we plan to make it available to the NAI community later this year.

Highlights

- The operation of combining accurately calibrated IUE SW+LW spectra with photospheric stellar spectra has been streamlined and validated, using Hubble Space Telescope/Space Telescope Imaging Spectrometer (HST/STIS) spectra and the same process devised by Cohen to create absolutely calibrated photospheric spectra for the Space Infrared Telescope Facility's (SIRTF's) calibration stars.

- It is vital to combine stellar photospheric spectra with empirical UV spectra when modeling planets, because UV is the prime driver of photochemistry in the atmospheres of any planets orbiting these stars.

- Even using stars with the same spectral type as the Sun does not result in real spectra that are similar. Chromospheric activity varies among solar−type stars so that the actual stellar flux incident on putative planets can be several times greater in an active G−dwarf than in an inactive star of the identical type.

- We have created a web−interfaced database that provides line−lists, absorption cross−sections, and images of the spectral response for 45 molecules that are important for modeling planetary atmospheres and biosignatures.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	planning support, research or analysis techniques
3	Life Finder	planning support, research or analysis techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The stellar spectra and line−list database discussed here are valuable products for planetary models that seek to understand the evolution and appearance of terrestrial planets both with and without life. As such, these products support mission design and planning for both the NASA Terrestrial Planet Finder mission, and its higher spectral−resolution successor, the NASA Life Finder mission.

Project Report: The Abiotic Planetary Model: The Upper and Lower Boundary Condition on the Atmosphere

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***The Abiotic Planetary Model: The Upper and Lower Boundary Condition on the Atmosphere***
Project Investigators:	***Rob Rye , Chris Parkinson***

Project Progress

We have made progress on a number of fronts toward establishing boundary conditions for planetary atmospheres in the VPL. The link between planetary thermal evolution and the generation of magnetic fields has been better elucidated through a series of publications by Nimmo and colleagues. Such fields shield atmospheres and biospheres from erosion by lethal doses of stellar radiation and as such are of great interest in astrobiology in general and in the VPL in particular. Also of great interest in astrobiology and the VPL is the treatment of hydrodynamic loss processes of chemical constituents from the upper planetary boundary layer. The details of the preliminary modeling techniques and model validation are given by Parkinson et al., to be submitted for publication July 2003, and are summarised below.

General geochemical (Yang, Holland and Rye 2002) and Fe isotopic studies of an older paleosol (2.75 Ga) has provided further understanding of elemental cycling on ancient Earth. These studies provide empirical constraints for validation runs of the VPL against Archean Earth. A reactive transport modeling study of a 2.2−2.4 billion year old (Ga) paleosol has yielded insights into the composition of Earth's atmosphere at that time. The paleosol modeling study is the first of a series of process driven kinetic models that will serve to characterize the interactions between atmospheres and planetary surfaces, and the tools developed in this highly specific model are highly transferable to more generalized models that are yet to come.

Existing hydrodynamic escape models produce solutions by integrating the coupled, time independent mass, momentum, and energy equations for the escaping gas from the homopause out to infinity. However, solving the one−dimensional, steady state approximation becomes problematic at the distance where the outflow becomes supersonic. We have developed a new technique for the treatment of hydrodynamic loss processes from planetary atmospheres (Parkinson et al. in prep) utilising the Godunov method. A detailed description of a first order Godunov scheme is given by Godunov

(1959), Gombosi (1984), and Leveque (2002). This method overcomes the instabilities inherent in modeling transonic conditions by solving the coupled, time dependent mass, momentum, and energy equations, instead of integrating time independent equations. We validate a preliminary model of hydrodynamic escape against simple, idealised cases (viz., steady state and isothermal conditions) showing that a robust solution obtains and then compares to existing cases in the literature as cited above. The general tools developed here will be applied to various problems such as the early Earth and Venus, and close−in extrasolar gas giant planets.

Highlights

- Team members Nimmo, Sleep and Zahnle submitted a paper examining the links between plate tectonics, thermal evolution and degassing for the Earth. This contribution attempts to reconcile geochemical observations with reasonable physical models, and is an example of the kind of boundary models that will ultimately be incorporated into the VPL.

- Nimmo continued to examine the relationship between planetary thermal evolution and magnetic field generation in a series of papers and abstracts (Nimmo, 2002; Williams and Nimmo, 2003; Nimmo et al., 2003). Magnetic field generation influences the rate of atmospheric loss as well as providing a shield against harmful charged particles, and is thus of critical astrobiological interest.

- In collaboration with Anbar of JPL(I) we presented the first Fe isotopic data on ancient paleosols at the Goldschmidt Conference. This data should help elucidate the Fe cycle on the Archean Earth.

- Preliminary research completed by team members Parkinson, Richardson and Yung (with a paper in preparation) delineates the methodology and validation of the planetary atmospheric hydrodynamic escape model for the VPL.

- Team members Parkinson and Yung submitted a Terrestrial Planet Finder (TPF) proposal entitled "Structure, Composition, and Evolution of Extrasolar Gas Giant Planets" to characterize and contribute to a theoretical understanding of gas giant planets found around other stars.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	TPF	Planning support and data analysis
2	Lifefinder	Planning support and data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The models under development in this task will be used to understand the plausible range of atmospheric and surface compositions for extrasolar terrestrial planets. The results of this modeling will also inform efforts to understand what these planets would look like, and the detectability of planetary characteristics, when viewed from missions such as TPF and Life Finder. As such, they will provide a valuable tool for mission planning and analysis of data returned by these missions.

Cross Team Collaborations

The iron isotope study of ancient paleosols has been pursued in collaboration with Ariel Anbar, who is a member both of JPL 1 and of the Harvard group. Results of this study suggest that Fe isotopes can be fractionated in anoxic weathering systems and conversely that the transport of Fe in the particular paleosols under study almost certainly took place under anoxic conditions.

Project Report: The Virtual Planetary Laboratory − The Life Modules

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***The Virtual Planetary Laboratory − The Life Modules***
Project Investigators:	***Rob Rye , James Kasting***

Project Progress

We have pursued three related avenues meant ultimately to lead to a coherent model of how detectable biosignatures may be produced on extrasolar planets. First, we have continued our assessment of life in aquifers and springs associated with terrestrial serpentinizing peridotite bodies. Several organisms have been isolated and a baseline for annual and seasonal ariations in geochemical conditions is emerging. This project should yield an understanding of the sorts of nutrient limitations faced by and the resultant biosignatures produced by life that might develop associated with rocks at the surface of an undifferentiated water−rich terrestrial planet. We hope to use such understanding to constrain models of life on earliest Earth and on hypothetical young extrasolar planets.

Along the second avenue we have been developing an anaerobic early Archean ecosystem model. This work by Kharecha, Siefert and Kasting has thus far focused on biological productivity and methane production prior to the origin of oxygenic photosynthesis. Without oxygenic photosynthesis, carbon fixation was limited by the availability of reductants. In the early Archean, this is essentially equivalent to being limited by the volcanic flux of hydrogen, which today is about 5 x 10^{12} mol/year. The model explicitly accounts for cycling of hydrogen and carbon through 4 processes: primary production by hydrogen utilizing methanogens, fermentation, methanogenesis and photolysis. We assume that methanogens must derive d30kJ/mol (~1 adenosine triphosphate (ATP) equivalent) in making 1 mol of methane. A series of scenarios have been run using an atmospheric chemistry model coupled with a stagnant boundary layer model to capture the surprising diffusion−limitation on delivery of hydrogen to the marine biota and methane to the atmosphere. Initial results indicate that if we assume the modern volcanic flux of hydrogen, then the atmosphere could contain up to ~350 ppmv of methane if hydrogen utilizing methanogens were the primary producers.

We have also initiated a dynamical model of a microbial ecosystem (Tinetti, Storrie−Lombardi), which includes interaction with the external environment, including the stellar flux. In this multicomponent model, individual microbial

species interact with each other, and their growth is governed by available energy and chemical resources, and limited by space. We continue to explore the stability of these equations, for both the autonomous and environment−coupled system. We are also working on expansion of the model to include stellar−driven photosynthetic life. In the case of photosynthetic life, the population growth and its periodicity will be determined by the available wavelength−dependent solar flux.

Highlights

- We have isolated several organisms that appear to grow at pH >11 and salinity
- Team member Rye has obtained funding from the Exobiology program for expanding work on the understanding of life processes associated with serpentinization of a peridotite body.

- A simple early Archean anaerobic ecosystem model has provided fresh insight into the manner in which methane levels are likely to be controlled in a world without oxygenic photosynthesis. Diffusion of hydrogen downward and methane upward through the air−sea interface was found to be of great importance in determining the partitioning of reducing equivalents between hydrogen gas and methane.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, comunities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
0	MARVEL	Science team member
2	TPF	Planning support and data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
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2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa,

biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
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Our work in modeling planetary atmospheres and calculating simulated spectra thereof could eventually be useful in analyzing TPF (Terrestrial Planet Finder) data. We are trying to determine what are the best bioindicator species and whether they could be observed in different types of atmospheres.

Field Expeditions

Field Trip Name: The Cedars	
Start Date: 8/16/02	***End Date:*** 08/18/02
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water samples from hyperalkaline springs for geochemical and microbiological analyses. We continued to explore the biology and the environment of hyperalkaline non−saline springs to assess the site as a possible analogue for Mars and for juvenile extrasolar planets, and to gather information pertinent as input to the life modules for the VPL (Collaborative with JPL/USC node).	
Members Involved: Michael Storrie−Lombardi	

Field Trip Name: The Cedars	
Start Date: 05/31/03	***End Date:*** 06/01/03
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water samples from hyperalkaline springs	

for geochemical and microbiological analyses. Samples of the travertine apron were collected in order to assess the relationship between microbes in the springs and the layered carbonate structures that form rapidly around them.

Members Involved: Rob Rye

Cross Team Collaborations

We are collaborating with Ken Nealson's JPL/USC team for much of the field−work component of this effort. Dr. Giovanna Tinetti (JPL/USC) is also collaborating with us on life−model development.

Project Report: The Virtual Planetary Laboratory − Synthesis and Architecture

Lead Team:	***Virtual Planetary Laboratory***
Project Title:	***The Virtual Planetary Laboratory − Synthesis and Architecture***
Project Investigators:	***Chris Parkinson , David Crisp***

Project Progress

Many environmental processes contribute to the reflected stellar and emitted thermal spectrum of a planet. To simulate these processes for a range of extrasolar terrestrial planets, the VPL will incorporate radiative transfer, climate, chemical, geological, exogenic, and biological algorithms. Given a series of initial conditions, these methods will use a forward time−stepping approach to march the environment toward a plausible equilibrium state. The radiative transfer, climate and chemical modules are based on well tested, existing codes. The other modules are being developed in parallel with the model integration activity.

A modular VPL software architecture design will:

1. minimize changes to existing codes,
2. allow flexible evolution rates (time−splitting) between processes,
3. allow parallel development of algorithms for environmental processes, and
4. optimize the combined model for parallel computing

This architecture is illustrated in Figure 1. The "Initialize" block contains an assumed initial state (stellar type, distance from star, environmental characteristics) and specific process−control information and convergence criteria. The major time−step loop contains a series of processors (exogenic, geology, chemistry, climate, biology) connected by "translators". Each translator takes the output from the previous module, combines it with information from the initiation module and an evolving common database, and writes input files that can be read by the next processor. The rapidly evolving processors (e.g. chemistry, climate, biology) might execute internal time−step loops between major time−steps to ensure stability. Time−stepping continues until convergence criteria are satisfied. The VPL then outputs a spectrum of the planet for evaluation by the instrument simulator.

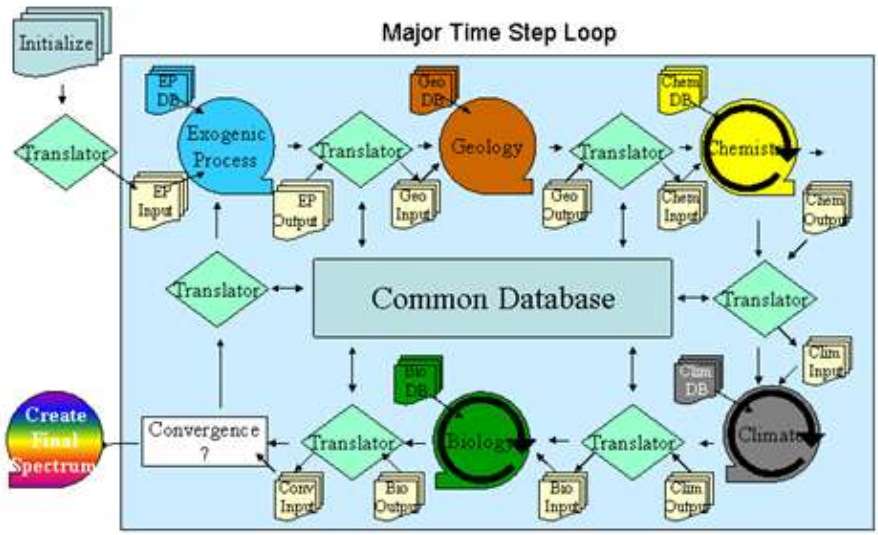

Figure 1. *Preliminary Architecture Design for the Virtual Planetary Laboratory. The design consists of five component models that represent classes of environmental processes. Communication and control between the models will be provided by translation programs and a central database.*

This year we defined the basic architecture, and the requirements for the Translators and Common database. Integration of the chemistry and climate models will happen first. The remainder of the modules will initially be specified as static "state vectors", and later replaced as the full models come on line.

Highlights

- The basic VPL architecture has been defined.
- Planning of the data interchange and interface for the VPL components and work on the database model has been started.
- Coupling of the climate and radiative transfer models is well under way, work has started on the climate/geology interface, and development of the atmospheric hydrodynamic escape and its coupling to the chemistry model has been explored. (Parkinson et al., 2003).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning support, data analysis
3	Life Finder	planning support, data analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
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** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

TPF and Life Finder

Integrating the chemistry, radiative transfer, and climate modules under development here are a crucial core component of the combined VPL model, which will allow us to model plausible extrasolar planet environments, and ultimately, their appearance from space. This information will be important for both TPF and Life Finder mission planning and data analysis.

Cross Team Collaborations

Postdoc Dr. Giovanna Tinetti from the USC/JPL team has collaborated with us on this project. Working with co−I Rob Rye, she has explored the transmission of thermal information at the soil interface between the climate model and the geological and weathering models.

Fellowships: Virtual Planetary Laboratory

There are no Postdoctoral Fellowships for this team.

EPO: Virtual Planetary Laboratory

These are the Education and Public Outreach activities for the Virtual Planetary Laboratory.

Planning for a Focus Group on the Science Communication of Astrobiology

Cherilynn Morrow presented a draft plan for the formation of a Focus Group on the Science Communication of Astrobiology to the NAI EPO leads at the NAI conference in Tempe, AZ (Feb 2003). She and Carol Oliver of the Australian Centre for Astrobiology began the process of co−developing a proposal to NAI Central. Early investigations at the Tempe conference and other meetings suggest that interest is very high on the part of both scientists and educators in the field of astrobiology, both within and outside of NAI. International interest is high as well in Spain and England, as well as Australia.

We envision that the focus group will help to connect NAI EPO efforts to other major EPO projects (both national and international) related to astrobiology. It will also provide fora for addressing challenging communication issues defined by the astrobiology community, such as how you know when you've successfully communicated across disciplines, and how to handle the fiercely held misunderstandings people often have about life elsewhere and about the origins and evolution of life on Earth and elsewhere (e.g. alien abductions and young−Earth creationism).

The focus group would address the full spectrum of science communication, including formal education, informal education, public outreach, and news/media. In the next year, Morrow and Oliver plan to proceed with the development and submission of the Focus Group proposal for consideration by the NAI Executive Committee.

Group Leadership, Advising, and Meeting Organization: The Virtual Planetary Laboratory

Sometimes education and public outreach occurs behind the scenes. The leadership and organization of focus groups, advisory committees, and science and education conferences are a vital service to the community.

For the NASA Astrobiology Institute's General Meeting in Tempe, AZ, 10−12 February 2003, Dr. Victoria Meadows was responsible for a variety of tasks. She was not only on the Program Organizing Committee, but she was also session chair and organizer for "The Search For Habitable Planets Beyond

Our Solar System" with six invited speakers focusing on the astrobiological research required to support the Terrestrial Planet Finder mission (TPF). Dr. Cherilynn Morrow and Dr. James Harold were supported by the Jet Propulsion Laboratory (JPL) Virtual Planetary Laboratory (VPL) program to attend the NAI General Meeting. Morrow and Harold met with the VPL research team and attended several seminars, effectively enhancing the perspective and progress of the JPL VPL E/PO effort.

Dr. Meadows was also the NAI Focus Group Leader and meeting chair for the proposed Biosignatures group, and served as the host for this year's NASA Astrobiology Institute's Executive Council Meeting held in Pasadena, California.

Dr. Cherilynn Morrow presented a draft plan for the formation of a Focus Group on the Science Communication of Astrobiology to the NAI EPO leads at the NAI conference in Tempe, AZ (Feb 2003). For more information, please see entry entitled "Planning for a Focus Group on the Science Communication of Astrobiology."

Dr. Francis Nimmo acted as advisor to the Science Definition Teams for The Jupiter Icy Moon Orbiter (JIMO) on likely ice shell structure and topography.

Family Guide to Life Elsewhere in the Universe

The JPL 2 EPO Team, led by the Space Science Institute (SSI), is planning to develop a "Family Guide to Life Elsewhere in the Universe". The Guide will be a collection of engaging pictures, puzzles, poetry, and projects that stimulate dialogue and activity between children and their parents or other significant adults in informal learning environments.

Much learning in life takes place in informal environments outside the classroom. We envision this Guide being of value wherever kids and adults find themselves together and excited about learning. Home schooling, traveling science exhibits, community outreach booths, family programs in museums, and public talks by scientists provide access to families interested in science. The "Family Guide" aims to extend the learning potential of these experiences and lead to greater awareness and understanding of what is known about the search for life elsewhere. The Guide will assume little or no prior knowledge about astrobiology.

Although the Guide is intended primarily for informal learning environments, we plan to relate Family Guide content to the national science education standards.

We will begin the Guide with a page−long "Tips to Guide Your Child's Enjoyment of Learning" developed this past year to help adults understand that being a good learning companion to kids is NOT the same as being the expert who tells all the answers.

This past year we established a basic framework for the contents of the Guide. Overall goals of the Guide are:

1. To stimulate dialogue and activity between children and their parents or extended family
2. To provide an opportunity for co−learning with parent and child
3. To provide clear answers to common questions and to challenge common misconceptions
4. To offer clear direction about how to obtain more information or useful products related to family learning

This next year we will be collaborating with NAI scientists and educators to assist us with identifying key themes and messages to thread throughout the Guide. We envision the Guide to be of value to the EPO efforts of all NAI teams.

Science Seminars and Presentations: The Virtual Planetary Laboratory

The members of the Virtual Planetary Laboratory were privileged to have been invited to share their knowledge at many prestigious institutions and conferences this year: Professor Jim Kasting was invited to give talks at the Goldschmidt Conference, the University of Delaware, Northwestern University, the American Geophysical Union (fall meeting), NASA Astrobiology Institute's General Meeting, the American Association for the Advancement of Science, and the State University of New York. Dr. Kasting contributed talks to the International Society for the Study of the Origin of Life, entitled: "Mantle Redox Evolution and the Rise of Atmospheric O2". He was further honored by being invited by his own Pennsylvania State University to present a seminar entitled: "Methane Greenhouses and Anti−greenhouses on the Early Earth".

Dr. Victoria Meadows was invited to present talks at the University of Washington, the University of California, Santa Barbara, and Pennsylvania State University. She was also invited to be a plenary speaker at the International Astronomical Union, the Caltech Plenary Science Seminar (California Institute of Technology), and Division 32 Plenary Science Seminar (Jet Propulsion Laboratory). Dr. Meadows was invited by Dr. Charles Elachi to present the Virtual Planetary Laboratory as the "Jet Propulsion Laboratory Science Highlight" at the lunch time talk for the JPL external Science Advisory Council. She was also invited to present this talk to the Observatories of the Carnegie Institute of Washington.

Interviews and News Articles: Virtual Planetary Laboratory

Dr. Victoria Meadows was interviewed by the Sydney Morning Herald as well as ABC radio in Sydney, Australia, in support of her talk regarding the Virtual Planetary Laboratory at The Australian Museum in July 2002. She was also interviewed extensively by NOVA for their four part documentary on Origins, specifically a segment on remote−sensing life detection, as well as by the JPL spotlight series, "Creating Planets in Cyberspace". The videotaped portion of her interview was preceded by two extensive telephone interviews. The Virtual Planetary Laboratory has also been presented on CNN.com entitled: Cyberlab Brewing Up New Planets.

Contributing to Graduate and Undergraduate Education: The Virtual Planetary Laboratory

Professor Rob Rye (USC), Professor Jim Kasting (Penn State), and Dr. Victoria Meadows (JPL/Caltech) have devoted a considerable amount of time to the dissemination of scientific knowledge and expertise, focusing on astrobiology and the search for extraterrestrial life.

Dr. Kasting presented a series of six assorted lectures for the Agouron Geobiology course at the USC Wrigley Institute on Catalina Island.

Dr. Meadows taught a weeklong course on astrobiology to students at the Universidad de Compultense de Madrid, in Madrid, Spain.

Dr. Rye, with Dr. Ken Nealson, taught a graduate course presenting the links between life and the planet it inhabits at USC entitled: The Living Planet.

Dr. Meadows is hosting three students this summer who will be assisting Dr. Giovanna Tinetti and Dr. Chris Parkinson in their efforts in providing chemistry and architecture models for the Virtual Planetary Laboratory. One of these students, William Fong, is a returning summer student who further requested Dr. Meadows to be his mentor for a Scientific Writing Course given at California Institute of Technology this past school year.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
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Members: Virtual Planetary Laboratory

Team Members sorted by current team.

Name:	Mark Allen
Email:	Mark.Allen@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Jeremy Bailey
Email:	jab@aaoepp.aao.gov.au
Institution:	Anglo−Australian Observatory
Name:	Edward Bolton
Email:	Edward.Bolton@yale.edu
Institution:	Yale University
Name:	Linda Brown
Email:	Rebecca.A.Butler@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Rebecca Butler
Email:	Rebecca.A.Butler@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Sarah Chamberlain
Email:	chamberlain_sarah@yahoo.com.au
Institution:	Macquarie University
Name:	Sonia Chernobieff
Email:	sonia.chernobieff@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Martin Cohen

Email:	mcohen@astron.berkeley.edu
Institution:	University of California, Berkeley
Name:	David Crisp
Email:	david.crisp@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	David Des Marais
Email:	ddesmarais@mail.arc.nasa.gov
Institution:	Ames Research Center
Name:	William Fong
Email:	William@its.caltech.edu
Institution:	California Institute of Technology
Name:	James Harold
Email:	harold@colorado.edu
Institution:	Space Science Institute
Name:	James Kasting
Email:	kasting@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Pushker Kharecha
Email:	pushker@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Kara Krelove
Email:	kjk176@cox.net
Institution:	Arizona State University
Name:	Cynthia McClure
Email:	Cynthia.McClure@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Ian McKewan

Email:	ljm@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Victoria Meadows
Email:	Vsm@ipac.caltech.edu
Institution:	Jet Propulsion Laboratory
Name:	Hanh Milam
Email:	Hanh.Milam@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Cherilynn Morrow
Email:	camorrow@colorado.edu
Institution:	Space Science Institute
Name:	Francis Nimmo
Email:	Nimmo@ess.ucla.edu
Institution:	University of California, Los Angeles
Name:	Chris Parkinson
Email:	Chris.Parkinson@jpl.nasa.gov
Institution:	California Institute of Technology
Name:	Catherine Quinn
Email:	Catherine.Quinn@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Mark Richardson
Email:	mir@gps.caltech.edu
Institution:	California Institute of Technology
Name:	Rob Rye
Email:	rye@usc.edu
Institution:	University of Southern California
Name:	Antigona Segura

Email:	Antigona@essc.psu.edu
Institution:	Pennsylvania State University
Name:	Janet Siefert
Email:	siefert@stat.rice.edu
Institution:	Rice University
Name:	Norman Sleep
Email:	norm@pangea.stanford.edu
Institution:	Stanford University
Name:	Heather Snively
Email:	hastrobio@yahoo.com
Institution:	University of California, Santa Cruz
Name:	Darrell Sommerlatt
Institution:	Pennsylvania State University
Name:	Carl Steefel
Email:	steefel1@llnl.gov
Institution:	Lawrence Livermore National Laboratory
Name:	Michael Storrie−Lombardi
Email:	mike@kinohi.org
Institution:	Kinohi Institute
Name:	Giovanna Tinetti
Email:	tinetti@earth.usc.edu
Institution:	University of Southern California
Name:	Thangasamy Velusamy
Email:	velu@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Name:	Yuk Yung
Email:	yly@gps.caltech.edu

Institution:	California Institute of Technology
Name:	Kevin Zahnle
Email:	kzahnle@mail.arc.nasa.gov
Institution:	Ames Research Center

Focus Groups: Introduction

The purpose of the NAI Focus Group initiative is to mobilize expertise from across the Institute and the wider scientific community towards the rapid advancement of a defined area of research, mission planning, or other activity of particular importance to astrobiology. Innovative, interdisciplinary efforts seeking synergy among various research fields are particularly encouraged.

Three new Focus Groups were formally established this past year, bringing the total number of NAI Focus Groups to nine. The new groups, the Titan, Impacts and Virus Focus Groups, exemplify the scope of research encompassed by astrobiology and the NAI; representing the evolution of life on Earth, the potential for life elsewhere in our Solar System, and the effects of cosmic forces on the development of a planet's biota. In addition to all of their separate activities, described below, all of the NAI Focus Groups met this year in a series of exciting and well−attended break−out sessions at the Year 2003 General Meeting of the Institute. These sessions provided an opportunity for NAI investigators representing the breadth of disciplines contributing to astrobiology to come together and apply their expertise towards a single objective.

Focus Groups: Astromaterials

Focus Group:	***Astromaterials***
Project Title:	***Astromaterials Focus Group***
Chair:	***David McKay***

Project Progress

Astromaterials Focus Group

The Astromaterials Focus Group was proposed by PI David McKay in 2000 and initiated at the NAI General Meeting in 2001. The Objective of the Focus Group is to coordinate and facilitate astrobiological investigations of Mars meteorites; terrestrial analogs of potential Mars samples; sample acquisition, collection technology and procedures to advance the development of instruments and techniques for examining all astromaterials for evidence of past or present Life.

Focus group members were actively involved in the Lunar and Planetary Science Conference session titled "Carbonate and Magnetite in ALH84001" in March 2002. The Focus Group also organized the workshop titled "Magnetotactic Bacteria on Mars Earth and in ALH84001", hosted by the NASA Ames Research Center in June 2002.

The Focus Group met at the NAI General Meeting in 2003 and agreed to concentrate on the topic "Secondary Minerals in Martian Samples". Specifically, Focus Group members will promote the study of secondary minerals in meteorites from Mars. These clays, carbonates, and salts −− indicative of the interaction of water with rock on Mars −− have been identified in every Martian meteorite so far examined. As discussed in our Mars Meteorite section in the Research and Management Plan, it is extremely important to have these samples investigated by as wide a cross section of the astrobiology community as possible. Consequently, we will actively solicit and promote these studies using the Astromaterials Focus Group as a vehicle. One goal is to break out of the narrow meteorite community (which mostly lacks expertise in biology) and make the Mars meteorites much more accessible to the broad astrobiology community including both NAI members and interested investigators outside NAI.

A comprehensive study of Martian secondary minerals is particularly timely considering the three spacecraft scheduled to land on Mars within the next year. NASA's twin Mars Exploration Rovers will be the first landed spacecraft with the capability to determine mineralogy. Their primary landing site

candidates (Meridiani Planum and Gusev Crater) are both expected to show strong evidence of water−rock interactions. The European Space Agency's Beagle 2 lander is also capable of determining soil mineralogy, as well as directly measuring volatiles incorporated in the soil.

To facilitate these studies of Mars meteorites, we propose to:

- Organize, through the Astromaterials Focus Group, a Consortium Study on Martian Secondary Alteration of Nakhlites.
- Produce and document a set of petrographic thin sections of all NASA−collected Martian meteorites (initially Nakhlites), concentrating on secondary mineralization. These thin sections will be made available to researchers through the Johnson Space Center Astromaterials Acquisition and Curation Office. Secondary zones will be identified and highlighted in petrographic images.
- Work with the Smithsonian museum, the National Institute of Polar Research of Japan, and other collections to try to arrange for the loan of thin sections to add to the collection of NASA−produced thin sections.
- Organize a workshop devoted to "Secondary Minerals and Textures in Martian Rocks and Soils". The workshop will bring together researchers studying Martian meteorites and colleagues analyzing data from the Mars landers.
- Publish a workshop report, preferably a special issue of a peer−reviewed journal, containing the publications of the consortium, and papers from the mission scientists.

The consortium and workshop will be organized by David McKay, Carlton Allen, and Susan Wentworth at JSC plus other members (e.g., Laurie Leshin) of the Astromaterials Focus Group.

Focus Group Description & Activities

The Astromaterials Focus Group had its beginnings as an interest meeting at the NAI General Meeting in 2001 at the Carnegie Institution of Washington in Washington DC. At this meeting the importance of astromaterial research was discussed at length as vital component to astrobiology research. It was after that initial interest meeting that Dr. McKay proposed a formal request for an official NAI Focus Group. Official Focus Group meetings correspond to NAI General Meeting 2003 and the next one to be held at ABSciCon Meeting in 2004.

The first workshop was held in June 2002. This workshop, sponsored by NAI, was on the ALH84001 magnetite origin question. This workshop was held at NASA AMES, Moffett Field, CA. A publication resulted from this workshop that covered magnetotaxis in terrestrial magnetotactic bacteria and followed the argument for the evidence for and against preserved magnetotaxis in Martian meteorite ALH84001. The consensus from this workshop is more research of ALH84001 and other Martian meteorites is necessary to answer the question if ALH84001 magnetites are the preservation of past life on Mars or an abiotic processes that has no current earth analog to date.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Astromaterials Focus Group

Project Members for *Astromaterials Focus Group*

Name:	Carlton Allen
Email:	Carlton.c.allen@nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Peter Buseck
Email:	pbuseck@asu.edu
Institution:	Arizona State University
Role:	
Name:	Simon Clemett
Email:	simon.j.clemett@jsc.nasa.gov, sclemett@ems.jsc.nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Role:	
Name:	Everett Gibson
Email:	everett.k.gibson1@nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Laurie Leshin
Email:	laurie.leshin@asu.edu

Institution:	Arizona State University
Role:	
Name:	John Lindsay
Email:	John.f.lindsay1@jsc.nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Teresa Longazo
Email:	teresa.g.longazo1@jsc.nasa.gov, tlongazo@ems.jsc.nasa.gov
Institution:	Hernandez Engineering
Role:	
Name:	James Lyons
Email:	jrl@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	David McKay
Email:	David.s.mckay@nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Kevin McKeegan
Email:	kdm@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Michelle Minitti
Email:	Michelle.Minitti@asu.edu
Institution:	Arizona State University
Role:	
Name:	Penny Morris−Smith

Email:	penny.a.morris−smith1@jsc.nasa.gov
Institution:	University of Houston
Role:	
Name:	Theodore Snow
Email:	Theodore.Snow@casa.colorado.EDU
Institution:	University of Colorado, Boulder
Role:	
Name:	Kathie Thomas−Keprta
Email:	kthomas@ems.jsc.nasa.gov, Kathie.Thomas−Keptra1@jsc.nasa.gov
Institution:	Lockheed Martin
Role:	
Name:	Kay Tobola
Email:	kay.w.tobola1@jsc.nasa.gov, ktobola@hotmail.com
Institution:	Johnson Space Center
Role:	
Name:	Susan Wentworth
Email:	susan.j.wentworth1@jsc.nasa.gov
Institution:	Lockheed Martin
Role:	

NASA ASTROBIOLOGY INSTITUTE
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Focus Groups: Ecogenomics

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report:

Project Members for

Name:	Sarah Earley
Email:	earley@argyre.colorado.edu
Institution:	University of Colorado, Boulder
Role:	Research Staff
Name:	William Friedman
Email:	ned@colorado.edu
Institution:	University of Colorado, Boulder
Role:	Co−Investigator
Name:	Vasant Jadhav
Email:	jadhav@stripe.colorado.edu
Institution:	University of Colorado, Boulder
Role:	Research Staff
Name:	Owen Toon
Email:	btoon@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Role:	Co−Investigator

Focus Groups: Europa

Focus Group:	***Europa***
Project Title:	***Europa Focus Group***
Chair:	***Ronald Greeley***

Project Progress

The Europa Focus Group (EFG) was organized to foster research dealing with the Jupiter moon, Europa, and its potential as a habitat for past or present life. In addition, the EFG considers the principal science objectives for future exploration of Europa by spacecraft, including the critical measurements needed to understand its astrobiological significance.

Membership in the EFG includes planetary scientists, biologists, terrestrial sea−ice experts, oceanographers, and space science technologists. The EFG is open to all interested members of the scientific community and functions primarily through open workshops. The workshops provide a venue in which participants can share relevant research results and establish collaborations that might not otherwise occur. During the workshops the participants also address specific issues important for the exploration of Europa, such as defining instruments to fly on future missions.

Two workshops were held in this reporting period. At the September 2002 workshop, the scientific strategy for the exploration of Europa was discussed and the objectives for a landed mission were formulated. Specific investigations and measurements were identified and prioritized. The results were then presented to the National Academy of Sciences (National Research Council (NRC)) study team responsible for formulating the exploration strategy for the outer planet satellites in the coming decade. The results from the EFG were incorporated into the NRC final report.

The Arctic Ice Field Conference, held in Barrow, Alaska, in April 2003, was organized to provide participants with the opportunity to observe sea−ice first−hand in order to have a better understanding of the differences and similarities of a terrestrial ice province compared with Europa. Through an aerial reconnaissance and ground excursions, participants should gain a better appreciation of the physics, chemistry, and biology of sea ice.

Focus Group Description & Activities

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Galileo	Member of the science flight team
2	JIMO	Co−chairman, NASA Scientific Definition Team
3	Europa Lander	Science definition

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The Europa Focus Group has discussed the science goals, objectives, and investigations for future missions to Europa. With the cancellation of the Europa Orbiter last year, there is a window of opportunity to revisit the overall strategy for exploration. In part, the plans for Solar System exploration, including Europa, will be guided by the "Decadal Survey" which was conducted by the National Research Council; its report, along with recommendations, have been released. Three members of the EFG are on the NRC panel (2 on the steering group, 1 on the large satellites panel). Results from the EFG discussions for the science strategy for Europa have been input to the NRC panel as part of the community involvement in planning for future exploration.

Field Expeditions

Field Trip Name: Arctic Ice Field Conference	
Start Date: 22 April 2003	***End Date:*** 27 April 2003
Continent: North America	***Country:*** USA

State/Province: Alaska	***Nearest City/Town:*** Barrow, AK
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Description of work: Examination of sea ice	
Members Involved: Ronald Greeley	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Europa Focus Group

Project Members for *Europa Focus Group*

Name:	L. Montoya
Email:	montoya@nuclecu.unam.mx
Institution:	UNAM (Mexico)
Role:	
Name:	David Agresti
Email:	agresti@uab.edu
Institution:	University Alabama Birmingham
Role:	
Name:	Louis Allamandola
Email:	lallamandola@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Jeffrey Bada
Email:	jbada@ucsd.edu
Institution:	University of California, San Diego
Role:	
Name:	Amy Barr
Email:	amyb@bogart.colorado.edu, amyb@alumni.caltech.edu
Institution:	University of Colorado, Boulder
Role:	
Name:	Deborah Bass
Email:	deborah.s.bass@jpl.nasa.gov

Institution:	Jet Propulsion Laboratory
Role:	
Name:	Max Bernstein
Email:	mbernstein@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	David Blake
Email:	dblake@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Diana Blaney
Email:	diana.l.blaney@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Baruch Blumberg
Email:	bblumberg@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Henry Bortman
Email:	hbortman@pacbell.net
Institution:	NASA Astrobiology Institute
Role:	
Name:	Jerome Borucki
Email:	jborucki@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Karen Bradford

Email:	kbradford@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	

Name:	Karen Brinton
Email:	karen.brinton@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Bob Carlson
Email:	rcarlson@lively.jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Christian Caron
Email:	caron@springer.de
Institution:	Springer−Verlag (Germany)
Role:	

Name:	David Caron
Email:	dcaron@usc.edu
Institution:	University of Southern California
Role:	

Name:	Frank Carsey
Email:	fcarsey@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Ara Chutjian
Email:	ara.chutjian@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Chris Chyba
Email:	chyba@seti.org
Institution:	SETI Institute
Role:	

Name:	Benton Clark
Email:	benton.c.clark@lmco.com
Institution:	Lockheed Martin
Role:	

Name:	Simon Clemett
Email:	simon.j.clemett@jsc.nasa.gov, sclemett@ems.jsc.nasa.gov
Institution:	Johnson Space Center
Role:	

Name:	David Cole
Email:	david.m.cole@erdc.usace.army.mil
Institution:	USA CRREL
Role:	

Name:	Eric Collins
Email:	rec3141@u.washington.edu
Institution:	University of Washington
Role:	

Name:	Max Coon
Email:	max@nwra.com
Institution:	Northwest Res. Assoc.
Role:	

Name:	John Cooper
Email:	jfcooper@pop600.gsfc.nasa.gov
Institution:	GSFC Raytheon

Role:	
Name:	Dale Cruikshank
Email:	dcruikshank@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Andrew Czaja
Email:	aczaja@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Steven D'Hondt
Email:	dhondt@gso.uri.edu
Institution:	University of Rhode Island
Role:	
Name:	Brad Dalton
Email:	bdalton@mail.arc.nasa.gov
Institution:	SETI Institute
Role:	
Name:	Leonard David
Email:	newsspace@space.com
Institution:	Space.com
Role:	
Name:	Wanda Davis
Email:	wdavis@mail.arc.nasa.gov
Institution:	SETI Institute
Role:	
Name:	Jody Deming
Email:	jdeming@u.washington.edu

Institution:	University of Washington
Role:	
Name:	Thomas Dowiak
Email:	wdowiak@uab.edu
Institution:	University Alabama Birmingham
Role:	
Name:	Jason Dworkin
Email:	Jason.P.Dworkin@nasa.gov
Institution:	GSFC Raytheon
Role:	
Name:	Hajo Eicken
Email:	hajo.eicken@gi.alaska.edu
Institution:	University of Alaska
Role:	
Name:	Lisa Faithorn
Email:	lfaithorn@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Role:	
Name:	Larry Feinberg
Email:	larry.feinberg@asu.edu
Institution:	Arizona State University
Role:	
Name:	David Fernández Remolar

Email:	dfernandez@trasto.cbm.uam.es, geomicrobiol@altavista.com
Institution:	Centro de Astrobiologia
Role:	
Name:	Michael Flynn
Email:	mflynn@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Marilyn Fogel
Email:	fogel@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	
Name:	Christan Fritsen
Email:	cfritsen@dri.edu
Institution:	DRI
Role:	
Name:	Gian Gabriele Ori
Email:	ggori@sci.unich.it
Institution:	In't Res. School of Planetary Sciences
Role:	
Name:	Rebecca Gast
Email:	rgast@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Role:	
Name:	Perry Gerakines
Email:	gerakines@uab.edu
Institution:	University Alabama Birmingham
Role:	

Name:	Zann Gill
Email:	sgill@mail.arc.nasa.gov
Institution:	NASA
Role:	

Name:	Nicolas Glansdorff
Email:	nglansdo@vub.ac.be
Institution:	Vrije University, Brussels Belgium
Role:	

Name:	James Granahan
Email:	james.granahan@baesystems.com
Institution:	BAE Systems
Role:	

Name:	Ronald Greeley
Email:	greeley@asu.edu
Institution:	Arizona State University
Role:	

Name:	Will Grundy
Email:	grundy@lowell.edu
Institution:	Lowell Observatory
Role:	

Name:	James Head
Email:	james_head_III@brown.edu
Institution:	Brown University
Role:	

Name:	Tracey Herrera
Email:	therrera@ess.ucla.edu
Institution:	University of California, Los Angeles

Role:	
Name:	Paul Holland
Email:	pholland@thorleaf.com
Institution:	Throleaf Research Inc.
Role:	
Name:	Christopher House
Email:	chouse@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	Louis Irwin
Email:	lirwin@utep.edu
Institution:	University of Texas at El Paso
Role:	
Name:	Robert Johnson
Email:	rej@virginia.edu
Institution:	University of Virginia
Role:	
Name:	Torrence Johnson
Email:	torrence.v.johnson@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Jeffrey Kargel
Email:	jkargel@usgs.gov
Institution:	USGS Menlo Park
Role:	
Name:	Jozef Kazmierczak
Email:	jkaz@twarda.pan.pl

Institution:	Polish Acad. Sciences
Role:	
Name:	Stephan Kempe
Email:	kempe@geo.tu−darmstadt.de
Institution:	TU, Darmstadt
Role:	
Name:	Bishum Khare
Email:	bkhare@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Krishan Khurana
Email:	kkhurana@igpp.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	R.M. Killen
Email:	rkillen@swri.edu
Institution:	SWRI
Role:	
Name:	Jim Klemaszewski
Email:	klem@asu.edu
Institution:	Arizona State University
Role:	
Name:	Jennifer Kwong
Email:	jkwong@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	A. Lane

Email:	arthur.l.lane@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Matthew Levy
Email:	mattlevy@mail.utexas.edu
Institution:	University of Texas, Austin
Role:	
Name:	Jere Lipps
Email:	jlipps@uclink4.berkeley.edu
Institution:	University of California, Berkeley
Role:	
Name:	Robin Lloyd
Email:	rlloyd@hq.space.com
Institution:	Space.com
Role:	
Name:	James Lyons
Email:	jrl@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Nicholas Makris
Email:	makris@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	
Name:	Adam Maloof
Email:	maloof@eps.harvard.edu
Institution:	Harvard University
Role:	

Name:	Ram Manvi
Email:	rmanvi@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Giles Marion
Email:	gmarion@dri.edu
Institution:	DRI
Role:	

Name:	Tom McCollom
Email:	tom.mccollom@lasp.colorado.edu
Institution:	University of Colorado, Boulder
Role:	

Name:	Tom McCord
Email:	tom@kahana.higp.hawaii.edu
Institution:	University Hawaii
Role:	

Name:	Christopher McKay
Email:	cmckay@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Name:	Gary McMurty
Email:	garym@soest.hawaii.edu
Institution:	University Hawaii
Role:	

Name:	Miles McPhee
Email:	mmcphee@starband.net
Institution:	McPhee Research Co.

Role:	
Name:	Stanley Miller
Email:	slm@chem.ucsd.edu
Institution:	University of California, San Diego
Role:	
Name:	Jeff Moore
Email:	jmoore@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	William Moore
Email:	bmoore@artemis.ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	David Morrison
Email:	David.Morrison@nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Rafael Navarro−Gonzalez
Email:	navarro@nuclecu.unam.mx
Institution:	UNAM (Mexico)
Role:	
Name:	Susanne Neuer
Email:	susanne.neuer@asu.edu
Institution:	Arizona State University
Role:	
Name:	Robert Pappalardo
Email:	robert.pappalardo@colorado.edu

Institution:	University of Colorado, Boulder
Role:	
Name:	Victor Parro Garcia
Email:	parrogv@inta.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Gerald Patterson
Email:	Gerald.patterson@colorado.edu
Institution:	University of Colorado, Boulder
Role:	
Name:	Meredith Payne
Email:	mcpayne@asu.edu
Institution:	Arizona State University
Role:	
Name:	Cynthia Phillips
Email:	phillips@seti.org
Institution:	SETI Institute
Role:	
Name:	Carl Pilcher
Email:	cpilcher@hq.nasa.gov
Institution:	MVA Incorporated
Role:	
Name:	Olga Prieto Ballesteros
Email:	olpriba@ceu.es
Institution:	Centro de Estudios Universitarios
Role:	
Name:	Daniel Prieur

Email:	daniel.prieur@univ−brest.fr
Institution:	University de Bretagne Occidentale
Role:	
Name:	Louise Prockter
Email:	louise.prockter@jhuapl.edu
Institution:	JHU
Role:	
Name:	Matt Pruis
Email:	matt@nwra.com
Institution:	Northwest Res. Assoc.
Role:	
Name:	Guillermo Rodriguez
Email:	guillermo.rodriguez@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Valeria Routt
Email:	Valeria.Routt@asu.edu, routt@asu.edu
Institution:	Arizona State University
Role:	
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Scott Sandford
Email:	ssandford@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Name:	Paul Schenk
Email:	schenk@lpi.usra.edu
Institution:	Lunar and Planetary Institute
Role:	

Name:	Greg Schmidt
Email:	gschmidt@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Name:	Erland Schulson
Email:	erland.schulson@dartmouth.edu
Institution:	Dartmouth College
Role:	

Name:	Dirk Schulze−Makuch
Email:	dirksm@geo.utep.edu
Institution:	University of Texas at El Paso
Role:	

Name:	Miles Smith
Email:	miless@u.washington.edu
Institution:	University of Washington
Role:	

Name:	Steven Smith
Email:	Steven.J.Smith@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Nicole Spaun
Email:	nspaun@mail.arc.nasa.gov
Institution:	Ames Research Center

Role:	
Name:	John Spencer
Email:	spencer@lowell.edu
Institution:	Lowell Observatory
Role:	
Name:	Timothy Swindle
Email:	tswindle@u.arizona.edu
Institution:	University of Arizona
Role:	
Name:	Lesile Tamppari
Email:	leslie.tamppari@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Aaron Thode
Email:	thode@REVERB.MIT.EDU
Institution:	Massachusetts Institute of Technology
Role:	
Name:	Steven Vance
Email:	svance@ess.washington.edu
Institution:	University of Washington
Role:	
Name:	Luis Vazquez−Martinez
Email:	lvazquez@fdi.ucm.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Keith von der Heydt
Institution:	Woods Hole Oceanographic Institution

Role:	
Name:	Brian Wade
Email:	brian.wade@asu.edu
Institution:	Arizona State University
Role:	
Name:	Kimberly Warren−Rhodes
Email:	kwarren−rhodes@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Chuck Weisbin
Email:	charles.r.weisbin@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Llyd Wells
Email:	chimera1@ocean.washington.edu
Institution:	University of Washington
Role:	
Name:	Ying Xu
Email:	xuying@vub.ac.be
Institution:	Vrije University, Brussels Belgium
Role:	
Name:	Kevin Zahnle
Email:	kzahnle@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Daniel Zeigler
Email:	zeigler.1@osu.edu

Institution:	Ohio State University
Role:	

Name:	Wayne Zimmerman
Email:	wayne.f.zimmerman@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Focus Groups: Evogenomics

Focus Group:	***Evogenomics***
Project Title:	***Evolutionary Genomics Focus Group***
Chairs:	***S. Blair Hedges , James Lake***

Project Progress

Progress Report for the Evolutionary Genomics Focus Group
2002−2003

Blair Hedges and James Lake, Co−chairs

Progress report for Year 5

The purpose of the Evolutionary Genomics Focus Group (EvoGenomics) is to coordinate, combine, and enhance research efforts involving evolutionary genomics across the multiple disciplines and institutions represented in the astrobiology community. EvoGenomics is a unique collaboration of astrobiologists combining expertise in molecular evolutionary analysis, organic chemistry and biochemistry, Earth history, and paleontology.

This last year has been extremely productive for EvoGenomics. More than 30 papers have been published, or are in press, by the laboratories of the focus group. Many of these articles have been published in high profile journals such as *Science*, *Nature*, and *Proc. Nat. Acad. Sci.*

Broadly speaking, the focus group emphasizes three areas of enquiry. These are: the evolution of gene function, the evolution of multicellular animals and of eukaryotes, and horizontal gene transfer and prokaryotic evolution. Major discoveries in these three areas are described below.

Research Discoveries

The Evolution of gene function. Outstanding work has been performed by the Benner group, University of Florida, in the area of synthetic biology. First they have developed new tools to correlate events in the genomic record with the paleontological and geological records. These include tools to date gene duplications, identify pathways, and reconstruct ancestral proteins from extinct organisms to test hypotheses. For example, they have correlated the emergence of fermentation in yeast with the emergence of fermentable fruits in angiosperms. Work from their lab, and elsewhere, has been summarized in two important reviews (Benner, S.A., *Science* 297, 1121, 2002; Benner, S. A. *Nature* 421, 118, 2003).

In collaboration between UCLA and Penn State University, House (PSU), Runnegar (UCLA), and Fitz−Gibbon (UCLA) have related the geobiological record to the tree of life, using whole genome−based trees. The study involved a genomic tree of 52 prokaryotes and will appear soon in Geobiology (in press).

In the Lake lab, Anne Simonson and Jim Lake (UCLA) proposed a mechanism for protein synthesis based on atomic resolution ribosomal structures (Simonson Lake, *Nature*, 2002). This mechanism is extremely significant for the evolution of protein synthesis because ribonucleic acid (RNA) molecules, rather than proteins, are the essential components of the mechanism. Hence it suggests how today's RNA/Protein world may have started from a RNA world, and thereby potentially answers a chicken or egg type question, in this case suggesting that RNA was first.

The evolution of multicellular animals and of eukaryotes. David Jacobs' group, UCLA, has continued to be extremely productive in relating developmental genetics to early animal evolution. His group has made significant advances in deciphering the origin of sensory structures; in proposing terminal addition as the primitive mode of development in the bilateral animals; in analyzing potential homologies in bilateral animal skeleton building; and in carefully analyzing import issues relating to using protein clocks to date the metazoan radiation.

Blair Hedges' group (Penn State University) has been extremely productive, and has published several studies involving evolutionary relationships, and the timing of the radiation of multicellular life using large numbers of genes. In ongoing work, his analyses predict an early origin for multicellular much earlier than so far shown by the fossil record (Hedges et al., in preparation). He also published significant reviews (Hedges, *Nature Rev. Gen.*, 2002; Hedges Kumar, *Trends in Gen.*, 2003).

Horizontal gene transfer and prokaryotic evolution. In collaboration between the Riley laboratory (Woods Hole) and the Lake lab (UCLA), the search to find genes that are subject to more frequent horizontal gene transfer (HGT) continues. In preliminary studies we are finding that there are several discriminating factors that influence the frequency of HGT.

In a separate study, the Lake lab has found that HGT has potentially accelerated bacterial genome innovation and evolution. In particular, a large whole genome analysis indicated that new genes are being introduced into bacterial groups 10,000 times faster than possible without HGT (Jain, Rivera, Moore, Lake, *Mol. Bio. Evol.*, in press).

Education/Public Outreach.

EvoGenomics has been active in public outreach this last year. Hedges received a National Science Foundation (NSF) grant to establish a three−year summer training program in astrobiology for undergraduates. Approximately 10 students will be admitted each year from colleges and universities other than Penn State. The Benner group has been active in several initiatives,

namely the NASA−to−National Institutes of Health (NIH), the NASA−to−Department of Defense (DoD), and the NASA−to−Department of Energy (DoE) initiatives. These initiatives are bringing the topics that NASA supports within its purview to these other agencies. This approach appears to be highly effective. The Lake group hosted Prof. Todd Gary (Tennessee State University) during the summer of 2002. The results were extremely successful, and the sabbatical helped strengthen the professional and personal links between a large minority feeder institution and Astrobiology. Their experiences were communicated with other faculty at the annual Astrobiology meeting in Phoenix in February 2003. Dr. Maria Rivera (UCLA) frequently lectured to faculty and undergraduates from predominately minority institutions, explaining her research and the opportunities and excitement of EvoGenomics. Lectures were given at the Minority Institutions Astrobiology Collaborative Meeting, NASA Goddard Space Flight Center, Greenbelt, Maryland, in September 2002; at the Mexican American Engineering and Science Society Annual Meeting in Anaheim, California, in October 2002; and at NASA Week at Bennett College in Greensboro, North Carolina, in March 2003.

For EvoGenomics
Jim Lake, Professor UCLA

Focus Group Description & Activities

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Project Report: Evolutionary Genomics Focus Group

Project Members for *Evolutionary Genomics Focus Group*

Name:	Steven Benner
Email:	benner@chem.ufl.edu
Institution:	University of Florida
Role:	
Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Role:	
Name:	James Garey
Email:	garey@chuma.cas.usf.edu, garey@chuma1.cas.usf.edu
Institution:	University of South Florida
Role:	
Name:	J. Gogarten
Email:	gogarten@uconn.edu
Institution:	University of Connecticut
Role:	
Name:	S. Blair Hedges
Email:	sbh1@psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	Christopher House
Email:	chouse@geosc.psu.edu

Institution:	Pennsylvania State University
Role:	
Name:	David Jacobs
Email:	djacobs@ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Joseph Kirschvink
Email:	kirschvink@caltech.edu
Institution:	California Institute of Technology
Role:	
Name:	Sudir Kumar
Email:	s.kumar@asu.edu
Institution:	Arizona State University
Role:	
Name:	James Lake
Email:	lake@mbi.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Charles Marshall
Email:	cmarshall@oeb.harvard.edu
Institution:	Harvard University
Role:	
Name:	Monica Riley
Email:	mriley@mbl.edu
Institution:	Marine Biological Laboratory
Role:	
Name:	Lynn Rothschild

Email:	Lynn.J.Rothschild@NASA.gov
Institution:	Ames Research Center
Role:	

Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	

Name:	Mitchell Sogin
Email:	sogin@mbl.edu
Institution:	Marine Biological Laboratory
Role:	

Focus Groups: Impacts

Focus Group:	***Impacts***
Project Title:	***Biological Consequences of Impacts***
Chairs:	***Peter Ward , Frank Kyte***

Project Progress

The impact of asteroids, comets, and other objects must play a fundamental role in the origin, evolution, and extinction of life. Impacts are a primary mechanism of planetary accretion and are responsible for the delivery of water and organic matter to young planets. Large−body impacts may inhibit the formation of life in the early history of planetary development. Once life has taken hold, impacts can play an important role in the path followed by evolution, such as the mass extinctions that are now known to be coincident with the Chicxulub impact event at the Cretaceous−Tertiary boundary. This is not just a terrestrial problem. If life exists on Mars, Europa, or other planets outside our solar system, impacts must have played a fundamental role there as well. Impact may even play a role in transporting organisms between planetary objects.

The NAI Impact Focus Group can aid in coordinating the research in this field. Understanding the processes that relate impacts to the origin and evolution of life is an inherently interdisciplinary problem that requires expertise in diverse fields ranging from astronomy to paleobiology. The Impacts Focus Group can play an important role in bringing these experts together, developing collaborations, coordinating research, and organizing meetings and field trips for research and educational purposes. We believe that this can best be accomplished with a series of workshops that will be aimed at bringing participants together in an interactive setting for the purpose of identifying specific problems and achievable goals, followed up by actual sample collection and analysis. This is still a very new focus group. Our plan is to organize a workshop of interested parties on an annual basis to develop these collaborations.

Focus Group Description & Activities

In February, 2002, a workshop on the topic of "Impacts and the Origin, Evolution, and Extinction of Life." This was organized by Frank Kyte and Peter Ward and held at UCLA (abstracts and program at http://www.ess.ucla.edu/rubey/index.html). About 30 distinguished scientists, half of whom were members of NAI, discussed their research. Also in attendance were about 70 scientists and students who were either active in

this field or interested in learning about it. This workshop highlighted the very diverse interests of the participants, but it also showed that we could work together and identify areas of common interest and important goals. At least four areas of immediate need were clearly identified: 1) more detailed samples and analyses of old extinction horizons (e.g., the Triassic/Jurassic boundary), 2) better age dating of known terrestrial impact craters for correlation to the stratigraphic record, 3) better models of the physical effects of impacts, and 4) protocols for blind samples and tests of controversial results, such as reports of fullerenes and 3He in Permian/Triassic sediments. Several papers generated by this workshop were published in the Spring 2003 issue of Astrobiology (edited by Frank Kyte) and are available free at http://www.liebertpub.com/ast. A direct result of this workshop was the formation of the Impact Focus Group. We have now organized sample collection of the Triassic/Jurassic boundary, an important mass extinction with a reported possible connection to asteroid impact. We are also in the early planning stages of obtaining samples for blind testing of key Permian/Triassic boundary samples.

Highlights

- Papers from the Rubey Colloquium on "Impacts and the Origin, Evolution, and Extinction of Life" were published in the Spring 2003 issue of Astrobiology.
- A Field expedition was made to collect Triassic/Jurassic (T/J) samples.
- Focus Group Members Don Lowe and Gary Byerly organized a field conference on Archean Surface Processes in Barberton, South Africa. Although this conference focused mainly on processes of the early Earth, it included examination of the oldest known impact deposits on Earth (3.2 to 3.5 Ga).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Field Expeditions

Field Trip Name: Triassic/Jurassic sampling	
Start Date: 4/8/03	***End Date:*** 4/11/03
Continent: North America	***Country:*** USA
State/Province: Nevada	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): New York Canyon	***Keywords:***

Description of Work: Collection of fossils and samples for geochemical analysis at a classis [PLS VERIFY SPELLING] Triassic/Jurassic boundary section

Members Involved:

NASA ASTROBIOLOGY INSTITUTE
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Project Report: Biological Consequences of Impacts

Project Members for *Biological Consequences of Impacts*

Name:	Mark Allen
Email:	Mark.Allen@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	Focus Group Member
Name:	Michael Arthur
Email:	arthur@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	Focus Group Member
Name:	Luannf Becker
Email:	lbecker@quake.crustal.ucsb.edu
Institution:	University of California, Santa Cruz
Role:	Focus Group Member
Name:	Baruch Blumberg
Email:	bblumberg@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	Focus Group Member
Name:	Bill Bottke
Email:	bottke@boulder.swri.edu
Institution:	Southwest Research Institute
Role:	Focus Group Member
Name:	Arthur Bowman
Email:	arthur.bowman@hamptonu.edu

Institution:	Hampton University
Role:	Focus Group Member
Name:	Sam Bowring
Email:	bowring@mit.edu,sbowring@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	Focus Group Member
Name:	Gary Byerly
Email:	gary@geol.lsu.edu
Institution:	Louisiana State University
Role:	Focus Group Member
Name:	Clark Chapman
Email:	cchapman@boulder.swri.edu
Institution:	Southwest Research Institute
Role:	Focus Group Member
Name:	Philippe Claeys
Email:	phclaeys@vub.ac.be
Institution:	Vrije University, Brussels Belgium
Role:	Focus Group Member
Name:	Charles Cockell
Email:	csco@pcmail.nerc−bas.ac.uk
Institution:	United Kingdom Astrobiology Forum
Role:	Focus Group Member
Name:	Christopher Dateo
Email:	cdateo@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	Focus Group Member
Name:	Luke Dones

Email:	luke@boulder.swri.edu
Institution:	Southwest Research Institute
Role:	Focus Group Member
Name:	Douglas Erwin
Email:	erwin.doug@nmnh.si.edu
Institution:	Smithsonian Institution
Role:	Focus Group Member
Name:	Ken Farley
Email:	farley@mail.gps.caltech.edu
Institution:	California Institute of Technology
Role:	Focus Group Member
Name:	Geoff Garrison
Email:	garrison@u.washington.edu
Institution:	University of Washington
Role:	Focus Group Member
Name:	Kathleen Grey
Email:	k.grey@dme.wa.gov.au
Institution:	Geological Survey of Western Australia
Role:	
Name:	David Grinspoon
Email:	david@boulder.swri.edu
Institution:	Southwest Research Institute
Role:	Focus Group Member
Name:	S. Blair Hedges
Email:	sbh1@psu.edu
Institution:	Pennsylvania State University
Role:	Focus Group Member

Name:	Winifred Huo
Email:	whuo@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	Focus Group Member

Name:	Robert Iasky
Email:	robert.iasky@mpr.wa.gov.au
Institution:	Geological Survey of Western Australia
Role:	Focus Group Member

Name:	Joseph Kirschvink
Email:	kirschvink@caltech.edu
Institution:	California Institute of Technology
Role:	Focus Group Member

Name:	Christian Koeberl
Email:	christian.koeberl@univie.ac.at
Institution:	University of Vienna
Role:	Focus Group Member

Name:	David Kring
Email:	kring@LPL.Arizona.Edu
Institution:	University of Arizona
Role:	Focus Group Member

Name:	Alix Krull
Email:	akrull@pangea.stanford.edu
Institution:	Stanford University
Role:	Focus Group Member

Name:	Lee Kump
Email:	kump@essc.psu.edu
Institution:	Pennsylvania State University

Role:	Focus Group Member
Name:	Frank Kyte
Email:	kyte@igpp.ucla.edu
Institution:	University of California, Los Angeles
Role:	Focus Group Member
Name:	Donald Lowe
Email:	lowe@pangea.stanford.edu
Institution:	Stanford University
Role:	Focus Group Member
Name:	Jonathan Lunine
Email:	jlunine@lpl.arizona.edu
Institution:	University of Arizona
Role:	Focus Group Member
Name:	James Lyons
Email:	jrl@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	Focus Group Member
Name:	Jesus Martinez−Frias
Email:	martinezfrias@mncn.csic.es
Institution:	Centro de Astrobiologia
Role:	Focus Group Member
Name:	William McKinnon
Email:	mckinnon@levee.wustl.edu
Institution:	Washington University
Role:	Focus Group Member
Name:	H. Melosh
Email:	jmelosh@lpl.arizona.edu

Institution:	University of Arizona
Role:	Focus Group Member
Name:	David Morrison
Email:	David.Morrison@nasa.gov
Institution:	NASA Astrobiology Institute
Role:	Focus Group Member
Name:	Arthur Mory
Email:	arthur.mory@mpr.wa.gov.au
Institution:	Geological Survey of Western Australia
Role:	Focus Group Member
Name:	Francis Nimmo
Email:	Nimmo@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	Focus Group Member
Name:	Adriana Ocampo
Email:	Adriana.Ocampo@rssd.esa.int
Institution:	ESTEC/ESA
Role:	Focus Group Member
Name:	Jens Ormo
Email:	ormo@inta.es
Institution:	Centro de Astrobiologia
Role:	Focus Group Member
Name:	Jonathan Payne
Email:	jpayne@fas.harvard.edu
Institution:	Harvard University
Role:	Focus Group Member
Name:	Maria Paz Zorzano

Email:	zorzanomm@inta.es
Institution:	Centro de Astrobiologia
Role:	Focus Group Member
Name:	Randall Perry
Email:	rsp@u.washington.edu
Institution:	University of Washington
Role:	Focus Group Member
Name:	Franco Pirajno
Email:	f.pirajno@dme.wa.gov.au
Institution:	Australian Astrobiology Centre − International Affiliate Member
Role:	Focus Group Member
Name:	Jeffrey Plescia
Email:	jplescia@usgs.gov
Institution:	USGS Flagstaff
Role:	Focus Group Member
Name:	Thomas Quinn
Email:	trq@astro.washington.edu
Institution:	University of Washington
Role:	Focus Group Member
Name:	Timothy Riedel
Email:	triedel@mail.arc.nasa.gov
Institution:	University of Texas, Austin
Role:	Focus Group Member
Name:	Bruce Simonson
Email:	bruce.simonson@oberlin.edu
Institution:	Oberlin
Role:	Focus Group Member

Name:	Luis Vasquez
Email:	lvazquez@eucmax.sim.ucm.es
Institution:	Centro de Astrobiologia
Role:	Focus Group Member

Name:	Malcolm Walter
Email:	malcolm.walter@els.mq.edu.au
Institution:	Macquarie University
Role:	Focus Group Member

Name:	Peter Ward
Email:	argo@u.washington.edu
Institution:	University of Washington
Role:	Focus Group Member

Name:	Jin Yugan
Email:	jinyugan@yahoo.com
Institution:	Nanjing Institute of Geology and Palaeontology
Role:	Focus Group Member

Name:	Nicolle Zellner
Email:	zellner1@llnl.gov
Institution:	Lawrence Livermore National Laboratory
Role:	Focus Group Member

Focus Groups: Mars

Focus Group:	***Mars***
Project Title:	***Mars Focus Group***
Chair:	***Jack Farmer***

Project Progress

Background:

The Mars Focus Group (MFG) was established to provide a forum within the NAI to identify important scientific goals, objectives and investigations for the astrobiological exploration of Mars and to help define mission priorities, measurement requirements and new technology developments needed to support Mars Astrobiology. Since its inception three+ years ago, membership of the NAI Mars Focus Group has grown to >100 participants, with representatives from a broad array of scientific disciplines within Astrobiology. To enrich our discussions, scientists outside of the NAI have also been encouraged to attend our meetings to help the group identify crucial programmatic recommendations for the astrobiological exploration of Mars. The Mars Focus Group has been helping meet a critical need within NASA and the broader Mars science community by providing regular scientific input and recommendations to Mars program planners to ensure proper implementation of astrobiologically−relevant Mars missions. Results of previous site reviews and discussion summaries have been archived on an NAI Mars Focus Group node of Arizona State University's Astrobiology Program website (http://astrobiology.asu.edu). The NAI Mars Focus Group has also supported site selection related web archiving activities by the Center for Mars Exploration (CMEX), based at NASA Ames. NAI MFG annual activity reports for previous years are on file at NAI Central, NASA Ames.

Past Activities:

In 2001 the Mars Focus Group responded to the programmatic crisis that ensued with losses of the Mars Climate Orbiter and Mars Polar Lander missions by preparing a white paper recommendation that defined program priorities for Astrobiology for the present decade of Mars exploration. This white paper was presented to a NASA Mars Architecture Team headed by Charles Elachi (now Director of JPL) and subsequently published and distributed to a broad spectrum of the Mars planning community.

In 2002, Mars Focus Group activities focused primarily on identifying high priority astrobiological targets on Mars for orbital remote sensing observations

by MGS and Odyssey and for in situ exploration by landed missions (e.g. MER). Reviews of key landing sites were conducted by videoconference, with follow−up discussions to define landing site options and recommendations for the 2003 Mars Exploration Rover (MER) mission. To ensure that astrobiologically−significant sites were considered during the landing site selection process for MER, specific site recommendations were presented by NAI Mars Focus Group members at a series of four community−lead workshops and also conveyed to NASA's MER Landing Site Selection Steering Committee. Two of the Focus Group's top candidate sites, Meridiani Planum (the so−called "hematite site") and Gusev Crater were ultimately selected as the primary landing site choices for the twin MER rovers. (These rovers will land on Mars early in 2004 and operate for 90 days).

During the Summer and Fall of 2002, the NAI Mars Focus Group participated in joint videoconference presentations and discussions with the Mars Exploration Payload Assessment Group (MEPAG), the primary community−based forum for providing scientific recommendations NASA for planning future Mars missions. Discussions focused on a variety of topics, including a programmtic overview, the 2009 Mars Smart Lander mission and payload, the role of Mars sample return(s), and planning for post−'09 Mars Program science investigations (i.e., "science investigation pathways"). Recommendations from these joint discussions were presented in draft form to the MEPAG in September 2002 with many of those recommendations carried forward into subsequent planning activities for the Mars Science Laboratory (2009) lander mission and investigation options for the decade of Mars exploration that will follow 2009.

In February of 2003, the Mars Focus Group met briefly during the NAI General meeting to review recent progress with the MER mission and to begin to outline potential future directions for the group. The initial three year charter for the group ended in December. However, given the programmatic importance to the NAI and the past effectiveness of the MFG in representing the broader Astrobiology community, the NAI recently renewed the group's charter indefinitely, making it a standing committee. The goal is provide continuity of important mission−related activities with rotating leadership.

The MFG will continue to look to the membership for recommendations about future directions/opportunities for the group to follow in the next few years. However, a few priorities have emerged the past year which include: 1) seeking ways to encourage MFG member participation in the MEPAG (Mars Exploration Payload Assessment Group), the principal community−based group for providing science input to NASA's Mars Program and 2) expand NAI member participation in Mars mission planning activities, including instrument development for future Astrobiology missions (especially in the area of extant life detection), 3) encourage involvement of NAI scientists as participating science team members in upcoming Mars missions.

In years past, several NAI astrobiologists were active members of MEPAG. But the fact is, Astrobiology has historically been under−represented in MEPAG meetings. And given the prominence of life−oriented themes in NASA's mission and vision statements, it is also worth noting that participation

of astrobiologists on other NASA Mars Program advisory groups (e.g. SSES, SScAC, etc.) has also been quite limited. To faciltate participation by Mars Focus Group members in future NASA mission strategic planning activities, the NAI should consider: 1) providing travel funding to ensure attendance at future MEPAG meetings and 2) seeking to expand participation of astrobiologists on standing NASA committtees. With regard to meeting crucial needs in the area of astrobiology instrumentation, the NAI MFG will work cooperatively with a new Astrobiology Instrumentation Focus Group to increase the involvement of biologists in technology development programs and to promote Astrobiology instrumentation developments for the next decade of Mars exploration. The Mars Focus Group will also work to encourage basic research activities in critical areas of Mars astrobiology that can directly contribute to future missions.

Focus Group Description & Activities

Highlights

- Landing sites selected for the twin MER rovers hold great interest for Astrobiology.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration

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Project Report: Mars Focus Group

Project Members for *Mars Focus Group*

Name:	Conel Alexander
Email:	alexander@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	
Name:	Ricardo Amils
Email:	ricardo.amils@uam.es, ramils@cbm.uam.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Sushil Atreya
Email:	atreya@umich.edu
Institution:	University of Michigan
Role:	
Name:	Alice Baldridge
Email:	alice.baldridge@asu.edu
Institution:	Arizona State University
Role:	
Name:	Brian Beard
Email:	beardb@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Role:	
Name:	Steven Benner
Email:	benner@chem.ufl.edu

Institution:	University of Florida
Role:	
Name:	Robert Blankenship
Email:	RBlankenship@asu.edu
Institution:	Arizona State University
Role:	
Name:	Baruch Blumberg
Email:	bblumberg@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Sam Bowring
Email:	bowring@mit.edu,sbowring@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	
Name:	Adrian Brown
Email:	adrianjonbrown@yahoo.com.au, abrown@els.mq.edu.au
Institution:	Australian Astrobiology Centre − International Affiliate Member
Role:	
Name:	Carmen Cordoba−Jabonero
Email:	cordobajc@inta.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Gary Coulter
Email:	coultergr@earthlink.net
Institution:	Colorado State University
Role:	
Name:	Andrew Czaja

Email:	aczaja@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	

Name:	Wanda Davis
Email:	wdavis@mail.arc.nasa.gov
Institution:	SETI Institute
Role:	

Name:	Rebecca Davis
Email:	rebecca.davis@asu.edu
Institution:	Arizona State University
Role:	

Name:	David Des Marais
Email:	ddesmarais@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Name:	Eileen Dunn
Email:	EEDunn@aol.com
Institution:	Arizona State University
Role:	

Name:	Douglas Erwin
Email:	erwin.doug@nmnh.si.edu
Institution:	Smithsonian Institution
Role:	

Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Role:	

Name:	David Fernández Remolar
Email:	dfernandez@trasto.cbm.uam.es, geomicrobiol@altavista.com
Institution:	Centro de Astrobiologia
Role:	

Name:	Tom Foltz
Email:	Foltz@asu.edu
Institution:	Arizona State University
Role:	

Name:	A. Gimenez
Email:	ag@laeff.esa.es
Institution:	Centro de Astrobiologia
Role:	

Name:	Matthew Golumbek
Email:	MGolumbek@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Julia Goreva
Email:	jgoreva@asu.edu
Institution:	Arizona State University
Role:	

Name:	Doug Grant
Email:	Frederick.Grant@asu.edu
Institution:	Arizona State University
Role:	

Name:	Ronald Greeley
Email:	greeley@asu.edu
Institution:	Arizona State University

Role:	
Name:	Victoria Hamilton
Email:	hamilton@higp.hawaii.edu
Institution:	University of Hawaii, Manoa
Role:	
Name:	Andrew Hock
Email:	ahock@ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	John Holloway
Email:	john.holloway@asu.edu
Institution:	Arizona State University
Role:	
Name:	Clark Johnson
Email:	clarkj@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Role:	
Name:	Thomas Kieft
Email:	tkieft@nmt.edu
Institution:	New Mexico Institute of Mining and Technology
Role:	
Name:	Andrew Knoll
Email:	aknoll@oeb.harvard.edu
Institution:	Harvard University
Role:	
Name:	Dana Kovaric
Email:	dkovaric@gseis.ucla.edu

Institution:	University of California, Los Angeles
Role:	
Name:	Timothy Lee
Email:	tjlee@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Robin Lloyd
Email:	rlloyd@hq.space.com
Institution:	Space.com
Role:	
Name:	Isela Maldonado
Email:	Isela.Maldonado@asu.edu
Institution:	Arizona State University
Role:	
Name:	Jesus Martinez−Frias
Email:	martinezfrias@mncn.csic.es
Institution:	Centro de Astrobiologia
Role:	
Name:	David McKay
Email:	David.s.mckay@nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Mark Messerli
Email:	mmesserli@mbl.edu
Institution:	Marine Biological Laboratory
Role:	
Name:	Michelle Minitti

Email:	Michelle.Minitti@asu.edu
Institution:	Arizona State University
Role:	

Name:	Michael Mischna
Email:	mischna@ucla.edu
Institution:	University of California, Los Angeles
Role:	

Name:	David Morrison
Email:	David.Morrison@nasa.gov
Institution:	NASA Astrobiology Institute
Role:	

Name:	Paul Niles
Email:	Paul.niles@asu.edu, pniles@asu.edu
Institution:	Arizona State University
Role:	

Name:	Nora Noffke
Email:	nnoffke@odu.edu
Institution:	Old Dominion University
Role:	

Name:	Victor Parro Garcia
Email:	parrogv@inta.es
Institution:	Centro de Astrobiologia
Role:	

Name:	Meredith Payne
Email:	mcpayne@asu.edu
Institution:	Arizona State University
Role:	

Name:	Maria Paz Zorzano
Email:	zorzanomm@inta.es
Institution:	Centro de Astrobiologia
Role:	

Name:	Juan Perez Mercader
Email:	mercader@laeff.esa.es
Institution:	Centro de Astrobiologia
Role:	

Name:	Sandra Pizzarello
Email:	Sandra.Pizzarello@asu.edu
Institution:	Arizona State University
Role:	

Name:	Jeffrey Plescia
Email:	jplescia@usgs.gov
Institution:	USGS Flagstaff
Role:	

Name:	Olga Prieto Ballesteros
Email:	olpriba@ceu.es
Institution:	Centro de Estudios Universitarios
Role:	

Name:	Margaret Race
Email:	mracemom@aol.com
Institution:	SETI Institute
Role:	

Name:	Jim Rice
Email:	jrice@asu.edu
Institution:	Arizona State University

Role:	
Name:	Valeria Routt
Email:	Valeria.Routt@asu.edu, routt@asu.edu
Institution:	Arizona State University
Role:	
Name:	Steve Ruff
Email:	ruff@tes.la.asu.edu, ruff@tes.asu.edu
Institution:	Arizona State University
Role:	
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Thomas Sharp
Email:	tom.sharp@asu.edu
Institution:	Arizona State University
Role:	
Name:	David Smith
Email:	dwsmith@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	
Name:	Leigh Ann Smith
Email:	lasmith@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Mitchell Sogin
Email:	sogin@mbl.edu

Institution:	Marine Biological Laboratory
Role:	
Name:	Sean Solomon
Email:	scs@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	
Name:	Valeria Souza
Email:	souza@servidor.unam.mx
Institution:	UNAM (Mexico)
Role:	
Name:	Christopher Staples
Email:	Christopher.staples@asu.edu, crstaples1@earthlink.net
Institution:	Arizona State University
Role:	
Name:	Mike Tice
Email:	mtice@pangea.stanford.edu
Institution:	Stanford University
Role:	
Name:	Allan Treiman
Email:	treiman@lpi.usra.edu
Institution:	Lunar and Planetary Institute
Role:	
Name:	Luis Vazquez−Martinez
Email:	lvazquez@fdi.ucm.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Brian Wade

Email:	brian.wade@asu.edu
Institution:	Arizona State University
Role:	

Name:	Veronia Zabala
Email:	MarsBum@hotmail.com
Institution:	Arizona State University
Role:	

Focus Groups: Mission to Early Earth

Focus Group:	***Mission to Early Earth***
Project Title:	***Mission to Early Earth***
Chairs:	***Ariel Anbar , Roger Buick , Stephen Mojzsis***

Project Progress

The search for life beyond Earth requires some concept of the conditions under which life originates and begins to evolve, and of the environmental "fingerprints" of primitive biospheres. This concept must be informed by a solid understanding of the only planet on which life is known to exist− the Earth. Hence, study of life and the environment on the early Earth is a critical component in developing mission plans for astrobiology space missions. This is the underlying rationale of the Early Earth Focus Group.

Background

The geologic record is increasingly sparse as one examines the conditions on the early Earth further back in time. Furthermore, the quality of material easily available is not high − particularly when interest in environmental and biological history leads to a focus on biogeochemical signatures that are not robust against oxidation and other alteration processes at the Earth's surface. From the earliest discussions among the Focus Group members, a consensus emerged that progress in "bio−environmental reconstruction" is fundamentally sample limited. This consensus in the community led directly to the concept that the Early Earth Focus Group might be most useful as a means to promote, provide justification for, and identify support for the acquisition and distribution of samples from the Precambrian, with a special focus on deep drilling to acquire pristine sediment samples from the near subsurface (1000 m).

This activity has the potential to stimulate participation and collaboration from across the Institute, one of the benefits of the NAI focus groups as originally conceived by its Director. In addition, these types of sampling activities can provide opportunities to test technologies that might prove useful in future Mars exploration. The projects under development by the Focus Group should, in particular, provide information useful in the development of the Terrestrial Planet Finder mission, by elucidating the history of oxygenic photosynthesis and the oxygenation of the atmosphere. This will help in the interpretation of future spectroscopic examination of the atmospheres of extrasolar planets.

A guiding principle of the Focus Group is that precious samples obtained by communal NAI−sponsored efforts should be carefully archived and made available to the research community. In this way, the Focus Group hopes to stimulate the development of a vigorous, collaborative, multidisciplinary sampling−and−research enterprise similar to that of the Ocean Drilling Program and NASA's lunar sampling and meteorite collection operations.

Hamersley Hole

In the first two years of the Focus Group, we developed plans for a specific drilling project in late Archean rocks of the Hamersley Basin, Western Australia, as the first step in a proposed "Deep Time Drilling Project". The goal of this project is to obtain clean core for biosignature and geochemical analysis to better understand the early evolution of life and its habitat during this critical time. In addition, this project will test the feasibility of a broader stratigraphic drilling program in Precambrian basins globally. A secondary drilling project is planned in the early Archean, sampling across the oldest land surface (the Warawoona−Coonterunah unconformity, ~ 3.5 Ga). Initial funding for the Hamersley core has been committed by the NAI as part of the Astrobiology Drilling Program.

The planned hole will be collared in the lower Dales Gorge Member of the Brockman Iron Formation, lower Hamersley Group. The site selected will be in the lowest metamorphic grade and least deformed part of the basin, along the front of the Hamersley Range. The hole, obtained using hydrocarbon−free diamond drilling techniques, will be about 1000 meters deep, drilling down to the uppermost flood−basalt of the Maddina Formation in the upper Fortescue Group. Hence, it will sample ~ 200 million years of late Archean geological history. It will pass through rocks providing the following types of data:

- Kerogenous black shales of the Mt. McRae, Mt. Sylvia, and Jeerinah Formations, and the Bee Gorge, West Angelas and MacLeod Members of other formations. This will provide material for analyses of $^{13}C_{organic}$, $^{34}S_{sulfide}$, redox−sensitive metal abundances and isotopic compositions, and hydrocarbon biomarkers;
- Banded iron formations (BIFs) of the Brockman and Marra Mamba Formations, shedding light on what controls the inception and cessation of BIF deposition;
- Carbonates of the Wittenoom Dolomite, providing material for $^{13}C_{carbonate}$, $^{34}S_{sulfate}$ and other isotopic tracers;
- Meteorite impact horizons in the Dales Gorge, Bee Gorge and Roy Hill Members, providing fresh samples for determining target geology and impactor composition.

Core materials will be analyzed for these and other tracers, and ultimately made available to the research community.

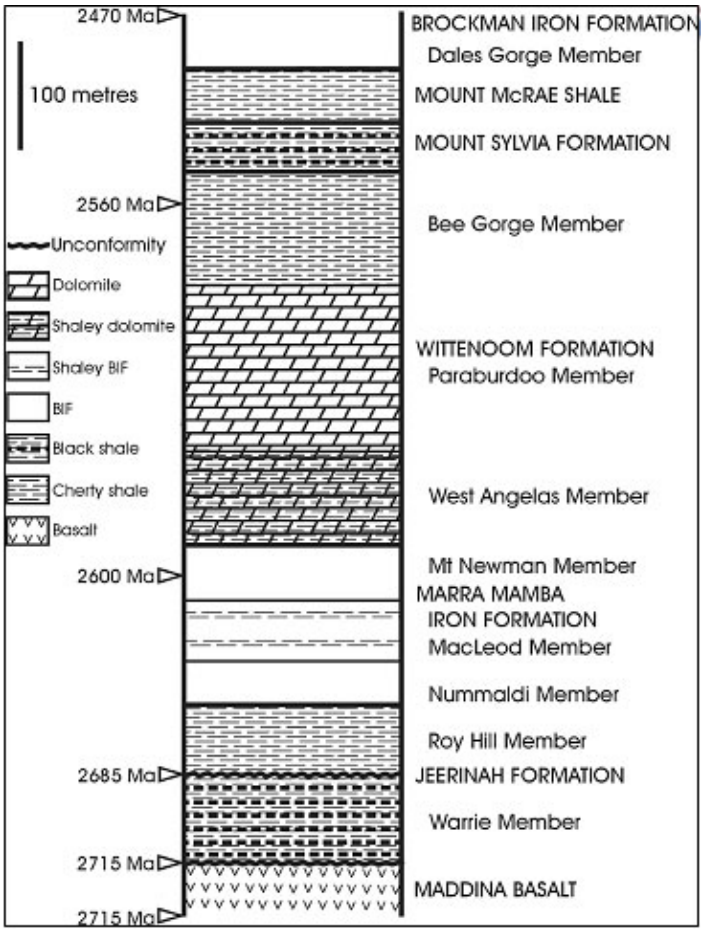

Fig. 1. *Stratigraphic section to be sampled by the Hamersley drill core of the Early Earth Focus Group*

Such research on some of the least−altered sediments of the late Archean will provide unique insight into: the rise of atmospheric oxygen and the oxygenation of ancient oceans; the chemical composition of ancient oceans; long−term global temperature regulation; the impact history of the early Earth and its effect on evolution; and the radiation of life, as recorded in molecular hydrocarbon biomarkers in carbonaceous sediments and stable isotope records.

The primary activity of the group during Year 5 was to develop plans for smooth integration of this drilling project into the newly formed Astrobiology Drilling Program (ADP). The Hamersley drill core of the Focus Group is presently planned for Summer 2004, as part of the ADP's efforts. A brief overview of the ADP is given below.

The Astrobiology Drilling Program

The Astrobiology Drilling Program (ADP) of the NASA Astrobiology Institute (NAI) is an initiative that aims to coordinate the activities of participating drilling projects, some of which may require supplementary support from the NAI. The ADP will be administered by NAI and directed by a steering committee that includes representation from current and former project leaders, the astrobiology community, and persons appointed by the NAI Director.

Appropriate participants from field site host countries will also be invited. Participating projects will be presented to the astrobiology research community prior to drilling so that scientists who are not members of the project team may register their interest in associated samples. Requests for access will be transmitted to the ADP steering committee and to the relevant project's lead. This creates an opportunity to modify the drilling plan in light of community requests. NAI funding may be available to support such modifications. Members of the original project team will retain privileged access to their core samples, nominally for one year from the time the core becomes available to them. If requests involve investigations that are not part of the original plan, the project leader may grant immediate access to core samples for specific purposes within this proprietary period. Archival of the drill cores is to be addressed, including the applicable national policies of host countries.

The ADP's efforts at collaborative distribution and analysis of materials are anticipated to generate increased productivity for participating drilling efforts. Individual projects will benefit from the opportunity to optimize and expand their objectives. Overall, the determined leveraging of projects will benefit the community scientifically and demonstrate a unity of purpose influential with funding sponsors. Two projects have adopted the ADP; the Deep Time Drilling Project initiated by the NAI's Early Earth Focus Group and the Archean Biosphere Drilling Project led by Dr. Munetomo Nedachi. These two groups are committed to working with each other, and with the broad astrobiology community.

Focus Group Description & Activities

A primary activity of Year 5 was development of plans to integrate the planned drilling activities of the Early Earth Focus Group into the Astrobiology Drilling Program (ADP) of the NAI. The latter program is in many ways an outgrowth of the Focus Group?s activities. It will serve as an ?umbrella? for collaborative early Earth sampling activities under NAI auspices. Focus Group leadership also played a key role in formulating policies for the ADP.

In the coming year, we anticipate intense activity raising external funds to conduct research on the anticipated drill core sampling; initiation of detailed logistical planning for sampling in Summer 2004; and continued work with the NAI Director to develop the ADP as a program that will facilitate both sampling and outreach to the broader astrobiology community.

Highlights

- NAI Astrobiology Drilling Program emerges as an outgrowth of Focus Group activity.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in

microorganisms
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

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Project Report: Mission to Early Earth

Project Members for *Mission to Early Earth*

Name:	Carlton Allen
Email:	Carlton.c.allen@nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Jan Amend
Email:	amend@levee.wustl.edu
Institution:	Washington University
Role:	
Name:	Ricardo Amils
Email:	ricardo.amils@uam.es, ramils@cbm.uam.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Ariel Anbar
Email:	anbar@earth.rochester.edu
Institution:	University of Rochester
Role:	
Name:	G. Arnold
Email:	gail@earth.rochester.edu
Institution:	University of Rochester
Role:	
Name:	Huiming Bao
Email:	hbao@ucsd.edu

Institution:	University of California, San Diego
Role:	
Name:	Ekaterina Bazilevskaya
Email:	eab204@psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	Brian Beard
Email:	beardb@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Role:	
Name:	Andrei Bekker
Email:	abekker@fas.harvard.edu
Institution:	Harvard University
Role:	
Name:	Carrine Blank
Email:	cblank@nature.berkeley.edu
Institution:	University of California, Berkeley
Role:	
Name:	Baruch Blumberg
Email:	bblumberg@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Henry Bortman
Email:	hbortman@pacbell.net
Institution:	NASA Astrobiology Institute
Role:	
Name:	Tanja Bosak

Email:	tbosak@gps.caltech.edu
Institution:	California Institute of Technology
Role:	

Name:	Arthur Bowman
Email:	arthur.bowman@hamptonu.edu
Institution:	Hampton University
Role:	

Name:	Sam Bowring
Email:	bowring@mit.edu,sbowring@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	

Name:	Susan Brantley
Email:	brantley@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	

Name:	Jochen Brocks
Email:	brocks@oeb.harvard.edu
Institution:	Harvard University
Role:	

Name:	Roger Buick
Email:	buick@ess.washington.edu
Institution:	University of Washington
Role:	

Name:	Sherry Cady
Email:	cadys@ch1.ch.pdx.edu
Institution:	Portland State University
Role:	

Name:	Don Canfield
Email:	dec@biology.sdu.dk
Institution:	Odense University
Role:	

Name:	Rosemary Capo
Email:	rcapo@pitt.edu
Institution:	University of Pittsburgh
Role:	

Name:	David Catling
Email:	davidc@atmos.washington.edu
Institution:	University of Washington
Role:	

Name:	Deneyse Churchill
Email:	churchil@essc.psu.edu
Institution:	Pennsylvania State University
Role:	

Name:	Carol Cleland
Email:	cleland@colorado.edu
Institution:	University of Colorado, Boulder
Role:	

Name:	Albert Colman
Email:	a.colman@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	

Name:	Andrew Czaja
Email:	aczaja@ess.ucla.edu
Institution:	University of California, Los Angeles

Role:	
Name:	Steven D'Hondt
Email:	dhondt@gso.uri.edu
Institution:	University of Rhode Island
Role:	
Name:	Jennifer Eigenbrode
Email:	eigenbro@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	James Elser
Email:	j.elser@asu.edu
Institution:	Arizona State University
Role:	
Name:	Douglas Erwin
Email:	erwin.doug@nmnh.si.edu
Institution:	Smithsonian Institution
Role:	
Name:	William Fagan
Email:	bfagan@asu.edu
Institution:	Arizona State University
Role:	
Name:	Jack Farmer
Email:	jack.farmer@asu.edu
Institution:	Arizona State University
Role:	
Name:	James Farquhar
Email:	jfarquhar@ucsd.edu

Institution:	University of Maryland
Role:	
Name:	David Fernández Remolar
Email:	dfernandez@trasto.cbm.uam.es, geomicrobiol@altavista.com
Institution:	Centro de Astrobiologia
Role:	
Name:	Katherine Freeman
Email:	kate@essc.psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	Eric Gaidos
Email:	gaidos@soest.hawaii.edu, gaidos@gps.caltech.edu
Institution:	University Hawaii
Role:	
Name:	Zann Gill
Email:	sgill@mail.arc.nasa.gov
Institution:	NASA
Role:	
Name:	Nathalie Grassineau
Email:	nathalie@gl.rhbnc.ac.uk
Institution:	RHUL (UK)
Role:	
Name:	David Grinspoon
Email:	david@boulder.swri.edu
Institution:	Southwest Research Institute
Role:	
Name:	Rose Grymes

Email:	rgrymes@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	

Name:	Mark Harrison
Email:	Mark.Harrison@anu.edu.au
Institution:	Australian National University
Role:	

Name:	Robert Hazen
Email:	r.hazen@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	

Name:	Tracey Herrera
Email:	therrera@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	

Name:	Kai−Uwe Hinrichs
Email:	khinrichs@whoi.edu
Institution:	Woods Hole Oceanographic Institution
Role:	

Name:	Andrew Hock
Email:	ahock@ucla.edu
Institution:	University of California, Los Angeles
Role:	

Name:	Tomas Hode
Email:	tomas.hode@nrm.se
Institution:	Swedish Museum
Role:	

Name:	Paul Hoffman
Email:	hoffman@eps.harvard.edu
Institution:	Harvard University
Role:	

Name:	Heinrich Holland
Email:	holland@eps.harvard.edu
Institution:	Harvard University
Role:	

Name:	Christopher House
Email:	chouse@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	

Name:	Munir Humayun
Email:	hum8@midway.uchicago.edu
Institution:	University of Chicago
Role:	

Name:	Stein Jacobsen
Email:	jacobsen@neodymium.harvard.edu
Institution:	Harvard University
Role:	

Name:	Bruce Jakosky
Email:	jakosky@argyre.colorado.edu
Institution:	University of Colorado, Boulder
Role:	

Name:	Charles James
Email:	ccjames@pst.ciw.edu
Institution:	Carnegie Institution of Washington

Role:	
Name:	Emmanuelle Javaux
Email:	ejavaux@aol.com
Institution:	Harvard University
Role:	
Name:	Clark Johnson
Email:	clarkj@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Role:	
Name:	Alan Kaufman
Email:	Kaufman@umd.edu
Institution:	University of Maryland
Role:	
Name:	Thomas Kieft
Email:	tkieft@nmt.edu
Institution:	New Mexico Institute of Mining and Technology
Role:	
Name:	Joseph Kirschvink
Email:	kirschvink@caltech.edu
Institution:	California Institute of Technology
Role:	
Name:	Paul Knauth
Email:	knauth@asu.edu
Institution:	Arizona State University
Role:	
Name:	Andrew Knoll
Email:	aknoll@oeb.harvard.edu

Institution:	Harvard University
Role:	
Name:	Lee Kump
Email:	kump@essc.psu.edu
Institution:	Pennsylvania State University
Role:	
Name:	John Lindsay
Email:	John.f.lindsay1@jsc.nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Donald Lowe
Email:	lowe@pangea.stanford.edu
Institution:	Stanford University
Role:	
Name:	Timothy Lyons
Email:	LyonsT@missouri.edu
Institution:	University of Missouri, Columbia
Role:	
Name:	James Lyons
Email:	jrl@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Craig Manning
Email:	manning@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Mary McHale

Email:	marylynn@nmt.edu
Institution:	Johnson Space Center
Role:	
Name:	Lucas Mix
Email:	lmix@oeb.harvard.edu
Institution:	Harvard University
Role:	
Name:	Stephen Mojzsis
Email:	mojzsis@colorado.edu
Institution:	University of Colorado, Boulder
Role:	
Name:	Penny Morris−Smith
Email:	penny.a.morris−smith1@jsc.nasa.gov
Institution:	University of Houston
Role:	
Name:	David Morrison
Email:	David.Morrison@nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Brett Nielan
Email:	b.neilan@unsw.edu.au
Institution:	U. New S. Whales
Role:	
Name:	Euan Nisbet
Email:	e.nisbet@gl.rhbnc.ac.uk
Institution:	RHUL (UK)
Role:	

Name:	Nora Noffke
Email:	nnoffke@odu.edu
Institution:	Old Dominion University
Role:	

Name:	Hiroshi Ohmoto
Email:	ohmoto@geosc.psu.edu
Institution:	Pennsylvania State University
Role:	

Name:	Shuhei Ono
Email:	s.ono@gl.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	

Name:	John Parnell
Email:	jparnell@abdn.ac.uk
Institution:	University of Aberdeen
Role:	

Name:	Victor Parro Garcia
Email:	parrogv@inta.es
Institution:	Centro de Astrobiologia
Role:	

Name:	Alexander Pavlov
Email:	pavlov@lasp.colorado.edu, pavlov@essc.psu.edu
Institution:	University of Colorado, Boulder
Role:	

Name:	Juan Perez Mercader
Email:	mercader@laeff.esa.es
Institution:	Centro de Astrobiologia

Role:	
Name:	Randall Perry
Email:	rsp@u.washington.edu
Institution:	University of Washington
Role:	
Name:	Robert Pidgeon
Email:	tpidgeon@cc.curtin.edu.au
Institution:	Curtain University
Role:	
Name:	Franco Pirajno
Email:	f.pirajno@dme.wa.gov.au
Institution:	Australian Astrobiology Centre − International Affiliate Member
Role:	
Name:	Jeffrey Plescia
Email:	jplescia@usgs.gov
Institution:	USGS Flagstaff
Role:	
Name:	Susannah Porter
Email:	suporter@ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Luke Probst
Email:	lwprobst@hotmail.com
Institution:	Rice University
Role:	
Name:	Birger Rasmussen
Email:	brasmuss@geol.uwa.edu.au

Institution:	University of Western Australia
Role:	
Name:	Nina Rosenberg
Email:	rosenberg4@llnl.gov
Institution:	Lawrence Livermore National Laboratory
Role:	
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Role:	
Name:	Rob Rye
Email:	rye@usc.edu
Institution:	University of Southern California
Role:	
Name:	William Schopf
Email:	schopf@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Daniel Schrag
Email:	Schrag@eps.harvard.edu
Institution:	Harvard University
Role:	
Name:	Rusty Schweickart
Email:	rs@well.com
Institution:	California Academy of Sciences
Role:	
Name:	Mukul Sharma

Email:	Mukul.Sharma@Dartmouth.EDU
Institution:	Dartmouth College
Role:	

Name:	Yanan Shen
Email:	yshen@oeb.harvard.edu
Institution:	Harvard University
Role:	

Name:	Janet Siefert
Email:	siefert@stat.rice.edu
Institution:	Rice University
Role:	

Name:	Norman Sleep
Email:	norm@pangea.stanford.edu
Institution:	Stanford University
Role:	

Name:	Alexei Smirnov
Email:	alexei@earth.rochester.edu
Institution:	University of Rochester
Role:	

Name:	Leigh Ann Smith
Email:	lasmith@ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	

Name:	David Smith
Email:	dwsmith@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	

Name:	Sean Solomon
Email:	scs@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	

Name:	Sherry Stafford
Email:	slsst52@pitt.edu
Institution:	University of Pittsburgh
Role:	

Name:	Brian Stewart
Email:	bstewart@vms.cis.pitt.edu
Institution:	University of Pittsburgh
Role:	

Name:	Roger Summons
Email:	roger.summons@mit.edu
Institution:	Massachusetts Institute of Technology
Role:	

Name:	Carol Tang
Email:	ctang@calacademy.org
Institution:	California Academy of Sciences
Role:	

Name:	John Tarduno
Email:	john@volterra.earth.rochester.edu
Institution:	University of Rochester
Role:	

Name:	Mike Tice
Email:	mtice@pangea.stanford.edu
Institution:	Stanford University

Role:	
Name:	Akiko Tomitani
Email:	a_tomitani@hotmail.com, tomitani@kueps.kyoto−u.ac.jp
Institution:	Harvard University
Role:	
Name:	Allan Treiman
Email:	treiman@lpi.usra.edu
Institution:	Lunar and Planetary Institute
Role:	
Name:	Luis Vasquez
Email:	lvazquez@eucmax.sim.ucm.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Malcolm Walter
Email:	malcolm.walter@els.mq.edu.au
Institution:	Macquarie University
Role:	
Name:	Benjamin Weiss
Email:	bweiss@gps.caltech.edu
Institution:	California Institute of Technology
Role:	
Name:	Llyd Wells
Email:	chimera1@ocean.washington.edu
Institution:	University of Washington
Role:	
Name:	Susan Wentworth
Email:	susan.j.wentworth1@jsc.nasa.gov

Institution:	Lockheed Martin
Role:	
Name:	Frances Westall
Email:	westall@cnrs−orleans.fr
Institution:	Lunar and Planetary Institute
Role:	
Name:	George Wetherill
Email:	wetherill@dtm.ciw.edu
Institution:	Carnegie Institution of Washington
Role:	
Name:	Anne Wilkins
Email:	a.d.wilkins@abdn.ac.uk
Institution:	University of Aberdeen
Role:	
Name:	Kosei Yamaguchi
Email:	kosei@geology.wisc.edu
Institution:	University of Wisconsin, Madison
Role:	
Name:	Thomas Yulsman
Email:	Tom.Yulsman@Colorado.EDU
Institution:	University of Colorado, Boulder
Role:	
Name:	Kevin Zahnle
Email:	kzahnle@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Focus Groups: Titan

Focus Group:	***Titan***
Project Title:	***Titan***
Chair:	***Jonathan Lunine***

Project Progress

Since the discovery of a methane atmosphere around Titan by Gerard Kuiper in 1944, Titan has been a world that has attracted much exobiological interest. Titan provides us with a planet−sized laboratory for testing the synthesis of organic compounds in a nearly neutral redox environment, over large spatial scales, both with and without liquid water. These natural chemical experiments could be ongoing today, and the products of such experiments in localized regions of elevated temperatures would be well preserved under the ambient 95 K temperatures and high atmospheric densities that shield the surface from destructive radiation.

The Cassini−Huygens mission will make a complete inventory of the surface from a variety of remote sensing and in situ techniques, over the time period late 2004 through late 2008. The Huygens atmospheric probe will descend to the surface in January 2005. Before and after that the Orbiter will undertake some 45 close flybys of Titan. The result of the Cassini−Huygens mission will be a level of understanding of the geology, geodesy, atmospheric physics and surface−atmosphere interactions on Titan rivaling that for Mars after the Mars Global Surveyor (MGS) mission (with the exception of a lack of a detailed global altimetric map of the body). Further, Cassini−Huygens will provide us with information regarding the distribution and nature of organics spread across the Titan surface. If surface compositional variations are found in the organics, especially correlated with apparent geologic activity or crustal melting, the interest in returning to Titan to sample those interesting places directly, for signs of oxygen−bearing organics like amino or carboxylic acids for example, will be high.

Indeed, NASA has already expressed interest in initial planning for a post−Cassini mission to Titan, and it appears likely that such a mission will be high on the list of astrobiologically interesting programs in the planetary decadal strategy now being prepared. It has become standard operating procedure for the NAI to play a key role in mission planning for astrobiologically interesting targets in part or in whole through conduct of focus groups. The Mars and Europa groups have been very effective in this regard. It is natural, then, that a similar effort be undertaken for Titan, and the timing is appropriate given NASA's interest in post−Cassini mission planning, and the

imminent arrival of Cassini−Huygens at Saturn.

The Titan Focus Group is open to all interested parties, but all individuals who desire to participate are asked to identify themselves, their institution, and to commit to a certain amount of time and activity. Hence casual chat room browsers is to be discouraged. Most of the work of the group is by e−mail, but two or three meetings of the focus group organized around convenient ancillary meetings (such as the NAI annual meeting) are conducted.

The four topical areas that shape the four white papers are staggered in time over the three years of the Titan Focus Group (TFG), and are organized in a logical intellectual order. The TFG is first considering the questions that motivate the astrobiological exploration of Titan, and generate a sharply focused set of scientific questions and objectives that will constrain the kinds of techniques to be applied post−Cassini. Once this is accomplished, the TFG will move into the phase of considering the techniques that should be used in the exploration of Titan beyond Cassini−Huygens, with a focus on the analysis of the organic chemistry of the surface. The effort is constrained by the results of a number of recent experimental studies. Experimental organic chemists, and not merely "Titanophiles", are involved in the TFG to ensure that this second topic reaches a realistic conclusion, and they will be actively sought. The third topic depends on the successful completion of the second. It concerns the types of missions to be conducted after Cassini− Huygens, as well as the types of analyses of Cassini−Huygens data required to constrain the next mission. Hence science payloads will be considered and winnowed down into a prioritized list, recommendations on number and types of sampling sites will be made, and explicit discussion of how Cassini−Huygens data should be used will occur to decide on the timing and scope of the mission as well as potential landing sites. Finally, as Cassini−Huygens begins its observations of Titan next year, the TFG will shift its attention to considering the early results from the first 8 flybys of Titan, and the Probe mission.

Our first topical area was tackled at the NAI conference in Tempe in February. A map of potential questions to be addressed by a follow−on Titan mission was sketched, and will be worked on further this fall. A necessary hiatus in the discussion has resulted from the NASA solicitation for "Vision missions", follow−ons to the current cohort of space science missions under study. A Titan organics mission is among these, and many focus group participants are involved in mission proposals. Until these are submitted, a self−imposed "blackout" on exchange of proprietary ideas is necessary and will end in September when proposals are due.

Work on aqueous environments that might exist on Titan during impacts resulted in a confirmation of earlier analytic modeling that showed 2−5% of a newly−formed crater (by volume) will be liquid after impact (assuming initially a water ice composition). Exploration of the implications for prebiotic activity on Titan will be discussed and pursued among the group.

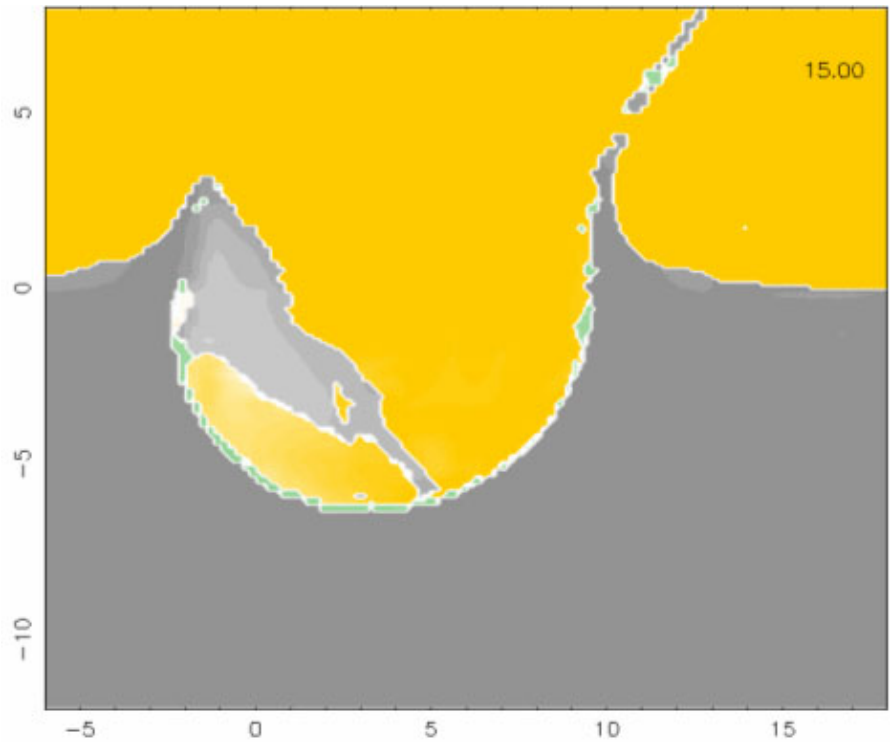

Figure 1 15 seconds into a multi−kilometer per second impact of a comet on Titan, green areas show where liquid water may be present. From Artemieva and Lunine, in press (*Icarus*).

Focus Group Description & Activities

Our first topical area was tackled at the NAI conference in Tempe in February. A map of potential questions to be addressed by a follow−on Titan mission was sketched, and will be worked on further this fall. A necessary hiatus in the discussion has resulted from the NASA solicitation for "Vision missions", follow−ons to the current cohort of space science missions under study. A Titan organics mission is among these, and many focus group participants are involved in mission proposals. Until these are submitted, a self−imposed "blackout" on exchange of proprietary ideas is necessary and will end in September when proposals are due.

Arrangements for a conference on future Titan missions to be held in Tucson were made in coordination with Cassini Project personnel, and will highlight Focus Group discussions.

Highlights

- Titan focus group recommends follow−on organic analyses of the surface after the Cassini−Huygens mission.

- Numerical simulations of impact processes on Titan suggest the existence of transient liquid water in places on the surface of this organic−rich moon.

Roadmap Objectives

- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Cassini	Co−I?s, Team Members, Interdisciplinary Scientists
2	NASA Vision missions	Multiple proposers

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

As Cassini−Huygens begins its observations of Titan next year, the TFG will shift its attention to considering the early results from the first 8 flybys of Titan, and the Probe mission, to assess implications for targeting of future probes to astrobiologically significant sites.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
[July 2002 - June 2003]

Project Report: Titan

Project Members for *Titan*

Name:	David Alburty
Email:	dalburty@mriresearch.org
Institution:	Midwest Research Inst.
Role:	
Name:	Mark Allen
Email:	Mark.Allen@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Sushil Atreya
Email:	atreya@umich.edu
Institution:	University of Michigan
Role:	
Name:	Emma Bakes
Email:	bakes@shivakali.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	John Baross
Email:	jbaross@u.washington.edu
Institution:	University of Washington
Role:	
Name:	Jack Beauchamp
Email:	jlbchamp@cco.caltech.edu

Institution:	California Institute of Technology
Role:	
Name:	Pat Beauchamp
Email:	Patricia.m.beauchamp@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	Steven Benner
Email:	benner@chem.ufl.edu
Institution:	University of Florida
Role:	
Name:	André Brack
Email:	brack@cnrs−orleans.fr
Institution:	Groupement des Recherches en Exobiologie
Role:	
Name:	Benton Clark
Email:	benton.c.clark@lmco.com
Institution:	Lockheed Martin
Role:	
Name:	Patrice Coll
Email:	coll@lisa.univ−paris12.fr
Institution:	Lisa−Univ. of Paris
Role:	
Name:	John Cooper
Email:	jfcooper@pop600.gsfc.nasa.gov
Institution:	GSFC Raytheon
Role:	
Name:	Christopher Dateo

Email:	cdateo@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	
Name:	Leonard David
Email:	newsspace@space.com
Institution:	Space.com
Role:	
Name:	Dennis Dougherty
Email:	dad@igor.caltech.edu
Institution:	California Institute of Technology
Role:	
Name:	Christopher England
Email:	cengland@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	
Name:	James Ferris
Email:	ferrij@mail.its.rpi.edu
Institution:	RPI
Role:	
Name:	Sherwin Gormly
Email:	Sherwin.gormly@ttemi.com
Institution:	Tetra Tech EM, Reno
Role:	
Name:	Jeffrey Hall
Email:	jhall@mail1.jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Winifred Huo
Email:	whuo@mail.arc.nasa.gov
Institution:	Ames Research Center
Role:	

Name:	Louis Irwin
Email:	lirwin@utep.edu
Institution:	University of Texas at El Paso
Role:	

Name:	Jean−Pierre Lebreton
Email:	Jean−Pierre.Lebreton@esa.int
Institution:	ESTEC/ESA
Role:	

Name:	Ralph Lorenz
Email:	rlorenz@lpl.arizona.edu
Institution:	University of Arizona
Role:	

Name:	Jonathan Lunine
Email:	jlunine@lpl.arizona.edu
Institution:	University of Arizona
Role:	

Name:	Gene McDonald
Email:	Gene.D.McDonald@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Name:	Christopher McKay
Email:	cmckay@mail.arc.nasa.gov
Institution:	Ames Research Center

Role:	
Name:	William Moore
Email:	bmoore@artemis.ess.ucla.edu
Institution:	University of California, Los Angeles
Role:	
Name:	Robert Pappalardo
Email:	robert.pappalardo@colorado.edu
Institution:	University of Colorado, Boulder
Role:	
Name:	Juan Perez Mercader
Email:	mercader@laeff.esa.es
Institution:	Centro de Astrobiologia
Role:	
Name:	Sandra Pizzarello
Email:	Sandra.Pizzarello@asu.edu
Institution:	Arizona State University
Role:	
Name:	Carolyn Porco
Email:	Carolyn@ciclops.swri.edu
Institution:	SWRI
Role:	
Name:	Francois Raulin
Email:	raulin@lisa.univ−paris12.fr
Institution:	Lisa−Univ. of Paris
Role:	
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov

Institution:	NASA Astrobiology Institute
Role:	
Name:	Dirk Schultze
Email:	dirksm@geo.utep.edu
Institution:	University of Texas at El Paso
Role:	
Name:	Edward Sittler
Email:	Edward.c.sittler.1@gsfc.nasa.gov
Institution:	NASA
Role:	
Name:	David Warmflash
Email:	david.m.warmflash1@jsc.nasa.gov, dwarmfla@ems.jsc.nasa.gov
Institution:	Johnson Space Center
Role:	
Name:	Wayne Zimmerman
Email:	wayne.f.zimmerman@jpl.nasa.gov
Institution:	Jet Propulsion Laboratory
Role:	

Intl. Partners: Introduction

NAI has a partnership program with international astrobiology organizations to provide collaborative opportunities between NAI's researchers and the global science community. Foreign astrobiology organizations can propose to become either Associate (formal agreement between NASA and the foreign government) or Affiliate members (no formal government agreements) of the NAI. During Year 5, there were five international Associate or Affiliates:

- Associates:
  - Centro de Astrobiologia (CAB)
  - Australian Centre for Astrobiology
- Affiliates:
  - United Kingdom Astrobiology Forum and Network
  - Groupement de Recherche en Exobiologie
  - European Exo/Astrobiology Network Association, EANA

Intl. Partners: Astrobiology Society of Britain

Astrobiology Society of Britain
Executive Summary
Director/Leader: Charles Cockell

Introduction

The Astrobiology Society of Britain emerged in 2003 from the UK Astrobiology Forum and Network. In an effort to formalize the network, which was previously an informal e−mail list of those in the UK interested in Astrobiology, the society was established. The Society maintains affiliate status with the NAI and is the professional society representing the astrobiology community in the UK. Its membership is international in scope and it has members from the US and European countries. The main purpose of the Society is to organize meetings and aid discussion amongst astrobiologists in the UK and to involve itself in international efforts such as fund raising for international fellowships.

Recent developments

UK Astrobiology Conference

In March 2003, the UK held its first astrobiology meeting in Girton College, Cambridge. The meeting was split into two days. The first day was a general meeting covering many aspects of astrobiology from the origins of life to robotic astrobiology. It was an inclusive day, with discussion encouraged amongst any members of the community with interests in astrobiology who wished to attend. The second day was a more specialist day, focusing on the conditions for the origin and emergence of life. Over 80 people attended the conference, including representatives from UK corporations with an interest in astrobiology.

Astrobiology Society of Britain

During the Girton meeting it was proposed that the UK astrobiology forum and network be disbanded and replaced by a new society that would more formally represent the interests of the UK astrobiology community. Whereas previously the forum was an unelected informal committee, the committee of the new society would be an elected, accountable structure. Over 50 people paid an initial membership fee of £5.00 to join the society. Following the meeting elections were held for the committee and the society was established.

Other developments

The Society comes into being during an exciting time for the UK in

astrobiology. The UK−led exobiology lander, the Beagle 2, is on its way to Mars and is expected to begin its work on the surface of Mars in December 2003. The Open University held its inaugural opening of its Center for Astrobiology early in the year, demonstrating the interest in astrobiology amongst UK universities. Other meetings with astrobiology themes have been held in the UK; for example the Society for General Microbiology held a special session on astrobiology. Within this context, the environment for the existence of the Society is good.

Future developments

The Society will hold its first committee meeting in September 2003, where the direction and future plans of the society will be discussed. Possible directions of the Society include:

- Planning another UK astrobiology meeting
- Raising funds with the Federation of Astrobiology Organizations (FAO) for an international fellowship.
- Promoting astrobiology by co−sponsoring meetings with other organizations
- Expanding its membership

General publications

Astrobiology 2003. Abstracts of the UK Astrobiology Meeting, Girton College, Cambridge (www.astrobiologysociety.org.uk)

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Intl. Partners: Australian Centre for Astrobiology

Australian Centre for Astrobiology
Executive Summary
Director/Leader:

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 5
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Intl. Partners: Centro de Astrobiologia (CAB)

Centro de Astrobiologia (CAB)
Executive Summary
Director/Leader:

Intl. Partners: European Exo/Astrobiology Network Association, EANA

European Exo/Astrobiology Network Association, EANA
Executive Summary
Director/Leader: André Brack

The European Exo/Astrobiology Network Association, EANA, was created to co−ordinate the different European centres of excellence in exo/astrobiology or related fields already organised in national networks. The specific objectives of EANA are to bring together European researchers interested in exo/astrobiology programmes and to foster their cooperation, to attract young scientists to this quickly evolving interdisciplinary field of research, to interface the Network with European bodies such as ESA, ESF, and the European Commission, and with non−European institutions active in the field, and to popularise exo/astrobiology to the public and to students. The EANA includes presently 12 European nations active in the field: Austria, Belgium, Denmark, France, Germany, Italy, Portugal, Spain, Sweden, Switzerland, The Netherlands, and United Kingdom.

EANA is affiliated with the NASA Astrobiology Institute. The formal affiliation was signed in September 2002 at the Graz Workshop by Rosalind Grymes, Deputy Director of NAI, during a reception hosted by the Governor of Syria in the historical Eggenberg Castle.

Recent activities (activities of CAB, GDR Exobio and UKAN will be reported separately)

Second European Workshop on Exo/Astrobiology
The Second European Workshop on Exo/Astrobiology was held in Graz, Austria, 16−19 September 2002, co−organised by EANA and the University of Graz and the Institute of Geophysics, Astrophysics and Meteorology. Attended by 320 participants, the workshop was oriented towards planetology. The scientific input of the Graz meeting was published as ESA SP−518.

Swedish Astrobiology Network, SWAN
SWAN held two national meetings, in GQteborg 1 October 2002 and in Örebro 17 March 2003. Discussions were primarily on how to promote astrobiology through joint courses in Sweden and on relations with EANA and the International Astrobiology Circle members.

European Commission COST Action
Within the framework of EC COST Actions to foster co−operation in a specific research area, the First COST D27 Workshop "Origin of life and early evolution" was held in Ravello, Italy, 17−20 October 2002. Approximately 70 participants took part in what was a very successful "kickoff" activity of the

group. Sessions were organized on prebiotic chemistry and chirality, astrobiology and early molecules, ribonucleic acid (RNA), cooperativity,self−replication, autocatalysis, and prelude to the Cell. The proceedings of the workshop will be published as a special issue of Origins of Life and Evolution of the Biosphere.

ISSI, International Space Science Institute activities in Astrobiology
The International Space Science Team "Prebiotic matter in space" is a consortium of 12 scientists, each representing a specific research field crucial to revealing the origin of life as a consequence of the evolving Universe. The ISSI Astrobiology team organized a workshop at the International Space Science Institute in Bern, Switzerland, between April 1−4, 2003 on the topic "Astrobiology − Future perspectives". The workshop was restricted to 35 top experts. The meeting results will be published in a book by Kluwer Academic Publisher in spring 2004.

EGS−AGU−EUG Joint Assembly in Nice
Several sessions at the European Geophysical Society − American Geophysical Union − European Union of Geosciences (EGS−AGU−EUG) Joint Assembly in Nice, France, from April 6 − 11, 2003, dealt with astrobiological topics. The session "Life on the fringe: biotic survival over geological time scales and in subglacial environments" was attended by about 75 participants. A special issue of "Astrobiology" will feature several keynote papers. The session "Water and life" was also very successfully attended by more than 70 participants. Many of the papers presented will be published in a Special Issue of the International Journal of Astrobiology.Darwin/TPF and the search for extrasolar terrestrial planetsThe conference, held in Heidelberg, Germany, 22−25 April 2003, was attended by about 200 participants. The topics covered included: Results of Planet Searches, New Search Strategies, Formation and Evolution of Planetary Systems, and Conditions for Life. Proceedings are currently in press in the ESA−SP series.

Beagle 2
Beagle−2, the UK led exobiology lander of the European Space Agency (ESA) 2003 Mars Express mission, comprises an integrated suite of instruments to optimize the search for evidence of life on Mars in subsurface and rock interior samples. The package includes instruments to study sample mineralogy (composition, macroscopic and microscopic structural and textural features), organics (elemental, molecular), oxidation state and petrology (major and minor element composition). Environmental characteristics will also be measured (atmosphere, radiation budget, temperature, pressure, wind speed and direction, humidity, dust activity). Launched on June 2, 2003, Beagle 2 will be operating on Mars in December 2003.

Future activities and objectives

The Third European Exo/Astrobiology Workshop will be hosted by the Centro de Astrobiologia in Madrid, November 18−20, 2003. The Workshop will be dedicated to the search for life on Mars.

The following objectives will be pursued:

- to enlarge EANA to other European countries active in Exo/Astrobiology, i.e. Finland, Hungary, Poland, Romania, and Russia
- to interface the Network with European bodies such as ESA, ESF, the European Commission and with non−European institutions active in the field
- to promote the Federation of Astrobiology Organisations, FAO
- to popularise Exo/Astrobiology to the public and to students

General publications

- Exo/Astrobiology, Proceedings Second European Workshop on Exo/Astrobiology, Graz 2002, Ed. H. Lacoste, ESA Special Publication ESA SP−518 (2002). "Astrophysical and Astrochemical Insights into the Origin of Life", Reports on Progress in Physics 65, 1427−1487 (2002), co−authored by the ISSI Team members.

Prepared by André Brack, President of EANA

Intl. Partners: Groupement de Recherche en Exobiologie

Groupement de Recherche en Exobiologie
Executive Summary
Director/Leader: Francois Raulin

GDR Exobio

GDR CNRS 1877, or Groupement de Recherche en Exobiologie, is a national federation of research laboratories in Exo/Astrobiology, created by the National Centre of Scientific Research (CNRS) in 1999 and renewed in 2003. Its main goal is to promote, induce and coordinate the development of Exo/astrobiology scientific programs in France. It includes about 50 laboratories, and is supported by the CNRS and CNES (the French Space Agency).

4 main research topics are addressed:

- The ingredients of primitive life in their geological, planetological and interstellar context
- From the chemistry of the origins of life to the emergence of life: structures and functions of biological molecules
- Terrestrial life as a reference: fossils, biomarkers, extreme environments
- Habitats and signatures of extraterrestrial life

GDR Exobio has a scientific Council consisting of 19 scientists from different fields, including astrophysics, planetology, physics, chemistry, Earth sciences, life sciences, as well as philosophy and epistemology. The GDR has been affiliated with the NAI since November 2001.

Main recent activities

During the period July 2002−June 2003, the GDR Exobio, within the framework of its main 4 topics, has been active in several directions directly connected to NAI activities. Below are just a few examples of these activities, with the corresponding references given in the Reference list.

Several important results on Titan's organic chemistry (Raulin Owen 2002) have been obtained by joint studies involving GDR and other teams, including the determination of optical properties of Titan's tholins (Ramirez et al., 2002) and the potential presence of oxirane on Titan (Coll et al, 2003). Evidence that POM may be a precursor of formaldehyde in comets has been obtained through laboratory experimental data and modeling (Cottin et al, 2003). The development of methodologies and instrumentation for in situ exobiologically

oriented analyses of Martian soil has been reported by GDR US teams (Buch et al., 2003; Cabane et al, 2003).

The effects of solar radiation on amino acids and their derivatives exposed in Earth orbit has been examined (Barbier et al., 2002a,b; Boillot et al., 2002). The effects of interstellar and atmospheric mechanisms on the prebiotic synthesis have been studied (Meierhenrich et al., 2002). The identification of stable, biogenic, chiral aliphatic hydrocarbons by GCMswas demonstrated by Meierhenrich et al. (2003). An experiment simulating artificial meteorites showed that extraterrestrial sediments can reach the Earth (Brack et al., 2002a,b). Evidence for the fractionation of oxygen isotopes during entry of artificial meteorites into the Earth's atmosphere has been shown (Miller et al., 2002).

The environment of the early Earth as the context for early life on Earth and as an analogue for life on other planets has been the subject of a number of publications (Westall et al., 2002; Westall et al., 2003; Westall and Drake, 2003; Westall, 2003a,b,). Modern and ancient biofilms from the Early Archaean have been studied as analogues for potential extraterrestrial biofilms (Westall and Walsh, 2003; Walsh and Westall, 2003; Toporski et al., 2003a,b). It has been shown that previous investigations for microfossils and for a biogenic carbon isotope signal in the Early Archaean, 3.7 to 3.8 Ga rocks from Greenland did not take into account the presence of modern contaminating microorganisms (Westall and Folk, 2003). The evolutionary status of the earliest microfossils from 3.3−3.5 Ga rocks from Barberton and the Pilbara was examined by Westall (2003c) Stromatolitic microfossils preserved by hematite in the 2 Ga Gunflint Formation serve as an analogue for potential Martian microfossils in the Meridiani Planum hematite deposit (Allen et al., 2003).

The presence of various microbial eukaryotes in deep−sea hydrothermal settings and the association of potential biogenic signatures to sulfur−metabolizing bacteria have been shown (López−García, 2003a, 2003b).

Our efforts were also devoted to investigate one of the most important biological aspects of the origins of life, that is the ribonucleic acid (RNA) world hypothesis (Meli et al, J. Biol. Chem, 2002; 2003). On the other hand, we were able to show by Surface Enhanced Raman Spectroscopy (SERS) the detection of a subpicomolar amount of nucleic acid components trapped on mineral surfaces (Elamri et al, in press).

The search for indications of biological activity on extrasolar planets is also an important part of the studies that are carried out by the GDR team, which involve large−scale cooperation, especially with other teams linked to the NAI (Des Marais et al, 2003).

Exobio'03, the 3rd bi−annual National exo/astrobiology summer school, will take place in Corsica in September 2003. As for the 2 previous schools, it will be attended by close to 100 participants coming from astronomy and geophysics (60 persons) and from chemistry and biology. The program of this year includes: chronology: comparison of time scales in astronomy,

geophysics, chemistry and biology; impacts and Earth bio−geo evolution; Moon formation; chemical and biological evolution; auto−organisation and complexification; exoplanets; life on Mars, Titan, Europa; interstellar chemistry; Last Universal Common Ancestor (LUCA); and Artificial life.

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Future Hopes

The GDR wishes to participate in cooperative programs of research, on clearly identified topics, in the framework of its affiliation to NAI. The NAI connection should be a great opportunity to share and exchange researchers, in particular PhD students, to promote joint participation in research programs on Exo/astrobiology, and to use the synergy induced by the different ways of thinking and working of researchers from different origins to promote the wide field of Exo/astrobiology. Targets such as Titan, in relation to Cassini−Huygens, Mars and its international program of exploration, Europa and Extrasolar planets are already among the topics of high interest likely to be part of such joint research projects. In addition, the need for networking,

with new and efficient tools for teleconferencing (including asynchronous communication) remains a technical priority.

PREPARED BY
François Raulin, Director French GDR Exobio, affiliated to NAI

EPO: EPO Introduction

NAI's Education and Public Outreach (E/PO) 2002−2003

Reflecting a shift in the importance of education within NASA, the 2003 Strategic Plan for the Agency identifies 3 major mission statements, one of which is to "inspire the next generation of explorers." This mission is aligned with two goals: "Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics," and "Engage the public in shaping and sharing the experience of exploration and discovery." Astrobiology is well−suited to both goals, and the NASA Astrobiology Institute actively works towards meeting them.

NAI works within larger science education reform efforts to reach out to K−12 classrooms, museums and science centers, and the general public to inform and involve them in astrobiological research and to share the excitement of astrobiology discoveries. The NAI Lead Teams carry out E/PO efforts in their own communities and sometimes nationally, while the NAI Central office supports and extends their efforts at the national level. This year alone, NAI as a whole conducted over 27 intensive teacher workshops, gave more than 200 talks to various audiences, produced a new poster and supported the creation of a high school curriculum in astrobiology and other educational activities, as well as taught 15 undergraduate and graduate courses in astrobiology, held three different public information days/open houses, and gave at least 45 interviews to science journalists. Many of these activities are the result of extensive external partnerships with museums, other OSS missions, and sometimes directly with teachers and students. In this way, NAI has made significant strides towards encouraging students to seek and/or continue research and discovery opportunities in astrobiology and has engaged the public in the exciting questions of astrobiology.

In the pages that follow, please find complete listings of both the work done by the NAI Central team and by each of the Lead Teams. Questions regarding NAI's E/PO efforts can be directed to Krisstina Wilmoth at Krisstina.L.Wilmoth@NASA.gov or to any of the E/PO Leads identified with the individual Lead Team reports.

Virtual Institute: Virtual Institute

CONTINUED EVOLUTION OF THE VIRTUAL INSTITUTE

Members of the NAI community, including Associates and Affiliates, are situated at well over one hundred universities, research institutions and NASA Centers across the country and around the globe. Each NAI Team includes people not only from the Lead institutional site, but from a number of other locations as well. NAI members also come from many different research disciplines, representing the wide range of disciplinary expertise important to astrobiological exploration. Thus the NAI community exists as diverse and distributed group. This "virtual institute" is thus challenged to promote collaboration across geographical distances, scholarly disciplines, and institutional boundaries.

NAI's intent as a virtual institute is to catalyze and facilitate knowledge sharing and collaboration:

- among researchers within and across NAI Lead Teams
- with members of the larger astrobiology community
- with interested members of the public,

for the purposes of furthering astrobiology research, supporting the development of astrobiology as an important new field of science, and helping to shape and inform the scientific goals of NASA missions.

To implement this intention, NAI actively supports the development of a shared *culture of collaboration* . Important institutional culture goals include the identification and promotion of those social values and behaviors and the provision of those communication/collaboration tools that enable members to engage in: "easy collaboration from anywhere, anytime, with anyone". Such a culture of collaboration is something that evolves over time, shaped by shared experiences and the emergence of common goals and practices, as well as on−going member participation and feedback.

Overview of This Year's Projects

During this past year several projects were carried out to further the development of NAI as an effective virtual institute. Some had been initiated in previous years, but reached a new level of maturity and robustness during this fifth year of NAI's existence. Others represent new initiatives.

- NAI Seminar Series

- Other Virtual Classes, Seminars, Discussion Groups
- WebEx - a synchronous meeting tool
- LiveLink - a knowledge management/collaborative work space tool
- A Virtual Institute Component at the NAI Annual Meeting

Developmental Approach to the Virtual Institute

Before discussing the specifics of this year's projects it is worthwhile to briefly review the developmental approach that we are taking to make the concept of the virtual institute a successful reality. A four phase design cycle is guiding this process. The first phase, which was completed in 2002, was one of discovery, with the intention of identifying NAI members' needs regarding their scientific collaborations and their expectations regarding benefits and opportunities associated with membership in the virtual institute. Interviews with many members and a community−wide survey provided data for the NAI Communication/Collaboration Needs Assessment document.

Foremost among identified needs was a desktop solution to both real−time meetings with distributed colleagues, and asynchronous collaboration opportunities where colleagues could share and store work in a secure web−based environment. These and other member identified needs guided the next two phases of development of the institute's technology architecture, which occurred during the latter half of 2002 and the first quarter of 2003. These included research on and demonstrations of collaboration tools of potential interest to NAI, given assessed needs. WebEx, a collaboration tool supporting real−time meetings was selected first, with a pilot project launched in November of 2002 and completed in May, 2003. Livelink, a knowledge management/information repository tool was then selected, with a pilot launched in July of 2003. These pilots are discussed in greater detail below. The fourth phase in our developmental cycle, full−scale deployment of new collaboration practices or tools to the entire NAI community, is now underway with WebEx.

The developmental process is of course cyclical, not linear. With the shift in NAI membership, the inclusion of six new teams and the reconfiguration in many instances of the six NAI teams that were reselected in the recent CAN, it important to reassess member needs, as well as the overall developmental direction of the virtual institute. That will be an important aspect of our work in the next year.

In our reassessment we will continue to be guided by a focus on three distinct NAI arenas in which communication and collaboration need to be supported. These include

1. Lead institutional site to Lead institutional site:

enabling one−to−one and multi−site videoconferencing, data sharing, knowledge building and other collaborative work among PIs, CO−Is,

Post−Doctoral Fellows and other team members located at the Lead institutional sites.

2. Distributed teams/Focus Groups/small group collaborations:

enabling videoconferencing, data sharing, knowledge building and other collaborative work among NAI members who do not reside at Lead institutional sites as well as people at Lead sites who want to engage from the desktop rather than the conference room, and/or who want to collaborate with colleagues who are not at other Lead institutions.

3. NAI community−wide events, conferences, seminars:

enabling large groups of people at different geographical locations to meet together virtually for presentations and exchanges of various kinds. These groups may also include the larger Astrobiology community beyond the NAI itself, and/or interested members of the public.

Specific Projects

- ***NAI Video Seminar Series***

Director's Seminar Series

Launched in 2002, these monthly video seminars have become a regular event in the virtual institute calendar, drawing participants from many NAI teams, as well as open to others from the larger scientific and public communities. The seminars are hosted by one of the NAI Lead institutional sites. They are both webcast via the Internet and broadcast out to meeting rooms and/or desktops at other sites via the Polycom videoconferencing system. Slides and other documents or images are shared with the distributed audience using the WebEx meeting tool. WebEx also includes a chat feature that has been used to facilitate exchange between presenter and remote audience members.

The following seminars were offered in Year Five:

8/25/03 Linda Amaral Zettler − MBL

"Eukaryotes at pH Extremes"

7/28/03 Jim Tiedje − MSU

"Microbial and Genomic Insights In Microbial Life in Permafrost"

6/23/03 Jose Maria Gomez, David Hochberg − CAB

"Multicellular and Multicolonial Bacterial Patterns: Implications for

Astrobiology"

5/19/03 John Bally − CUB

"Star and Planet Formation"

4/28/03 Anurag Sharma − CIW

"Experimental Window into High Pressure Geobiology"

3/24/03 Tom Quinn − UOW

"The Formation of Giant Planets"

2/24/03 David Smith − URI

"Probing the Limits of Earth's Deep Biosphere "

11/25/02 Bruce Runnegar − UCLA

"Sulfur Cycling on the Early Earth"

10/28/02 Michael Storrie−Lombardo − VPL

"Life Detection and Sensors:Bio−Info−Nano Science"

The Forum for Astrobiology Research Seminar Series

This monthly video seminar series, piloted last year, was fully launched early in 2003. The seminars feature presentations by NAI Post−Doctoral Fellows, as well as astrobiology graduate and undergraduate students drawn from NAI Lead Teams.

These forums have also become well attended monthly events, and have promoted dialogue and professional networking among NAI community members.

The following seminars were given during this past year:

9/8/03 Sara Martinez − CUB

"Looking for Hydrothermal Systems on Mars: An Integrated Study of

Spectroscopic, Thermal, and Imaging Data"

7/14/03 Kevin Boyce − HAR

"How to Make a Leaf? 400 Million Years of Repeated Answers to the Same

Evolutionary Question"

6/9/03 Ruth Ley − CUB

"The Amazon Basin of the Mud World: Dizzying Microbial Diversity at

Guerrero Negro's Salt Mats"

5/12/03 Henry Scott ? CIW

"Chemical Stratification and Hydrocarbon Stability in Large Icy Satellites"

4/14/03 Michelle Minitti

"Assessing the Effect of Impact Shock on Water in Amphibole: Implications

for the Martian Meteorites"

3/10/03 Alex Pavlov − CUB

"Atmospheric Methane and Oxygen in Archean and Proterozoic. Constraints

from Sulfur"

- ***Other Virtual Classes, Special Seminars, Discussion Groups***

- NAI Special Seminar

In addition to the two regularly scheduled NAI Seminar Series, occasional Special Seminars are also offered. In Year Five the following special event was implemented:

11/1/02 Peter Jenniskens − ARC

"An Astrobiology Mission to Explore the 2002 Leonid Storm"

- University of Washington Astrobiology Seminar Series

During this last year Tom Quinn of the UOW Lead Team proposed that NAI broadcast the presentations given in the UOW weekly Astrobiology series. Other sites were able to view the seminars in real−time, either in their conference rooms or individually at the desktop through a webcast. These seminars drew on a number of scientists associated with other NAI teams, and offered NAI members and others yet another opportunity for the knowledge sharing and exchange that the virtual institute aims to foster. Presenters for the Spring quarter, 2003, are listed below.

5/27/03 Robert Blankenship

"The Transition from Anoxygenic to Oxygenic Photosynthesis and How it Changed the Earth"

5/20/03 Roger Buick

"A Subsurface Biota in the Archean?"

4/29/03 Tori Hoehler

"Energetic Habitability: Boundary Conditions for Life−as−We−Know−It"

4/22/03 Jack Farmer

"Microbial Biosedimentology of some Extreme Terrestrial Environments with Implications for the Exploration for Extraterrestrial Life"

4/15/03 Geoff Garrison

"Geochemical Seasonality in a Unique AquaticEnvironment: Who Needs

Oxygen, Anyway?

- Pennsylvania State University Astrobiology Seminar Series

In the Fall semester of 2002, members of the PSU Lead Team collaborated with colleagues at the University of Pittsburgh and the State University of New York at Stony Brook on a for credit course open to students from all three institutions. and presented through a "virtual classroom". Using PolyCom cameras provided by NAI to all three sites, a "virtual classroom" was created, which allowed three way engage among students and faculty from each site. This experiment in distance learning was extremely well received by participants at all three sites and a commitment has been made to continue this seminar offering in the Fall of 2003.

- ***WebEx - a synchronous meeting tool***

Extensive research was conducted on commercially available real−time meeting tools, to identify best solutions for NAI. Given the all important NAI requirement of cross−platform compatibility for all desktop solutions, as well as other features, we selected WebEx for a 6 month pilot project. The pilot began in early November, 2002, and ended in early May of 2003. We introduced the use of WebEx into the monthly Executive Council videoconferences and the two NAI Seminar Series. A number of small project groups also tried out WebEx for their meetings during the pilot period.

Based on overwhelmingly positive feedback by those who utilized the tool during the pilot phase, we chose to continue WebEx for an 12 months more months, with additional options to extend our use for 12 months at a time. NAI members have found WebEx useful various types of meeting that involve more than voice only exchange. The software enables meeting participants to engage in data, document and application sharing from their desktops, as we;; as draw or take notes in real time on a whiteboard, create and implement polls, and chat privately with selected individuals, or with the whole group, attending the meeting, WebEx is now available for use by any NAI member who wishes to hold a meeting with colleagues on NAI−related matters.

- ***LiveLink - a knowledge management collaborative work space tool***

Research was also undertaken on collaboration tools that support document management, information sharing and storing, and secure collaborative workspaces. This category of tool is generally referred to as a knowledge management tool. Among those who research virtual organizations, it is generally regarded as a best practice that such organizations make some kind of share information repository and collaborative work space available to all its members. Such a virtual space facilitates document and data exchange, knowledge sharing and building and collaborative work projects.

After a close look at several strong candidates, we selected Livelink for a 7 month pilot by 100 users drawn from the NAI community. This pilot was launched in July 2003, and runs through February 2004.

Small groups of scientific collaborators from as many of the NAI lead teams as are interested, are being sought for participation in the Livelink pilot, as well as user groups from NAI Central and the IT Working Group. Hands−on evaluation of the tool by the NAI Central group. And feedback from pilot participants will determine whether we proceed with a licensing agreement to provide full deployment to all members of the NAI community.

- ***A Virtual Institute Component at the NAI Annual Meeting***

The Program Planning Committee for the NAI General Meeting held in February, 2003, determined that focus on the virtual institute concept and its implementation should be a part of the conference. As a result, several projects and events were undertaken.

The virtual institute was included for the first time as a category for poster submissions. Several members of the IT Working Group, and several NAI Central staff, as well as others, submitted proposals in the category and were invited to present posters. Posters included a general focus on virtual institute issues, such as the meaning of NAI membership, or the social and technical challenges of the virtual institute. Other posters presented projects undertaken by members of specific Lead Teams, such as the virtual classroom explored by PSU, data sharing tools linking the science laboratories of the MSU researchers, a wireless data sharing system for remote fieldworkers designed by members of the MBL Team, and an interactive portal interface designed by CIW Team members.

A special room was designated as a hands−on demonstration space for collaboration tools currently being offered to NAI members or explored by the NAI IT Working Group. Specific demonstration events were scheduled, and the room was also available for drop in visits by conference attendees interested in trying out tools or getting some personal coaching.

Finally, a Town Meeting was scheduled on the final day of the conference, and part of the discussion was focused on the virtual institute and its benefits and challenges to members. This was the first time a public forum with NAI had taken up this topic, and useful feedback as well as creative ideas emerged from this meeting.

Fellowships: NAI/NRC Fellows Introduction

Since its inception, the NASA Astrobiology Institute has been committed to training future generations of researchers that have a perspective of science that crosses the historical boundaries of academic disciplines. An integral part of this commitment has been the NAI/NRC Postdoctoral Fellowship Program. Administered in cooperation with the National Research Council, of the National Academy of Sciences, the NAI/NRC Postdoctoral Fellowship Program has now supported 21 NAI Fellows at 11 of its 15 Lead Teams. During this past year the NAI/NRC Program has increased its accessibility by now having two review cycles per year; with application due dates of February 1 and August 1.

NRC Associates selected through the NAI/NRC Program become Full Members of the NASA Astrobiology Institute and, as such, are included in the NAI database and online directory, invited to attend and submit abstracts for NAI General Meetings, given access to NAI Collaborative Tools, and are eligible for additional NAI Funding opportunities. NAI/NRC Fellows have, therefore, a wide spectrum of opportunities for further collaboration with NAI researchers, as well as the broader scientific community, and are expected to help define the new discipline of astrobiology.

Fellowships: All Teams

The NAI−NRC Postdoctoral Fellowship recipients for all teams are below.

Recipient: Seth Bordenstein
Project Title: Genomic determinants of parasitism and mutualism in bacterial endosymbionts
Advisor: Jennifer Wernegreen, Co−Investigator
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: July 2002

Recipient: Charles Boyce
Project Title: The use of living plants and fossil chemistry to study the morphological patterns and developmental processes of land plant evolution
Advisor: Andrew Knoll, Advisor
NAI Lead Team: Harvard University
Fellowship Began In: August 2002

Recipient: Virginia Edgcomb
Project Title: Hyperthermophiles of the hydrothermal vent subsurface: limits of life and extraterrestrial analogs
Advisor: Andreas Teske, Advisor
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: July 2002

Recipient: Geoff Garrison
Project Title: A Study of Marine and Terrestrial Stable Isotopic Geochemistry During the End−Permian and End−Triassic Mass Extinction Events
Advisor: Peter Ward, Advisor
NAI Lead Team: University of Washington
Fellowship Began In: January 2003

Recipient: Eric Gaucher
Project Title: Using functional genomics to infer the biology and chemistry of

the Last Common Ancestor
Advisor: Steven Benner, Advisor
NAI Lead Team: Scripps Research Institute
Fellowship Began In: July 1, 2002

Recipient: Marc Kramer
Project Title: Surface Hydrology and Microbial Ecology for Global Semi−Arid Ecosystems
Advisor: David Des Marais, Advisor
NAI Lead Team: Ames Research Center
Fellowship Began In: August 2001

Recipient: Ruth Ley
Project Title: Diversity and function of the sulfur−cycling community in hypsersaline microbial mats
Advisor: Norman Pace, Project Investigator
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: August 2002

Recipient: Sara Martinez−Alonso
Project Title: Identification and Study of Hydrothermal Systems on Mars Through Remote Sensing: Analysis of Regions of High Spectral Variance
Advisor: Bruce Jakosky, Advisor
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: September 2002

Recipient: Mark Messerli
Project Title: Physiological Regulation of Cytosolic pH in Eukaryotic Acidophiles
Advisor: Peter Smith, Advisor
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In: January 2002

Recipient: Michelle Minitti
Project Title: Chasing water on Mars: A geochemical approach using martian meteorites
Advisor: Laurie Leshin, Advisor

NAI Lead Team: Arizona State University
Fellowship Began In: August 2001

Recipient: Tracy Norris
Project Title: The Evolution of Desiccation Tolerance in Cyanobacteria
Advisor: Richard Castenholz, Project Investigator
NAI Lead Team: Ames Research Center
Fellowship Began In: August 2002

Recipient: Alexander Pavlov
Project Title: Organic and sulfur hazes in the Archean atmosphere: Climatic and photochemical consequences.
Advisor: Owen Toon, Advisor
NAI Lead Team: University of Colorado, Boulder
Fellowship Began In: February 19, 2002

Recipient: Susannah Porter
Project Title: Constraining the effects of taphonomic bias on the Cambrian explosion
Advisor: Bruce Runnegar, Advisor
NAI Lead Team: University of California, Los Angeles
Fellowship Began In: September 2002

Recipient: Henry Scott
Project Title: Oxidation of Organic Carbon Under High Pressure Hydrothermal Processing
Advisor: Russell Hemley, Project Investigator
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: July 2002

Recipient: Yanan Shen
Project Title: Environmental changes in the context of biological evolution during Neoproterozoic on the Yangtze Platform, a snowball Earth?
Advisor: Andrew Knoll, Advisor
NAI Lead Team: Harvard University
Fellowship Began In: April 2, 2001

Recipient: Michael Smoliar
Project Title: Re−Os study of hydrothermal processes in ordinary chondrites
Advisor: Conel Alexander, Advisor
NAI Lead Team: Carnegie Institution of Washington
Fellowship Began In: September 2002

Recipient: Christopher Staples
Project Title: The Evolutionary Connection between Photosynthesis and Nitrogen Fixation
Advisor: Robert Blankenship, Advisor
NAI Lead Team: Arizona State University
Fellowship Began In: July 2002

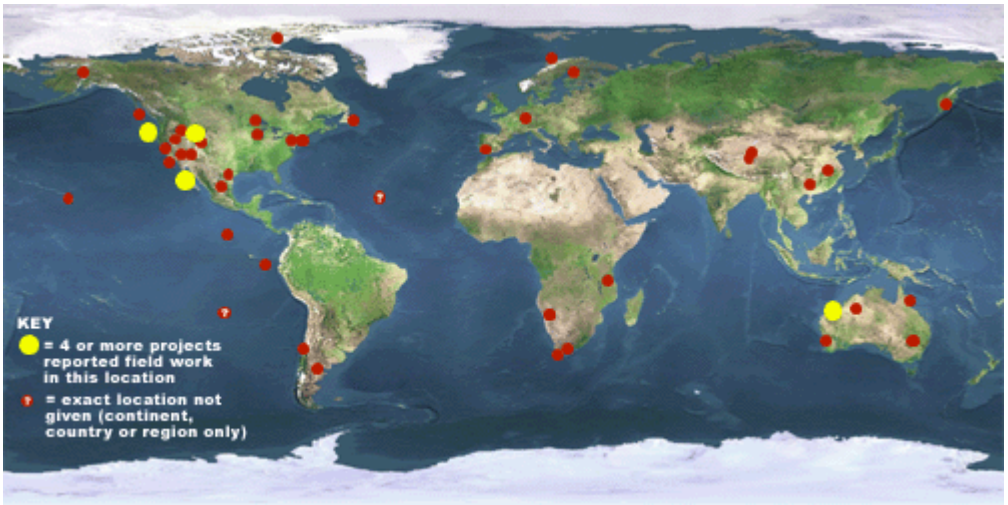
Recipient: David Warmflash
Project Title: Immunoassay life detection test
Advisor: David McKay, Advisor
NAI Lead Team: Johnson Space Center
Fellowship Began In: January 30, 2001

Publications: Introduction

- Bibliographic records here include various types of publications, e.g., journal articles, books, book chapters, meeting abstracts.
- Each record includes the status of the publication if it is not yet in print, e.g., in press, submitted, in preparation.
- Total record counts are given with each NAI Team Publications section.
- Publication lists can be displayed either as a full alphabetic list or in research project groups.

Appendix: Field Trip Map

The map and table with background data below have been created using data from NAI Year 5 Project Reports.



Key : Red Dot = Field work reported by one project.
Separate red dot used for each project reported in a given location.
Yellow Dot (Larger) = Locations where 4 or more projects reported field work
? and Red Dot = Uncertainties from vague reports on exact location
(only a continent, country, or territory reported for field work).

Appendix: Roadmap Objectives

Astrobiology and the roadmap

Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. Astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planet laboratory and field investigations of the origins and early evolution of life, and studies of the potent of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is neede that combines molecular biology, ecology, planetary science, astronomy, information science, spac exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiolo compels us to strive for the most comprehensive and inclusive understanding of biological, planeta and cosmic phenomena.

This NASA Astrobiology Roadmap outlines these multiple pathways for research and exploration a indicates how they might be prioritized and coordinated. The roadmap embodies the efforts of more than 200 scientists and technologists, including NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the broader community who ha no formal association with NASA.

Fundamental Questions

Astrobiology addresses three basic questions, which have been asked in some form for generation Astrobiology is exciting today because we have the technology to begin to answer them.

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

Principles

This roadmap emphasizes the following four principles that are fundamental to the operation of the Astrobiology Program:

- Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its succe depends critically upon the close coordination of diverse scientific disciplines and programs including space missions.
- Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.
- Astrobiology recognizes a broad societal interest in its endeavors, especially in areas such achieving a deeper understanding of life, searching for extraterrestrial biospheres, assessin the societal implications of discovering other examples of life, and envisioning the future of on Earth and in space.
- The intrinsic public interest in astrobiology offers a crucial opportunity to educate and inspir the next generation of scientists, technologists and informed citizens; thus a strong emphas upon education and public outreach is essential.

Roadmap Objectives

Objective No. 1.1: Models of formation and evolution of habitable planets

Objective No. 1.2: Indirect and direct astronomical observations of extrasolar habitable planets

Objective No. 2.1: Mars exploration

Objective No. 2.2: Outer Solar System exploration

Objective No. 3.1: Sources of prebiotic materials and catalysts

Objective No. 3.2: Origins and evolution of functional biomolecules

Objective No. 3.3: Origins of energy transduction

Objective No. 3.4: Origins of cellularity and protobiological systems

Objective No. 4.1: Earth's early biosphere

Objective No. 4.2: Foundations of complex life

Objective No. 4.3: Effects of extraterrestrial events upon the biosphere

Objective No. 5.1: Environment-dependent, molecular evolution in microorganisms

Objective No. 5.2: Co-evolution of microbial communities

Objective No. 5.3: Biochemical adaptation to extreme environments

Objective No. 6.1: Environmental changes and the cycling of elements by the biota, comunities, and ecosystems

Objective No. 6.2: Adaptation and evolution of live beyond Earth

Objective No. 7.1: Biosignatures to be sought in Solar System materials

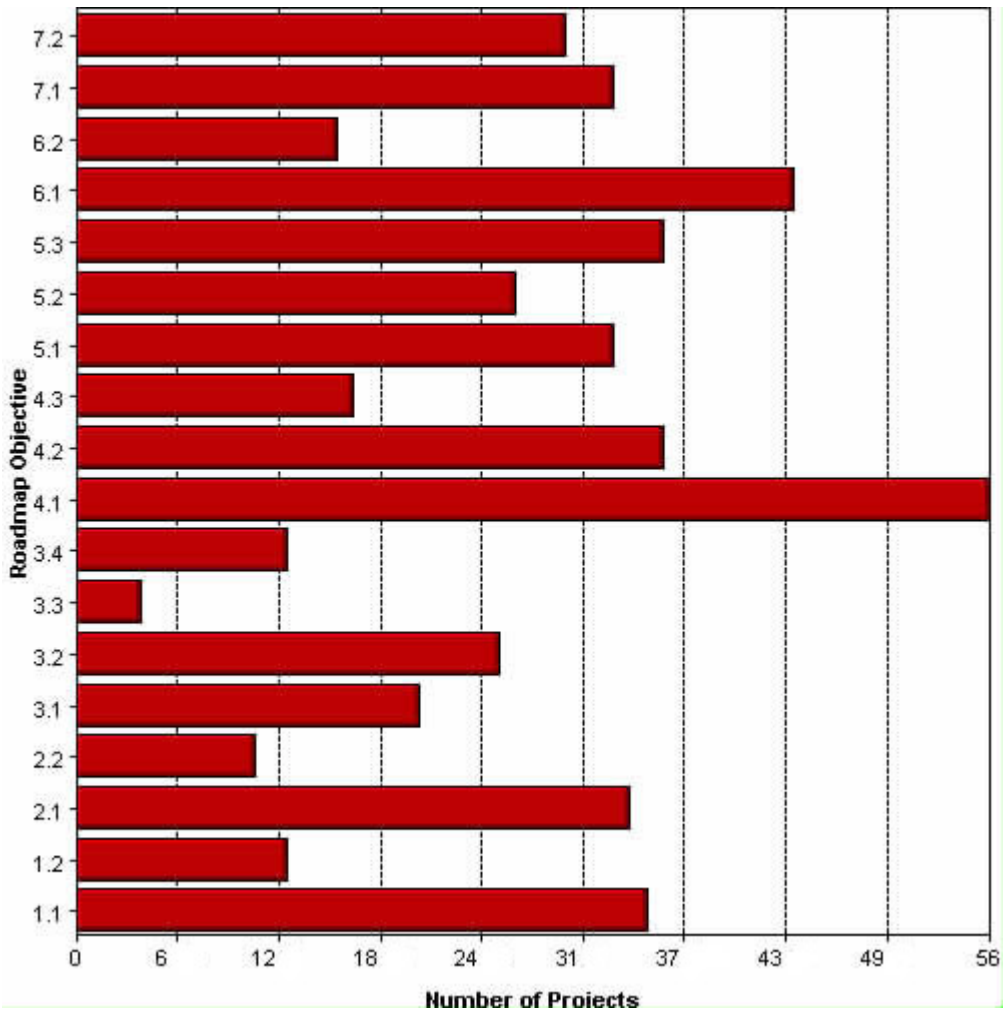
Objective No. 7.2: Biosignatures to be sought in nearby planetary systems

Appendix: Roadmap Statistics

Team Projects and Focus Group Activities Related to Roadmap Objectives

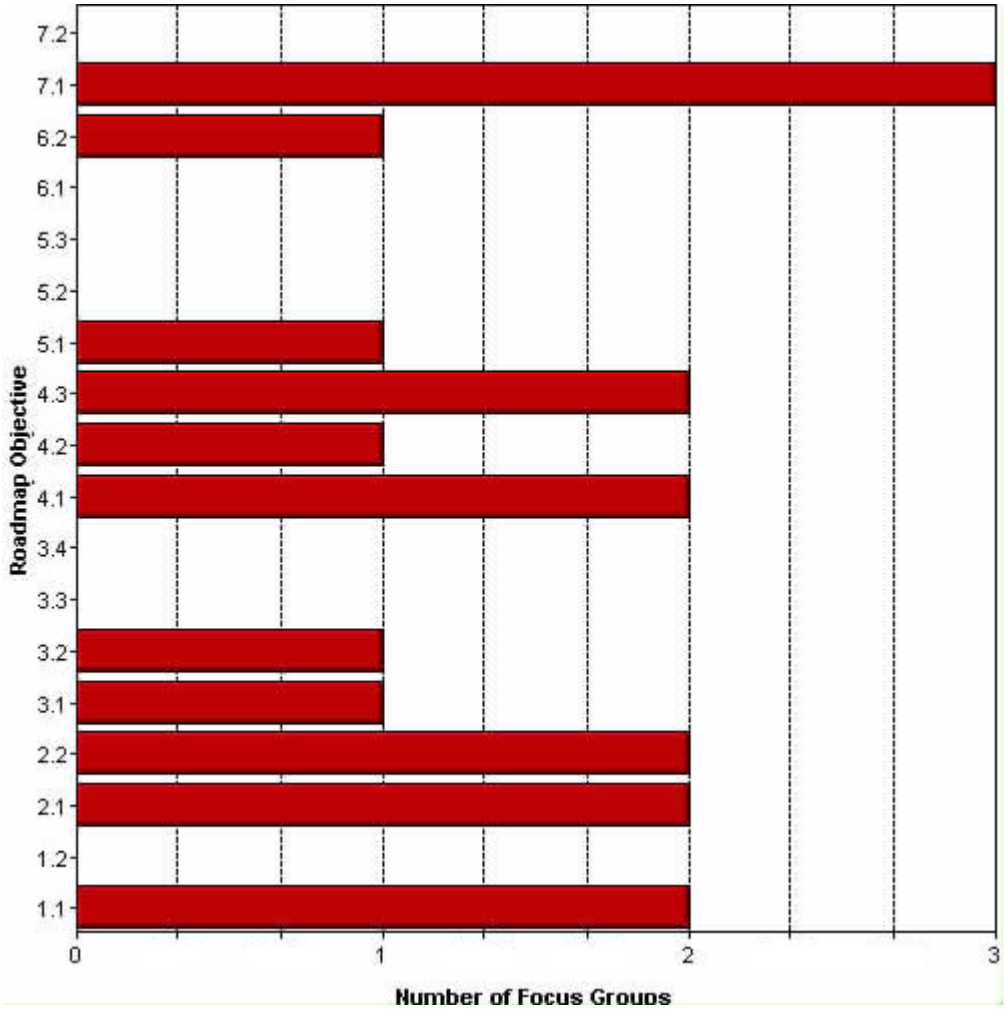
Click on a Roadmap Objective to view the related projects or focus groups.

Number of Team Projects per Roadmap Objective



Total Team Projects = 133. Most projects have several Roadmap Objectives.

Number of Focus Groups per Roadmap Objective



Total=7

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EPO: NAI Central

These are the Education and Public Outreach activities for the NAI Central.

Ask An Astrobiologist

Ask An Astrobiologist (http://nai.arc.nasa.gov/astrobio/index.cfm) is a web−based product for students and web users of all ages that offers keyword−searchable and categorized questions and answers in astrobiology and related science disciplines. Users are invited to browse the archive and submit new questions. The questions are answered by the NAI Senior Scientist, David Morrison. A few questions are identified for longer, higher profile answers in the section for "Featured Questions." Ask An Astrobiologist receives approximately 30 questions a month from readers of all ages and backgrounds, and based on the language of the questions, most come from the public, high school students, and teachers . Revisions this year included upgrades to the categorization and user process for submitting questions, new featured questions, an extensive video archive for career−related information, and a more uniform and timely preparation of responses by the NAI Senior Scientist.

Astro−Venture: An Interactive Project for Students

Astro−Venture (http://astroventure.arc.nasa.gov) is an educational, interactive, multimedia Web environment focusing on astrobiology. Developed by the Office of Education at NASA Ames Research Center and funded in part by NAI Central, this educational site designed for students in grades 5 − 8, allows students to role−play NASA occupations to learn about what makes a planet habitable to humans. Astro−Venture is divided into five sections: Astronomy, Biology, Geology, Atmospheric Sciences and Design A Planet. Each of the first four sections includes on−line multimedia modules and lessons. NAI provides scientific review and experts for webcasts and webchats. This year, the Astro−Venture team led numerous workshops with both teachers and students throughout the country. Three modules in atmospheric science, geology and biology were completed and released, and the Atmospheric Science Educator Guide, won two awards for excellence and was featured in three articles.

Astrobiology for Teachers: An Online Graduate Course

NAI supports teachers from across the US to enroll in a semester long graduate course in astrobiology. The course is one of several online offerings of the Montana State University in conjunction with the National Science

Teacher Association Institute. The two main goals of the course are (1) to provide information on the central concepts related to the field of astrobiology and (2) to provide experiences with using student−centered and inquiry−based curriculum materials for teaching astrobiology that are aligned with the National Science Education Standards. The course materials are astrobiology texts in common use and a specially designed set of lab activities, Life in the Universe â?? Activities Manual published by Prather, Offerdahl, Slater, 2003, Addison Wesley, to accompany one of the primary texts. While the course is asynchronous allowing participants to complete the work on their own time schedules, teachers must log in daily and complete several group projects during the semester. The course is evaluated summatively using the following data sources: (i) teacher−participant performance in the course overall; (ii) teacher−participant performance on exams; and (iii) teacher−participant comments on the course from the teachers' electronic community discussion groups. Twenty−three teachers completed the course this year. Information regarding upcoming courses can be found at http://btc.montana.edu/ceres/astrobiology/.

Cosmic Origins: Traveling Museum Exhibit

As one of the major themes of the traveling exhibit, astrobiology is well represented in the plans for the 3000 square foot traveling museum exhibit under development by the Space Science Institute. Under the working title of "Cosmic Origins," three major themes: star birth, extra−solar planets, and the search for life, are represented in this exhibit scheduled for completion in late 2004. NAI is providing microbiologists, John Spears and Brad Bebout, as advisors to the exhibit, as well as providing funding for professional development of the astrobiology content to museum educators. NAI's E/PO Manager, Krisstina Wilmoth, serves as the content lead in the search for life component. The exhibit will travel around the US over a 3−6 year life span targeting small to medium sized science centers and museums reaching over a million people. Information on the project can be found at: http://www.spacescience.org/Products/Exhibits/1.html.

Extraterrestrial Life Interactive Exhibit at the New York Hall of Science

The New York Hall of Science (NYHoS) is New York City's only hands−on science and technology center. Ranked as one of the best science museums in the country, the Hall is a leading innovator in exhibit technology and educational programming. More than 225 hands−on exhibits explore the wonder and excitement of biology, chemistry and physics. NAI Central is working with NYHoS towards the production of a 5000 square foot interactive exhibit for children on life beyond Earth and the extremes of life. Under the working title of Extraterrestrial Life, NYHoS is developing a permanent exhibit and discussing the possibility of a smaller traveling version. NAI scientists are on the review board for the exhibit and the content reflects much of the NAI's research on extremophiles. The exhibit will introduce children and families to the known conditions for life and what is considered extreme on Earth. These interactives will be followed up with explorations of habitable planets beyond

Earth. The lead for this project is Dr. Martin Weiss at NYHoS.

Micro*scope Website: Astrobiology Collections

NAI Central provides funding for the Micro*scope Website, developed through the Astrobiology Institute at the Marine Biological Laboratory at Woods Hole. It is an innovative biodiversity bioinformatics website that greatly improves access to information about microbes. Microbes were the only living things for most of the history of the Earth. Over 3.5 billion years ago they began the process of transforming this planet, making it habitable for those of us who came later. Bacteria and protists remain the dominant players in most known ecosystems. The numbers of bacteria and protists in the world is staggering − a single teaspoonful of seawater contains millions of bacteria and thousands of protists. The study of microbial communities is essential if we are to understand and manage the world around us and such studies prepare us for the exploration for life on other planets. Micro*scope provides teachers and students with high−quality, downloadable, digital light micrographs of microbes. Presently, the site contains software to manage names and classification; a classification of protists and bacteria; dynamic outlinks for internet searching; original data about microbes; a comprehensive classification of all protist genera and prokaryotes, including 4500 images of microbes with explanatory text; and a variety of educational resources, including Lucid taxonomic guides. Information in the site can be accessed by habitat, cell shape, alphabetic list of genus name, and formal classification. The site is continuing to expand and improve for larger public promotion by ensuring that all aspects work properly. New educational material, including hands−on classroom activities already developed by MBL, glossary terms, and a tutorial for using Lucid guides is under development in addition to a database of available K−12 hands−on activities in microbiology that details which aspects of the National Science Education Standards are met by each activity. The site is located at: http://www.mbl.edu/microscope.

NAI E/PO Representation at Professional Meetings for Scientists

In this past year, NAI Central E/PO has attempted to strengthen the role of education via science organizations. NAI Central staff were invited to give presentations in the education sessions of two significant science conferences: Bioastronomy 2002 (Hamilton Island, Australia), and The American Association for the Advancement of Science (AAAS), Pacific Division (San Francisco, CA). Additionally, NAI senior scientist David Morrison was featured at a special press briefing on the asteroid impact hazard at the annual meeting of the AAAS. The presentations included information on astrobiology education and the need for scientist involvement:

Dr. Rosalind Grymes and Krisstina Wilmoth co−presented "The NASA Astrobiology Institute: Reaching Within and Beyond" at the Bioastronomy Meeting, Hamilton Island, Australia, July2002.
Krisstina Wilmoth presented "Connecting Astrobiology Research Education" at the annual meeting of the AAAS Pacific Division in San Francisco, CA on June

17, 2003.

NAI E/PO Support Services

NAI Central coordinates representatives from the NAI Teams in monthly telecons and facilitates collaborative projects among them in addition to offering them support with educational materials and supplemental funding. Centralizing this information in the form of a webpage, NAI Central shares information on E/PO activities, houses presentations on E/PO projects, and offers general announcements, an interactive forum, and links to other relevant sites. For access to the NAI E/PO page, please contact Daniella Scalice at (dscalice@arc.nasa.gov).

NAI Central also represents all of NAI to the larger E/PO networks including two forums of the NASA Office of Space Science (OSS) Education Support Network. NAI Central attends monthly telecons and yearly retreats for the Origins Education Forum and the Solar System Education Forum. NAI Central also responds to all reporting requirements including the annual request for input to the education project database known as Edcats and participates in OSS group activities such as exhibits or projects. Specifically, NAI brings information regarding astrobiology to other E/PO programs and returns information on opportunities and new projects back to the NAI Teams. Information on the OSS Education Support Network and contact information is available at
http://oss−ecosystem.stsci.edu/.

NAI Minority Institution Research Sabbatical: Engaging Minority Institutions in Astrobiology

NAI Central supports a program for faculty at certified Minority Institutions to participate in research sabbaticals in astrobiology at NAI research sites. The Minority Institution Research Sabbatical (MIRS) is open to faculty at certified Minority Institutions and aims to support collaborations in astrobiologywhich will lead to joint research proposals successful in peer review competitions. The program began in 2002 and has created 4 scientific collaborations to date. Successful applications have been received from Tennessee State University, Florida A M University, and Howard University. The program also extends support to students of the participating faculty members to attend astrobiology science meetings and to become more familiar with the field of astrobiology. Applications are accepted year round, and host sites are currently available in a range of disciplines. Complete information is available at
http://nai.arc.nasa.gov/institute/miSabbatical.cfm.

NAI Webpages Focused on Teachers and Students

The NAI For Teachers section (http://nai.arc.nasa.gov/teachers/index.cfm) was recently reorganized to reflect a shift in focus from simply an online resource for educational materials to a comprehensive professional development tool.

Organized into seven categories, the For Teachers section houses a wealth of information for educators. From finding research opportunities tailor−made for teachers, to listing the latest goings on at museums nation−wide, educators for all grade levels are provided with the means to find ways to connect with research and other professional opportunities. The section also offers a monthly rotating professional development feature, as well as an archive full of astrobiology related classroom resources and student activities.

NAI Central E/PO also maintains webpages in the "For Students" section which offers on−line interactive projects and links to career information and the opportunity to ask questions via Ask An Astrobiologist.

Teachers Experience Astrobiology− A Series of Workshops, Short Courses, and Professional Meetings

NAI offers teachers of all levels many opportunities to engage with the science of astrobiology. These opportunities are offered at professional science education meetings such as the National Science Teacher's Association annual and regional meetings, the National Association of Biology Teachers' annual meeting, many state and regional conferences, and at our academic and research partner sites as well. Typical offerings include lectures and presentations by scientists combined with exposure to astrobiology classroom materials, and some research into core astrobiology concepts whenever possible. Many of the workshops are collaborative efforts between the NAI Teams, sometimes other NASA missions, and the Origins Education Forum. Astrobiology workshops are unique in that they provide interdisciplinary science topics with the focus on life in the universe which both captures student imaginations as well as addresses the trend in American middle and high schools towards integrated science courses. For more information on the NAI programs for teachers, visit: http://nai.arc.nasa.gov/teachers/

NAI Central and NAI E/PO members from Pennsylvania State, Marine Biological Laboratory, Johnson Space Center, Carnegie Institution of Washington, and NASA Ames Research Center collaborated on a five hour short course at the National Science Teachers Association Convention (NSTA) (www.nsta.org) in Philadelphia. The course was coordinated by members of PSU's E/PO team and was attended by over 50 middle and high school teachers. The workshop included science talks by Jim Kasting on "Planetary Evolution and Habitability" and Andrew Steele on "How to Spot a Martian." The short course also included demonstrations of hands−on activities, videos and interactive CD−ROMs related to Astrobiology. In addition to the short course, NAI also staffed a booth for the Origins Forum of the Office of Space Science in the exhibit hall where the 20,000 attending teachers were able to talk to researchers and get educational materials for their classrooms. For more details, see PSU's E/PO section.

NAI Central partnered with the Australian Centre for Astrobiology, the SETI Institute, and the Australian−American Fulbright Commission to conduct a first−ever science education symposium in tandem with a science meeting: Fulbright Symposium 2002: Science Education in Partnership. The pairing of

the two conferences allowed collaborations and dialog among attending scientists, educators and education specialists. Teachers from around the world participated in the five−day event held on Hamilton Island, Australia in July of 2002. The event focused on direct involvement in research for educators and on building collaborations between the two groups. For more information about the meeting or the publication, visit http://aca.mq.edu.au/fulbright/

Also this year, NAI Central staff coordinated and conducted a 90−minute remote workshop for a group of science teachers in Colorado Springs, CO. The NAI was invited to participate in this week−long professional development experience for educators sponsored by the US Space Foundation. Via the two−way audio/video polycom system and internet−based meeting software called Webex already extensively used by the NAI, an overview talk of the research of the NAI and a demonstration of two astrobiology classroom materials was successfully delivered.

Astrobiology educational materials were distributed at the NAI exhibit at the National Association of Biology Teachers (NABT) convention in Cincinnati, Ohio. NAI E/PO staff were able to interact with and answer questions asked by the attending teachers. NABT is "the leader in life science education." To date, more than 9,000 educators have joined NABT (www.nabt.org) to share experiences and expertise with colleagues from around the globe, keep up with trends and developments in the field, and grow professionally. NAI brings information on integrated science to this very key educational audience. NAI also supported the Ames Office of Education in an exhibit at the California Science Teacher Association Meeting in San Francisco. Approximately 3000 teachers attended this event.

Finally, NAI Central E/PO staff delivered talks at education meetings and public venues in late 2002 and 2003. These talks provided astrobiology content and context to both teachers and public audiences:
Dr. Lisa Faithorn and Krisstina Wilmoth co−presented "Collaboration: A Critical Orientation for Today's World" at the Fulbright Symposium, Hamilton Island, Australia, July 2002.
Dr. David Morrison presented "How Astronomers are Saving the World"at a public lecture sponsored by the International Astronomical Union in Sydney, Australia in July 2002.
"Searching for Life in the Solar System" featured Dr. David Morrison in a panel sponsored by the World Science Fiction Convention on August 29, 2002.
Dr. David Morrison presented "How Astronomers are Saving the World" as part of a public symposium sponsored by the Astronomical Society of the Pacific, Berkeley, CA on September 29, 2002.
"The Asteroid Impact Hazard" was presented by Dr. David Morrison at the Chabot Science Center in Oakland, CA on October 12, 2003.
Dr. David Morrison was one of three guests on an hour−long television program "Uncommon Knowledge" devoted to "Life in the Universe," taped on October 25, 2002.
Dr. David Morrison presented "Asteroids and Evolution" to the Seniors in Retirement civic club in Mountain View, CA on October 16, 2002.
"Astrobiology, Impacts, and Evolution" featured Dr. David Morrison at a special

public presentation at Ohlone College in San Mateo, CA on November 20, 2002.
"The Story of Astrobiology"was presented by Daniella Scalice at the 126th annul meeting of the American Association of Physics Teachers in Austin, Texas on January 14, 2003.
Dr. David Morrison presented "The Asteroid Impact Hazard" to graduate and undergraduate students at UC San Diego in a program sponsored by the California Space Grant University program, January 31, 2003.
"Impacts and Evolution" was presented by Dr. David Morrison to the Stanford University class on space life science and astrobiology, April 22, 2003
Dr. David Morrison presented "The Asteroid Impact Hazard" to the Mountain View, CA Kiwanis Club on May 7, 2003.
"What is Astrobiology?" was presented by Dr. David Morrison to the NASA Astrobiology Academy students on June 29, 2003.
Dr. David Morrison was a speaker and discussion leader on the topic of "Impacts and Evolution" for the NASA Astrobiology Academy on July 8, 2003.

Voyages Through Time: High School Curriculum

In partnership with NAI, the National Science Foundation, the California Academy of Sciences, and San Francisco State University, the SETI Institute has developed Voyages Through Time (VTT), a standards−based integrated science curriculum for high school centered on the unifying theme of evolution. Scientists, teachers, curriculum writers, and media specialists have created six CD−ROM modules that integrate astronomical, geological, and biological sciences. The sequence of lessons in each module is designed to promote students' understanding of science and skills as defined by the National Science Education Standards and Benchmarks for Science Literacy. The six modules, Cosmic Evolution, Planetary Evolution, Origin of Life, Evolution of Life, Hominid Evolution, and Evolution of Technology, use the constructivist approach of engage, explore, explain, elaborate, and evaluate (Biological Sciences Curriculum Study, 1996) as an instructional framework. NAI Central funded the VTT National Field Test and a CD−ROM sampler of the curriculum. Over 1500 CD−ROM samplers were distributed at science teacher conferences this year and a revised sampler will be distributed next year. The National Field Test took place from September 2001 through July 2002 in over 80 classrooms in 28 states. Teacher feedback was very positive, and the curriculum was revised following the national test evaluation summary reports. The curriculum was published in August 2003. More information about VTT can be found at http://www.voyagesthroughtime.org.

Yellowstone National Park Offers The Public A Portal To Astrobiology

NAI Central provided funding support to the Ames Astrobiology team to work with Yellowstone National Park (YNP) on a tiered, long term, public engagement program that includes exhibits, literature, field experiences, educator workshops, and "fireside chats" with astrobiologists that will reach the three million visitors of all ages who experience YNP each year. Understanding how life began on Earth is a natural starting point for

astrobiology. Yellowstone is providing insights into the origin and evolution of life and the potential for life to exist beyond Earth. Biochemical clues hint that early life might have lived in high−temperature environments, including hot springs. The park's hot springs provide a glimpse into the nature of the early biosphere. Ancient spring alcoves on the flanks of Martian volcanoes invite comparisons with YNP, whose fossil−rich sinter spring deposits may, in turn, resemble deposits on Mars. The NAI team is working with Yellowstone staff on several projects within the park including the development of ten exhibits that will illustrate astrobiology throughout the trails in Yellowstone. The team is also developing chapters on astrobiology and microbiology for the Yellowstone Resources and Issues Guide, which is a training manual for the interpretive research staff used to develop hikes and talks for the public. The Guide will be published and available for purchase from the gift stores throughout the park. It will also be available for virtual visitors through research libraries in the national park system, the Yellowstone National Park Web site and the NAI site. The team is also developing exhibit ideas to go into a planned new visitor center at Old Faithful geyser basin. This partnership with YNP is helping the general public to enhance their knowledge and skills and to access NASA research in astrobiology, including geology, microbiology, and space missions.

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Members: NAI Central

Team Members sorted by current team.

Name:	Shige Abe
Email:	sabe@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Marco Boldt
Email:	mboldt@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Karen Bradford
Email:	kbradford@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Estelle Dodson
Email:	kdodson@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Wendy Dolci
Email:	wdolci@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Lisa Faithorn
Email:	lfaithorn@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Kaye Faria
Email:	kfaria@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Julie Fletcher

Email:	jfletcher2@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Darlene Gadd
Email:	dgadd@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Edward Goolish
Email:	egoolish@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Patricia Gregory
Email:	pgregory@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Rose Grymes
Email:	rgrymes@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Jeni Joiner
Email:	jjoiner@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	David Morrison
Email:	David.Morrison@nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Janet Morrison
Email:	jmorrison@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Bruce Runnegar
Email:	brunnegar@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute
Name:	Krisstina Wilmoth

Email:	kwilmoth@mail.arc.nasa.gov
Institution:	NASA Astrobiology Institute