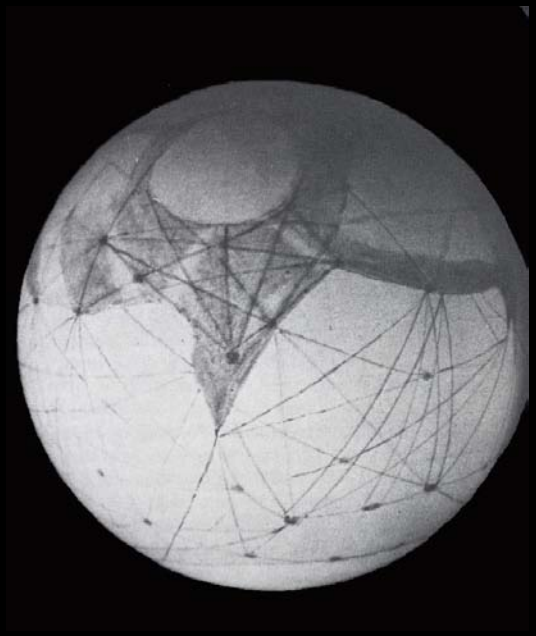
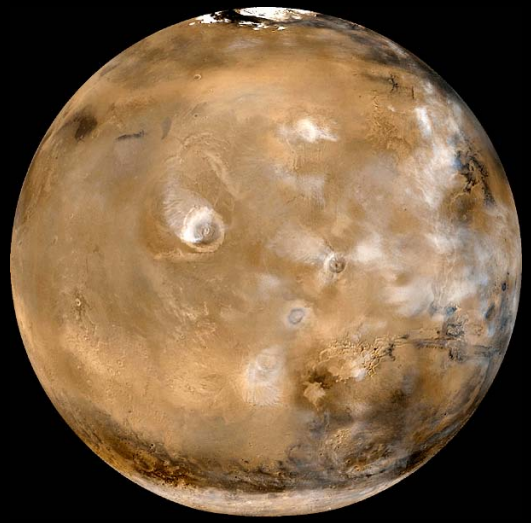
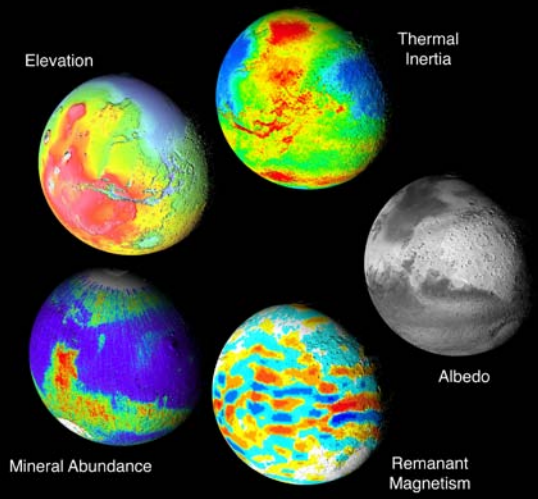
Future Mars Exploration for Habitable Environments and Life



Percival Lowell's Mars 1908



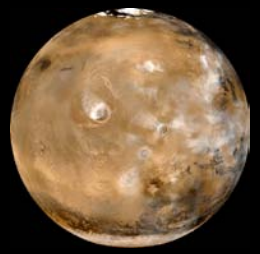
Mars 2000



Future Mars

David J. Des Marais
NASA Ames Research Center

+ the MER Athena and MRO CRISM teams, and many others



Mars Exploration Program Goals

Mars Exploration Program Analysis Group

1. Determine if life ever arose on Mars

(prebiotics, past & extant life, long-term evolution of Mars)

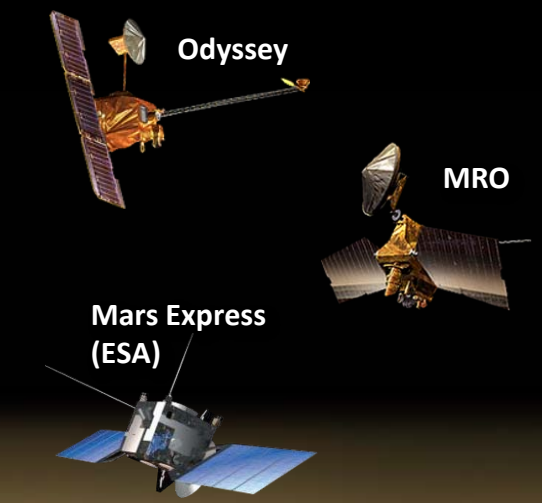
2. Understand the processes and history of climate on Mars

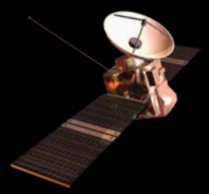
3. Determine the evolution of the surface and interior of Mars

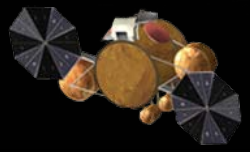
4. Prepare for human exploration

Launch Year

2000 to Present	2011	2013	2016	2018	2020 & Beyond
Odyssey, MRO, Mars Express (ESA)		MAVEN	TGO (ESA-NASA)		Mars Sample Return







Recent missions have discovered that Mars' surface reveals a diverse and dynamic history, including evidence for sustained interactions with liquid water.

By studying a potentially habitable, ancient environment, MSL is a bridge to future missions that focus on life detection or returning samples.

MEPAG Goal 1: Determine if life ever arose on Mars

Objective A. Characterize past habitability and search for evidence of ancient life

1. Characterize the prior habitability of environments, with a focus on resolving more habitable vs less habitable sites (establish geologic context, water availability, energy availability, bio-essential elements, and physicochemical environment)

2. Assess the potential of various environments to enhance preservation or hasten degradation of biosignatures; identify sites having high preservation potential (determine processes that degrade or preserve organics, physical structures, and chemical, mineralogical or isotopic indicators of metabolism)

3. Search for evidence of ancient life in environments having high combined potential for prior habitability and preservation of biosignatures (document any organic compounds, biophysical structures, and chemical, mineralogical or isotopic indicators of metabolism)

MEPAG Goal 1: Determine if life ever arose on Mars

Objective B. Characterize present habitability and search for evidence of extant life

1. Identify and characterize any presently habitable environments (establish geologic context, water availability, energy sources, bioessential elements, physicochemical conditions over time)

2. Assess the potential of various environments to enhance preservation or hasten degradation of biosignatures of extant life (determine processes that degrade or preserve types of biosignatures in surface regolith/rocks, evaluate conditions at depth with respect to biosignature degradation or degradation)

3. Search for evidence of ancient life in environments having high combined potential for habitability and preservation of biosignatures (e.g., seek evidence of ongoing metabolism, organic compounds, bioessential elements, stereochemistry, and bio-organic or biomineral structures)

MEPAG Goal 1: Determine if life ever arose on Mars

Objective C. Determine how the long-term evolution of Mars affected prebiotic chemistry and habitability

1. Characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs

2. Constrain evolution in the geological, geochemical, and photochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly as it bears on provision of chemical energy and … bioessential elements

3. Constrain the nature and abundance of possible energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions

4. Evaluate the presence and magnitude of oxidative or radiation hazards at the surface and in the shallow crust

Conditions That Could Sustain Life on Mars: Changes Over the Eons

MSL: Curiosity's Capabilities

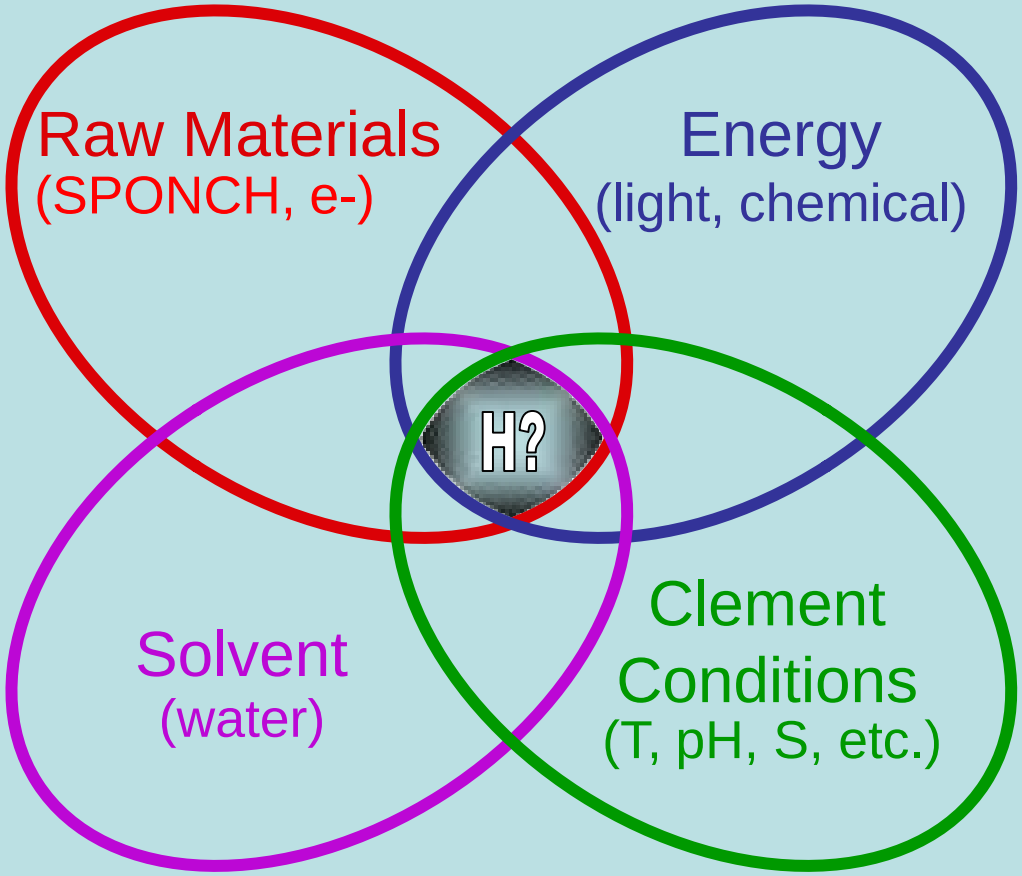
A Robotic Field Geologist

- Long life, ability to traverse many miles over rocky terrain
- Landscape and hand-lens imaging
- Ability to survey composition of bedrock and regolith

A Mobile Geochemical and Environmental Laboratory

- Ability to acquire and process dozens of rock and soil samples
- Instruments that analyze samples for chemistry, mineralogy, and organics
- Sensors to monitor water, weather, and natural high-energy radiation

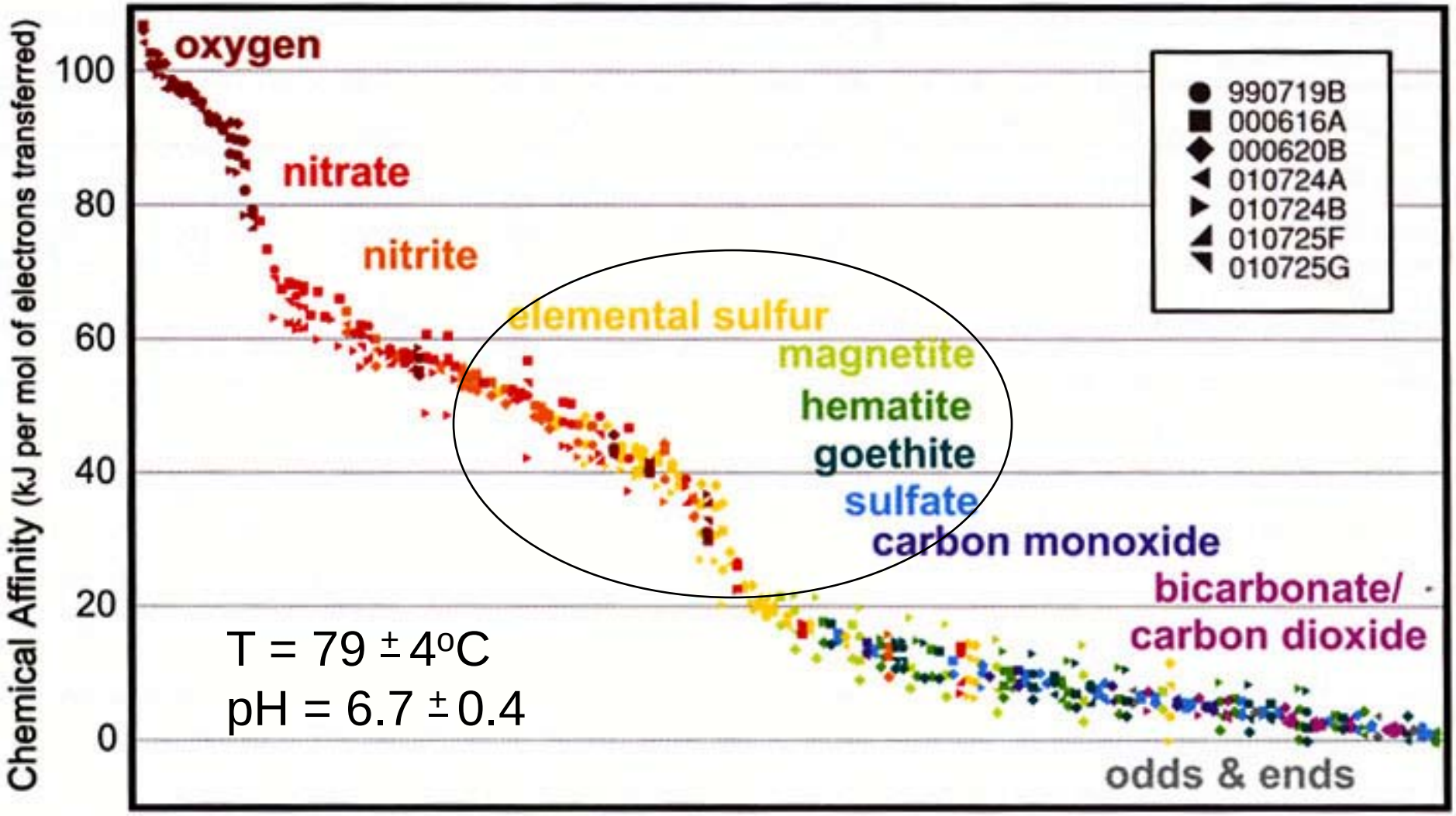
Requirements for Habitability (H)



Tori Hoehler

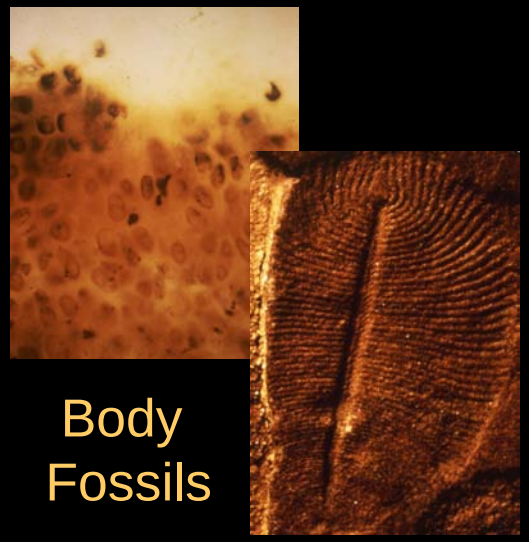
Energy for Life

Obsidian Spring, Yellowstone National Park

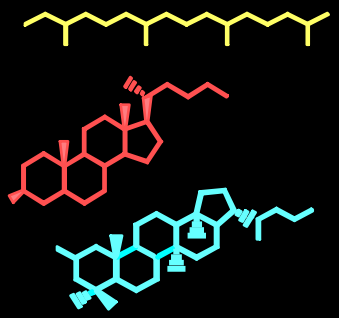


Shock, Holland, Meyer-Dombard & Amend (2005)

Biosignatures: what we look for…

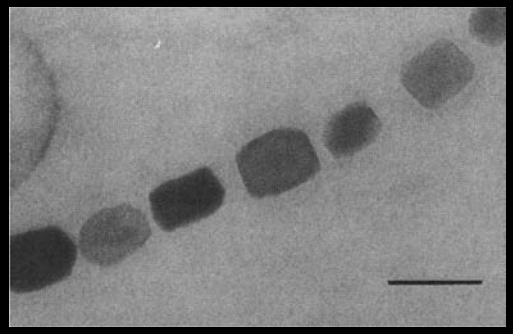


Body Fossils



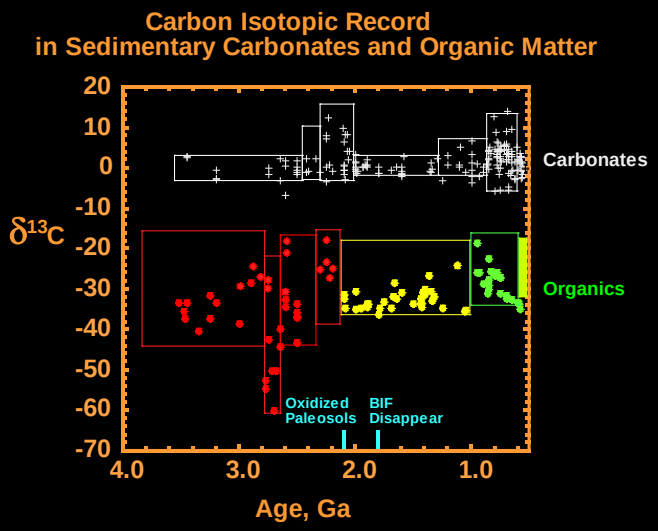
Chemical Fossils (Biomarkers)

Biofabrics



Biominerals

Atmospheric Gases



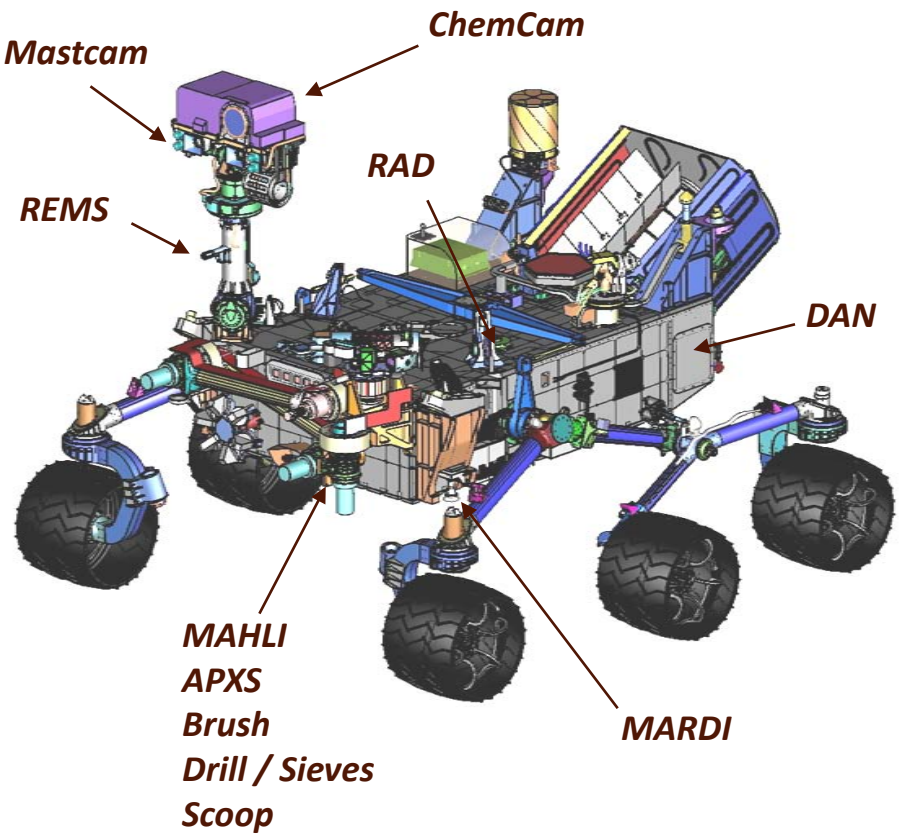
Stable Isotopes

Minerals & Rocks that Preserve Fossil Records

Residence Time		Dominant Process Controlling Loss
	Least Stable	
$<1 \times 10^4$ yrs	Ice	Climatic warming
$<1 \times 10^6$ yrs	Halides, sulfates	Dissolution
$<2 \times 10^8$ yrs	Metallic sulfides	Oxidation
$<3.5 \times 10^8$ yrs	Clay-rich shales Water-laid pyroclastics Marine carbonates Metallic oxides	Metamorphism Recrystallization Dissolution
$<3.8 \times 10^8$ yrs	Phosphates Silica	Deep burial Recrystallization Metamorphism
	Most Stable	

Farmer & Des Marais (1999)

Mars Science Laboratory Rover - Payload



Rover Width:	**2.8 m**
Height of Deck:	**1.1 m**
Ground Clearance:	**0.66 m**
Height of Mast:	**2.2 m**

REMOTE SENSING

Mastcam (M. Malin, MSSS) - Color and telephoto imaging, video, atmospheric opacity

ChemCam (R. Wiens, LANL/CNES) – Chemical composition; remote micro-imaging

CONTACT INSTRUMENTS (ARM)

MAHLI (K. Edgett, MSSS) – Hand-lens color imaging

APXS (R. Gellert, U. Guelph, Canada) - Chemical composition

ANALYTICAL LABORATORY (ROVER BODY)

SAM (P. Mahaffy, GSFC/CNES) - Chemical and isotopic composition, including organics

CheMin (D. Blake, ARC) - Mineralogy

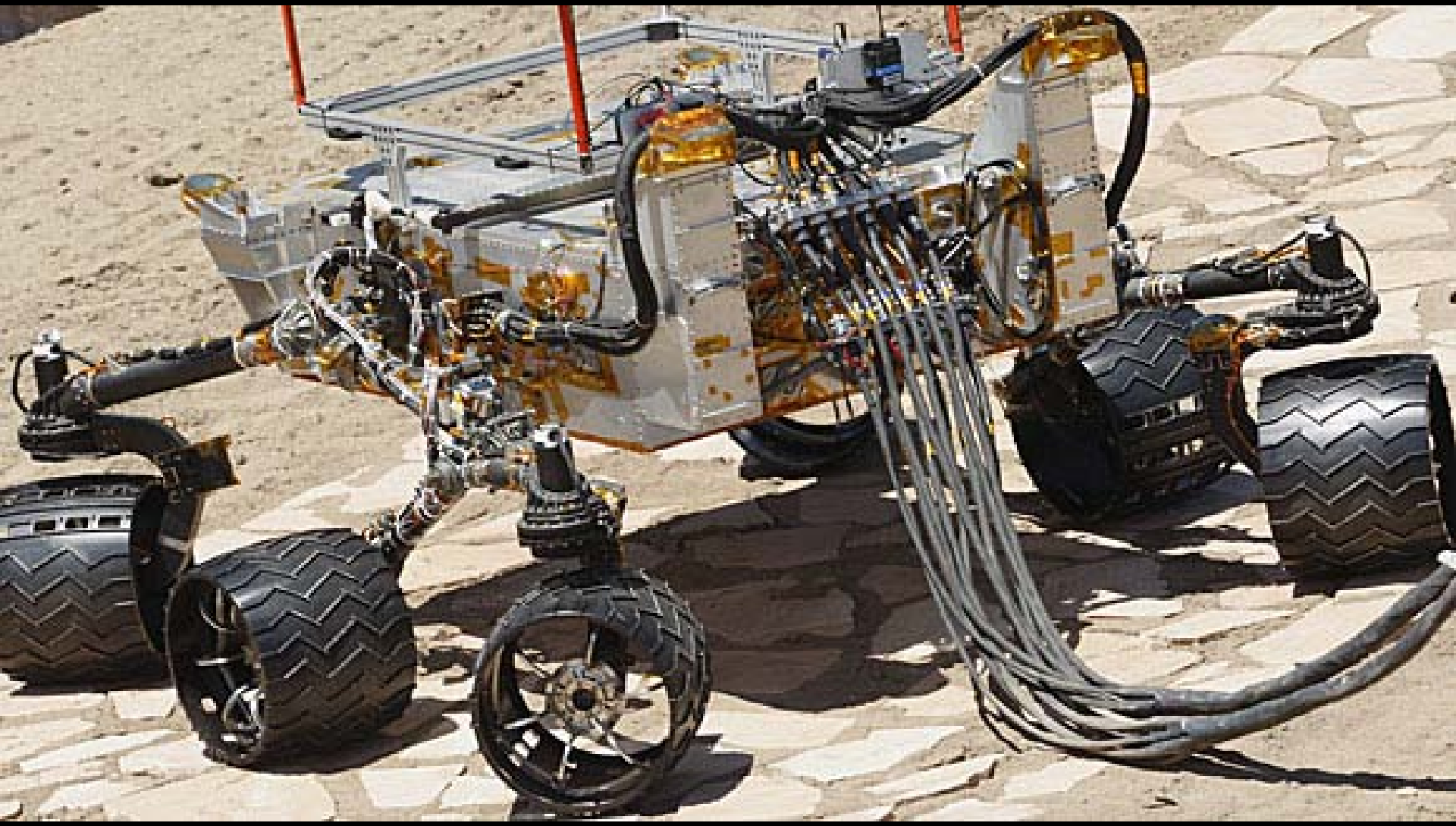
ENVIRONMENTAL CHARACTERIZATION

MARDI (M. Malin, MSSS) - Descent imaging

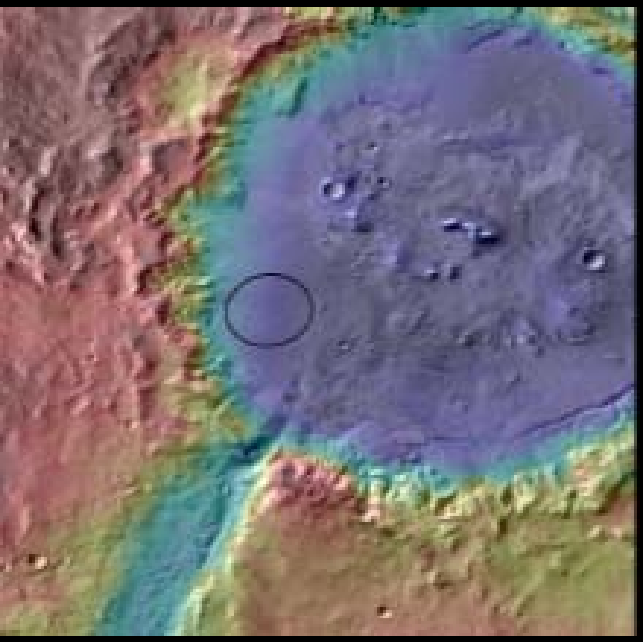
REMS (J. Gómez-Elvira, CAB, Spain) - Meteorology / UV

RAD (D. Hassler, SwRI) - High-energy radiation

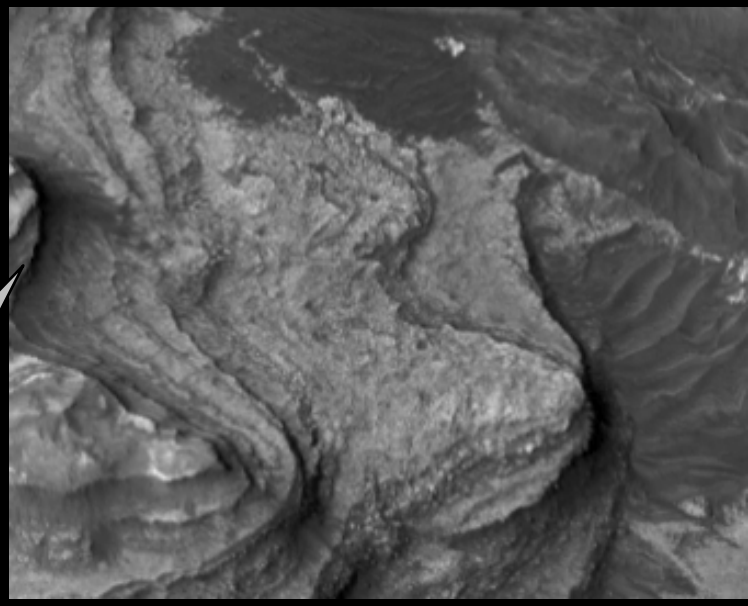
DAN (I. Mitrofanov, IKI, Russia) - Subsurface hydrogen



Candidate MSL Landing Sites

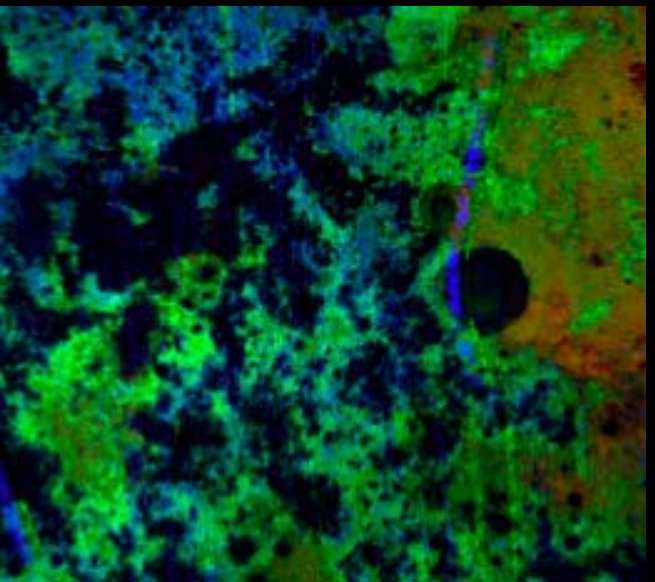


Holden crater:
bedrock
outcrops, alluvial fans, rich history of aqueous processing

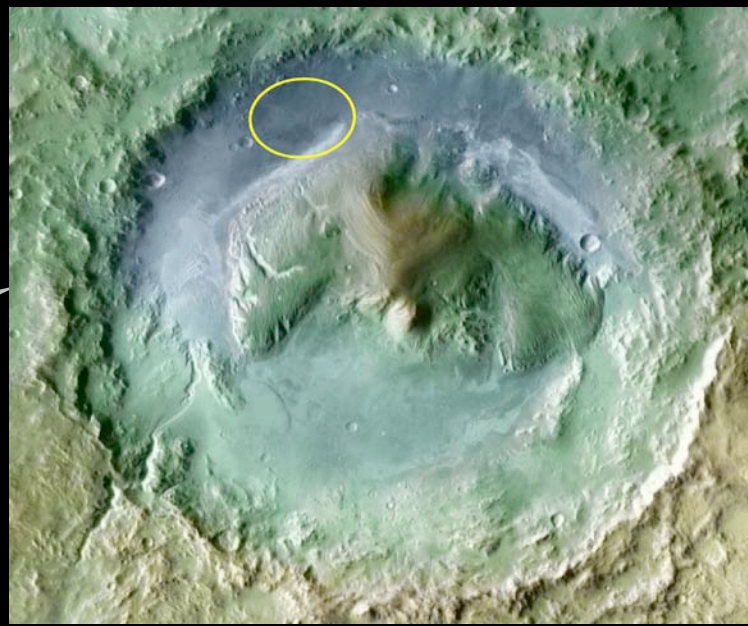


Eberswalde crater:
well defined delta suggests long duration water flow

Mawrth: strong CRISM and OMEGA signatures of Fe/Mg and Al phylosilicates – may be good preservation environment for organics



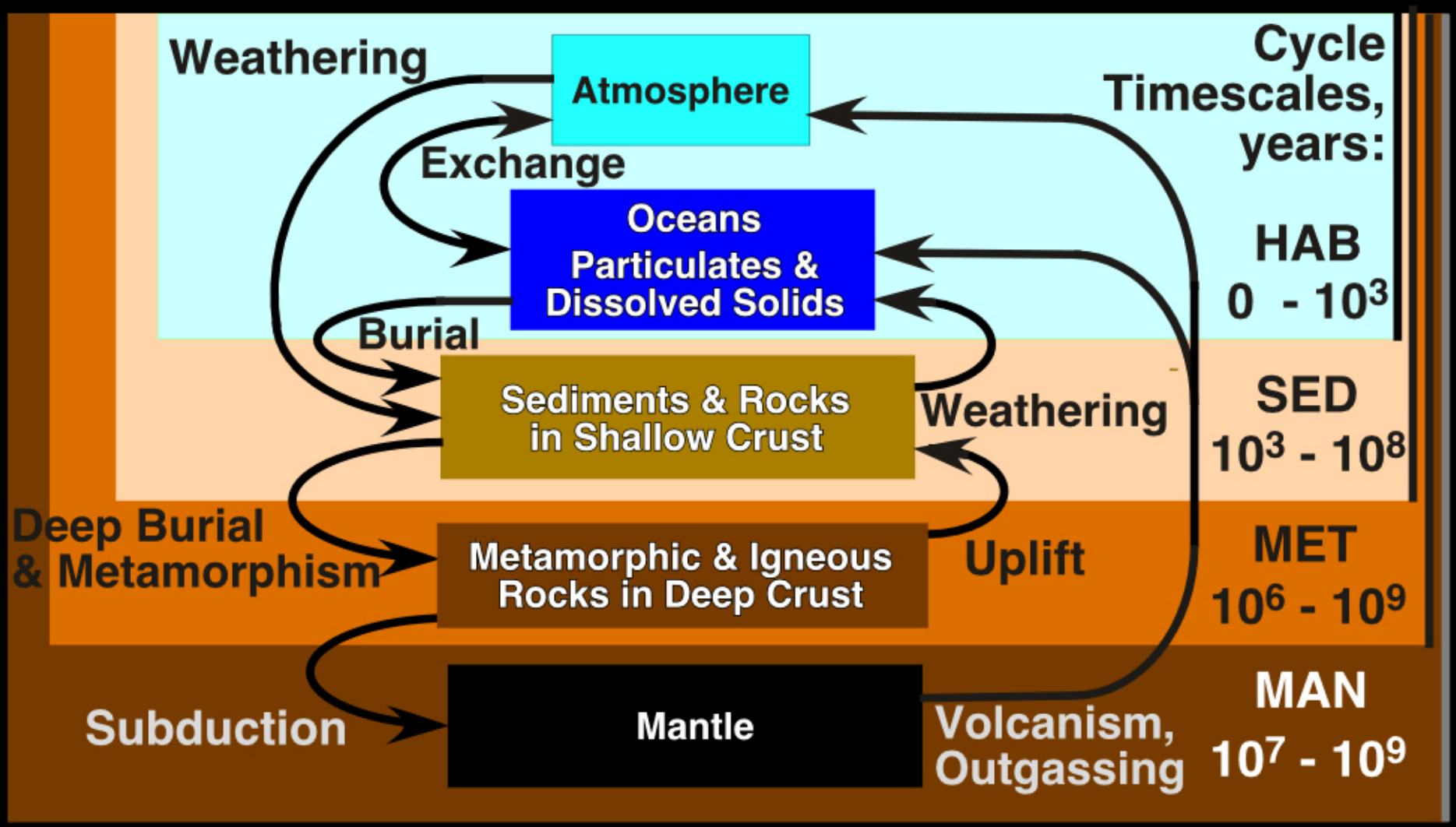
Gale crater: diversity of mineralogy in well defined layered sequences that could be traversed by MSL



Conditions That Could Sustain Life on Mars: Changes Over the Eons

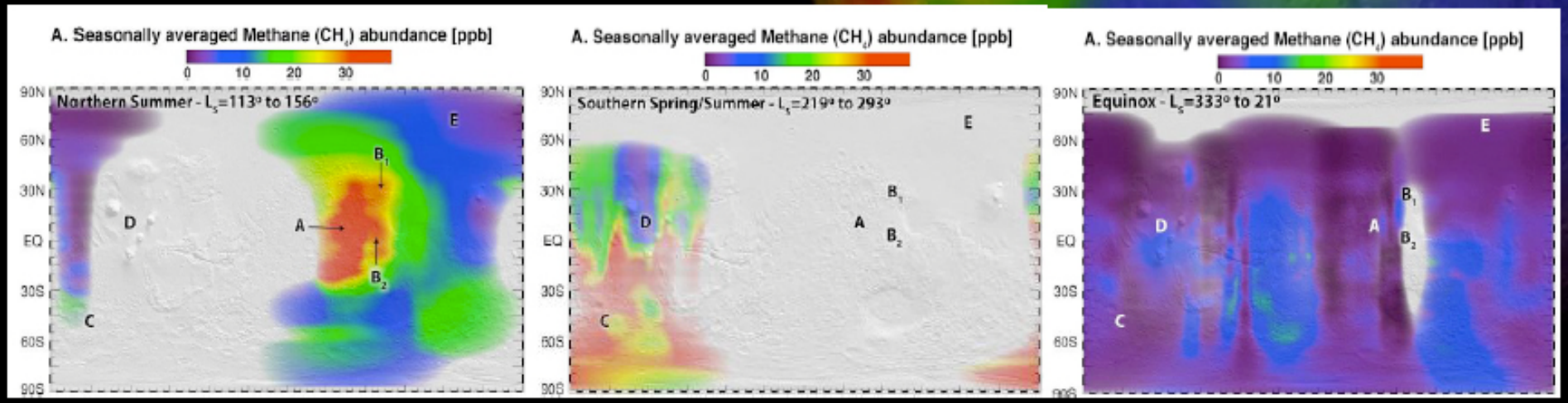
Subsurface aqueous activity today?
Atmospheric indicators?

Geochemical Cycles



Martian Methane: Issues (Forget et al.)

- The "conventional" atmospheric chemistry does not produce measurable methane variations on Mars, even in the case of a current, episodic, and localized source.
- The condensation/sublimation cycle of CO_2 should generate large-scale methane variations at high latitudes (*but they differ from what is observed*).
- CSHELL/NIRSPEC: In the most favourable case, an atmospheric CH_4 lifetime of less than 200 days (seasonal release) or ~2 Earth years (single event) is necessary to reproduce the observations.



Jan-Mar 2003 (MY26) | May-June 2005 (MY27) | Jan-Mar 2006 (MY27-28)

Martian Methane: Issues (Forget et al.)

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- CSHELL/NIRSPEC: In the most favourable case, an atmospheric CH_4 lifetime of less than 200 days (seasonal release) or ~2 Earth years (single event) is necessary to reproduce the observations.

- PFS: measurements at high latitudes require a lifetime of less than ~3 Earth years. Longitudinal variations at high latitudes and seasonal trends at mid-to-low latitudes cannot be reproduced.

- The CH_4 source: quantitative agreement with the observations requires considerable amounts:

~150 000 tonnes	CSHELL/NIRSPEC, seasonal release
~ 80 000 tonnes	CSHELL/NIRSPEC, single event
~ 50 000 tonnes	PFS, polar summer

Mid-Atlantic Ridge: 50 000-130 000 t yr^{-1} (Keir et al., 2005)

ExoMars 2016 Trace Gas Orbiter Instruments

MATMOS - **M**ars **A**tmospheric **T**race **M**olecule **O**ccultation **S**pectrometer

An infrared spectrometer coupled with a solar imager to detect very low concentrations of molecular constituents of the Martian atmosphere and map their distribution from solar occultations.

Principal Investigator: Paul Wennberg, California Institute of Technology, USA
Co-Principal Investigator: Victoria Hipkin, Canadian Space Agency, Canada
Participating countries: United States of America, Canada.

NOMAD – **N**adir and **O**ccultation for **MA**rs **D**iscovery

A spectrometer suite, covering a wide range of wavelengths (infrared, ultraviolet and visible), to identify the components of the Martian atmosphere.

Principal Investigator: Ann Carine Vandaele, Belgian Institute for Space Aeronomy, Belgium
Co-Principal Investigator: Giancarlo Bellucci, Istituto Nazionale di Astrofisica, Italy
Co-Principal Investigator: José Lopez Moreno, Instituto de Astrofísica de Andalucía, Spain
Co-Principal Investigator: Manish Patel, The Open University, United Kingdom
Participating countries: Belgium, Italy, Spain, United Kingdom, United States of America, Canada.

EMCS - **E**xo**M**ars **C**limate **S**ounder

An infrared radiometer to provide daily global measurements of temperature, pressure, dust, ice, and water vapour in the atmosphere to aid the analysis of the spectrometer data.

Principal Investigator: John Schofield, Jet Propulsion Laboratory, USA
Participating countries: United States of America, United Kingdom, France.

MAGIE - **M**ars **A**tmospheric **G**lobal **I**maging **E**xperiment

A wide-angle multi-spectral camera to provide global images in support of the other instruments.

Principal Investigator: Bruce Cantor, Malin Space Science Systems, USA
Participating countries: United States of America, Belgium, France, Russia.

HiSCI - **Hi**gh-resolution **S**tereo **C**olour **I**mager

A camera designed to take three-dimensional images of active processes (such as volcanism) that occur on the Martian surface and that are thought to release gases that could provide evidence of possible life on Mars.

Principal Investigator: Alfred McEwen, University of Arizona, USA
Co-Principal Investigator: Nicolas Thomas, University of Bern, Switzerland
Participating countries: United States of America, Switzerland, United Kingdom, Italy, Germany, France.

Mars Exploration Program's Evolving Strategy

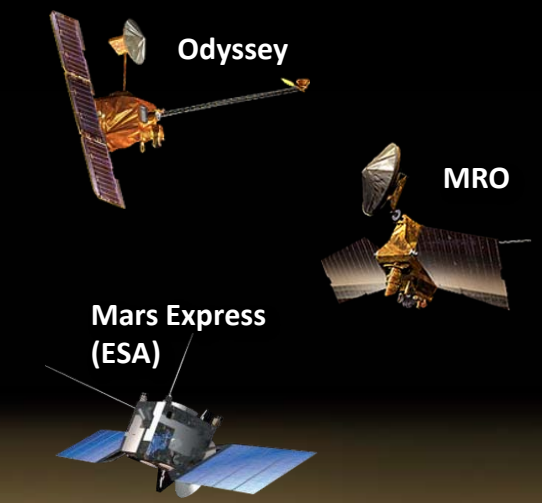
Prior Strategy: Multiple missions have addressed 'follow the water' and 'evaluate habitable environments' themes.

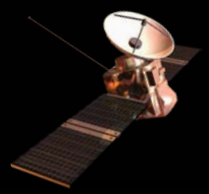
Result: Orbital and landed missions have revealed multiple terrain types with diverse evidence interpreted to indicate water and habitability potential.

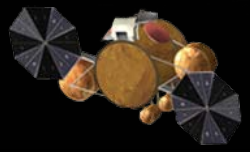
Strategic response: Plan a landed mission to seek possible signs of life or prebiotic chemistry in a 'high habitability potential' environment.

Launch Year

2000 to Present	2011	2013	2016	2018	2020 & Beyond
Odyssey, MRO, Mars Express (ESA)		MAVEN	TGO (ESA-NASA)		Mars Sample Return







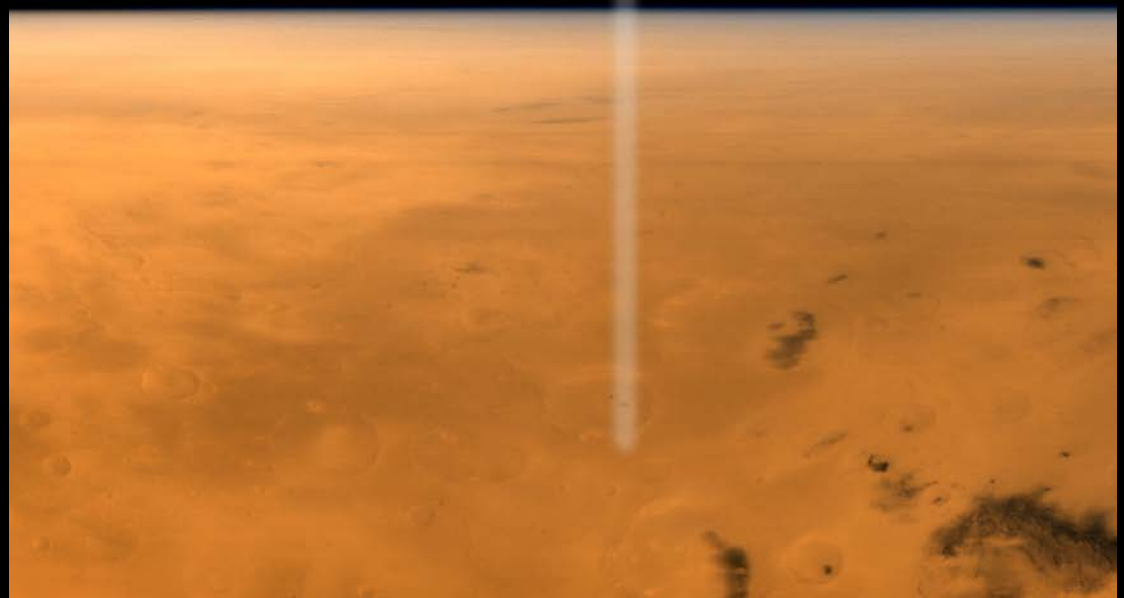
Recent missions have discovered that Mars' surface reveals a diverse and dynamic history, including evidence for sustained interactions with liquid water.

By studying a potentially habitable, ancient environment, MSL is a bridge to future missions that focus on life detection or returning samples.

Astrobiology

Mars Sample Return

bringing Mars to Earth



Sample Return is the Next Step

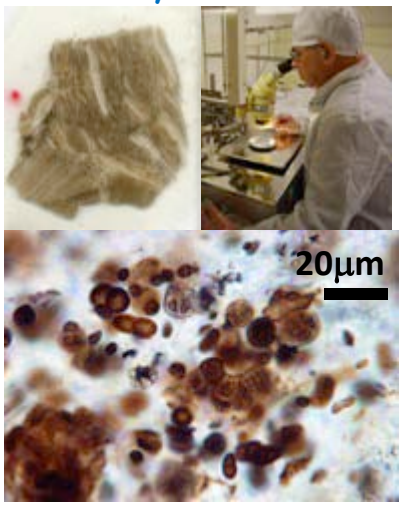
From ***Vision and Voyages for Planetary science in the Decade 2013-2022:***

"The analysis of carefully selected and well documented samples from a well characterized site [on Mars] will provide the highest scientific return on investment for understanding Mars in the context of solar system evolution and addressing the question of whether Mars has ever been an abode of life."

Committee on the Planetary Science Decadal Survey; National Research Council, March 2011

Reasons for returning samples for analysis on Earth…

Could use advanced instrumentation not amenable for flight to Mars.



Could employ techniques requiring complex sample preparation.

Could use a virtually unlimited array of different instruments, including future instruments not yet even designed.

Adapted from iMARS (2008); NRC Decadal Survey (2011)

Pre-decisional: for discussion purposes only

MSR Science Objectives – Prioritization

The science objectives were prioritized using the criteria below:

Top-level Prioritization Criterion:

✧ **The value of the incremental knowledge to be gained by returned sample analysis**

Ways in which returned sample analysis adds value (sub-criteria):

1. **Addresses science questions of high intrinsic priority (e.g. as judged by MEPAG, NRC, SSB, NASA & ESA Strategic Plans, etc.)**
2. **Address questions for which little meaningful progress can be made without sample return**
   a) Instrumentation hard/impossible to miniaturize or make robust enough for interplanetary flight
   b) Scale of investigation not amenable for in situ
   c) Sample prep impossibly complex
3. **Answers have higher definitiveness**
   a) Better accuracy, precision
   b) Results confirmed by alternate methods
4. **Addresses questions for which there is an advantage if the analytical approach can be discovery-responsive (analysis pathway not limited by instrument payload).**

Pre-decisional: for discussion purposes only

Prioritized Scientific Objectives, MSR

in Priority Order

1	Critically assess any evidence for past life or its chemical precursors, and place detailed constraints on the past habitability and the potential for preservation of the signs of life
2	Quantitatively constrain the age, context and processes of accretion, early differentiation and magmatic and magnetic history of Mars.
3	Reconstruct the history of surface and near-surface processes involving water.
4	Constrain the magnitude, nature, timing, and origin of past planet-wide climate change.
5	Assess potential environmental hazards to future human exploration.
6	Assess the history and significance of surface modifying processes, including, but not limited to: impact, photochemical, volcanic, and aeolian.
7	Constrain the origin and evolution of the martian atmosphere, accounting for its elemental and isotopic composition with all inert species.
8	Evaluate potential critical resources for future human explorers.

Mandatory: Determine if the surface and near-surface materials contain evidence of extant life

Pre-decisional: for discussion purposes only

Four Stages of Sample Return

Sample Caching Rover

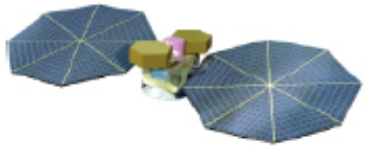
Launch from Earth/Land on Mars → Select Samples → Acquire/Cache Samples

Sample Canisters On Mars Surface *

Mars Sample Return Lander

Retrieve/Package Samples on Mars → Launch Samples to Mars Orbit

*Orbiting Sample (OS) in * Mars Orbit*



Mars Sample Return Orbiter

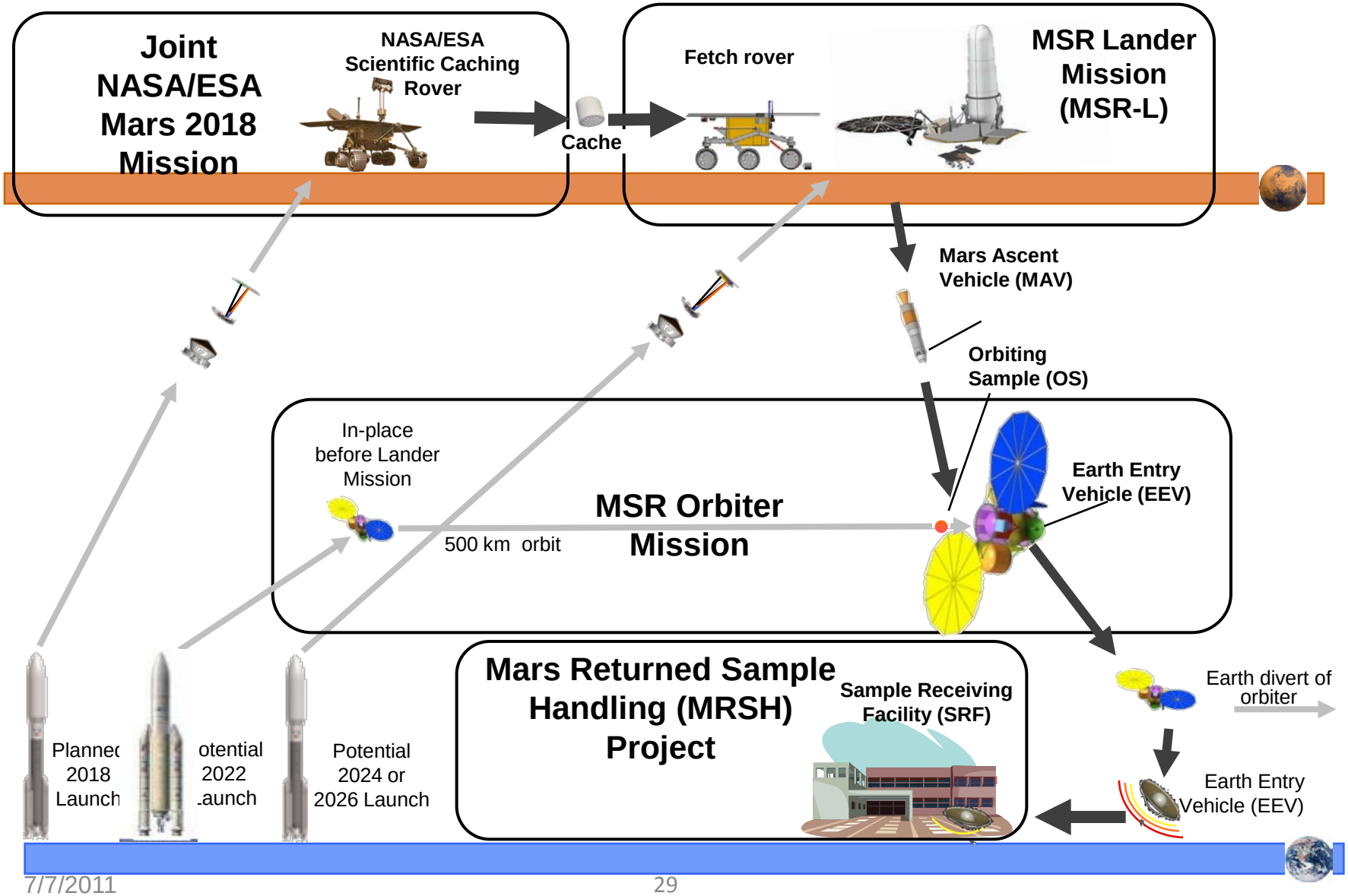
Capture and *Isolate* Sample Container → Return to Earth → Land on Earth

Orbiting Sample (OS) On Earth

Retrieve/Quarantine and Preserve Samples on Earth → Assess Hazards → Sample Science

**Note: Launch sequence of MSR-L/MSR-L can be switched: launching MSR-O first can provide telecom relay support for EDL/surface operation/MAV launch

A Proposed MSR Campaign – Joint NASA/ESA Planning



PRE-DECISION DRAFT: For Planning and Discussion Purposes Only

Sample Return: Overview

Prioritized MSR science objectives

Derived implications

- Samples required/desired to meet objectives
- Measurements on Earth

Critical Science Planning Questions for 2018

- Variations of interest?
- # of samples?
- Types of landing sites that best support the objectives?
- Sample size?
- Measurements needed to interpret & document geology and select samples?
- On-Mars strategies ?

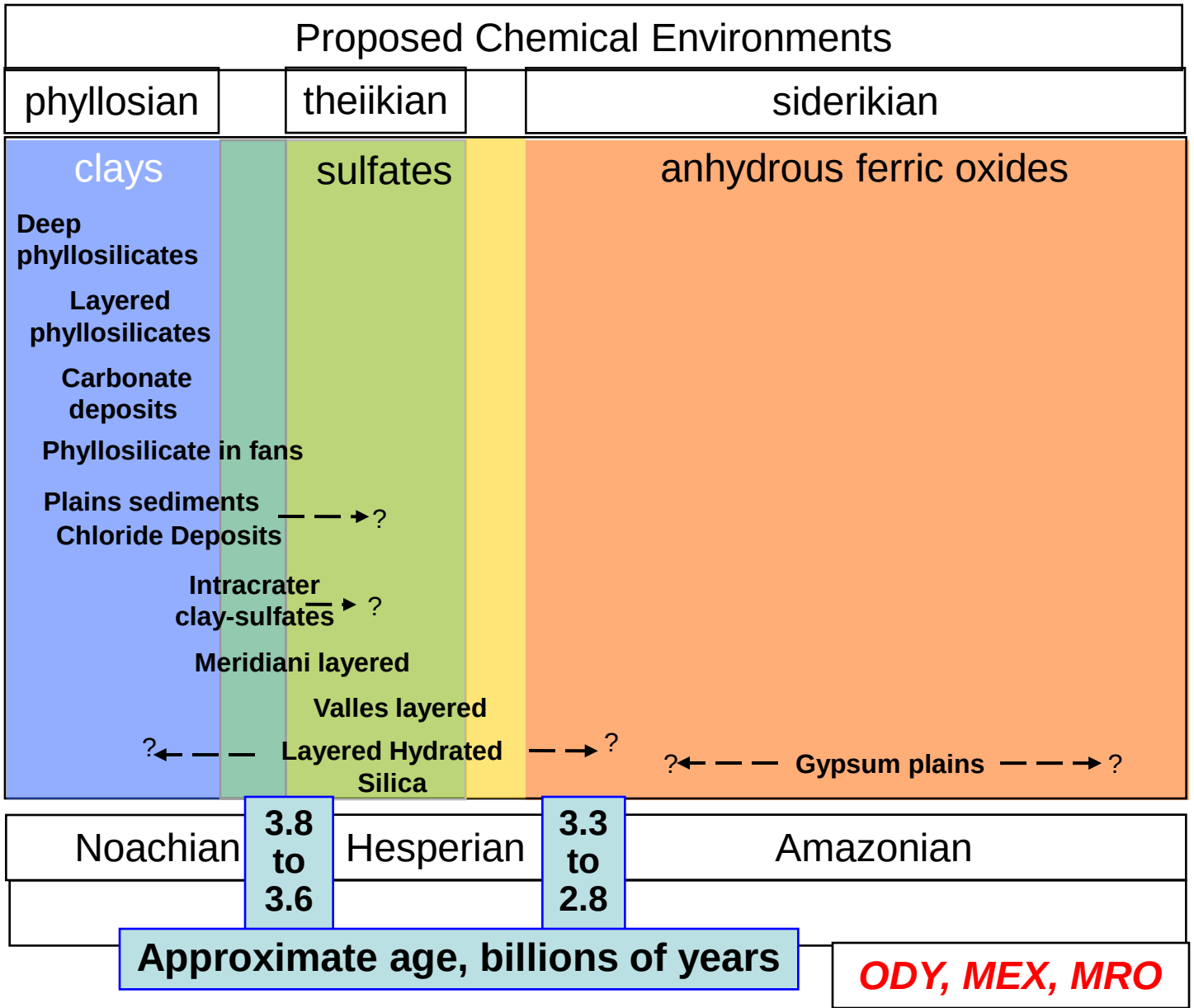
Engineering implications

- Sampling hardware
- Instruments on sampling rover
- EDL & mobility parameters, lifetime, ops scenario
- Sample preservation

Pre-decisional: for discussion purposes only

Past Decadal Results:

Mars Planetary Evolution

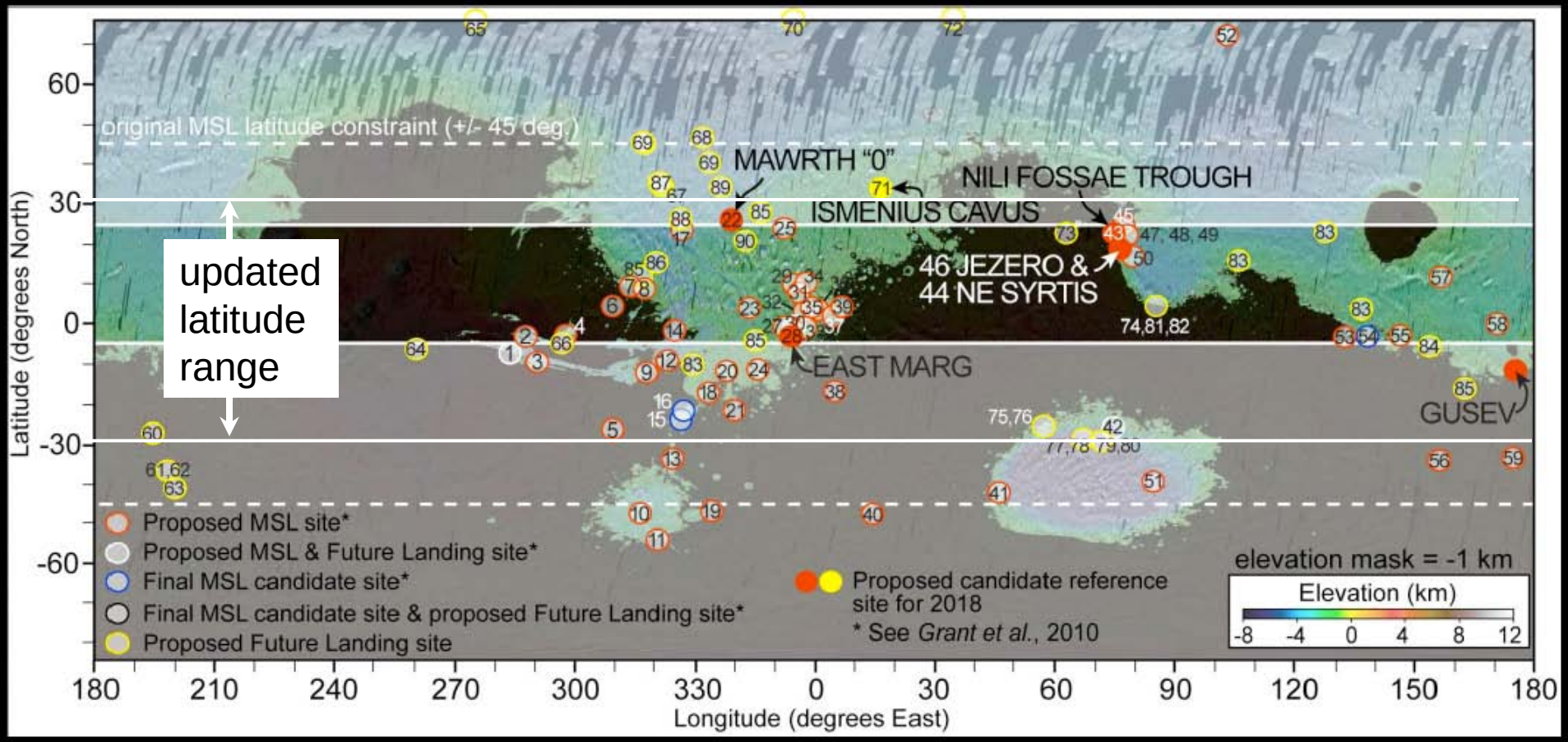


Coupled mineralogy and morphology define aqueous environments

Their character has evolved, indicating changing environments

Data support the hypotheses but indicate greater complexity in local environments

Potential Landing Sites



- Mask shows draft latitude and elevation constraints for MSR (as of Jan. 2011)
- All sites are community-proposed:
  - 59 sites from MSL landing site process, 26 sites from CDP future landing sites process
- Labeled sites are E2E-iSAG reference sites discussed on following slides

Sample Science General Principles: Sample Suites

1. Rock outcrops/geologic terrane have multiple properties that vary.
2. The variation that matters depends on the question, thus not all natural variations are equally important.
3. **A sample suite captures those variations whose measurements are required in order to characterize a particular process(es), environment or history.**
4. The differences between samples in a suite can be more important than their absolute values.

EXAMPLE: This suite is defined by variations in bulk chemistry

Sample collections designed around one or more sample suites maximize their potential for answering the highest priority scientific questions.

Extended from ND-SAG (2008); NRC Decadal Survey (2011)

Pre-decisional: for discussion purposes only

Regolith: Objectives and Priorities

PRIORITY ORDER

Goal IV sub-objectives (MEPAG Goals Document, 2010)

1. Determine if **extant life** is widely present in the martian near-surface regolith, and if the air-borne dust is a mechanism for its transport.
2. Assess the potential of regolith to be a **resource for hydrogen**.
3. Determine the possible **toxic effects of martian dust** on humans
   a) Assay for chemicals with known toxic effect on humans (e.g., Cr^{6+}).
   b) Characterize soluble ion distributions and reactions
   c) Analyze the shapes of martian dust grains to assess their possible impact on human soft tissue (especially eyes and lungs).
4. Characterize the particulates that could be **transported to hardware** through the air that could affect engineering performance (esp. seals, electrical properties, corrosion, bearings, and lifetime)

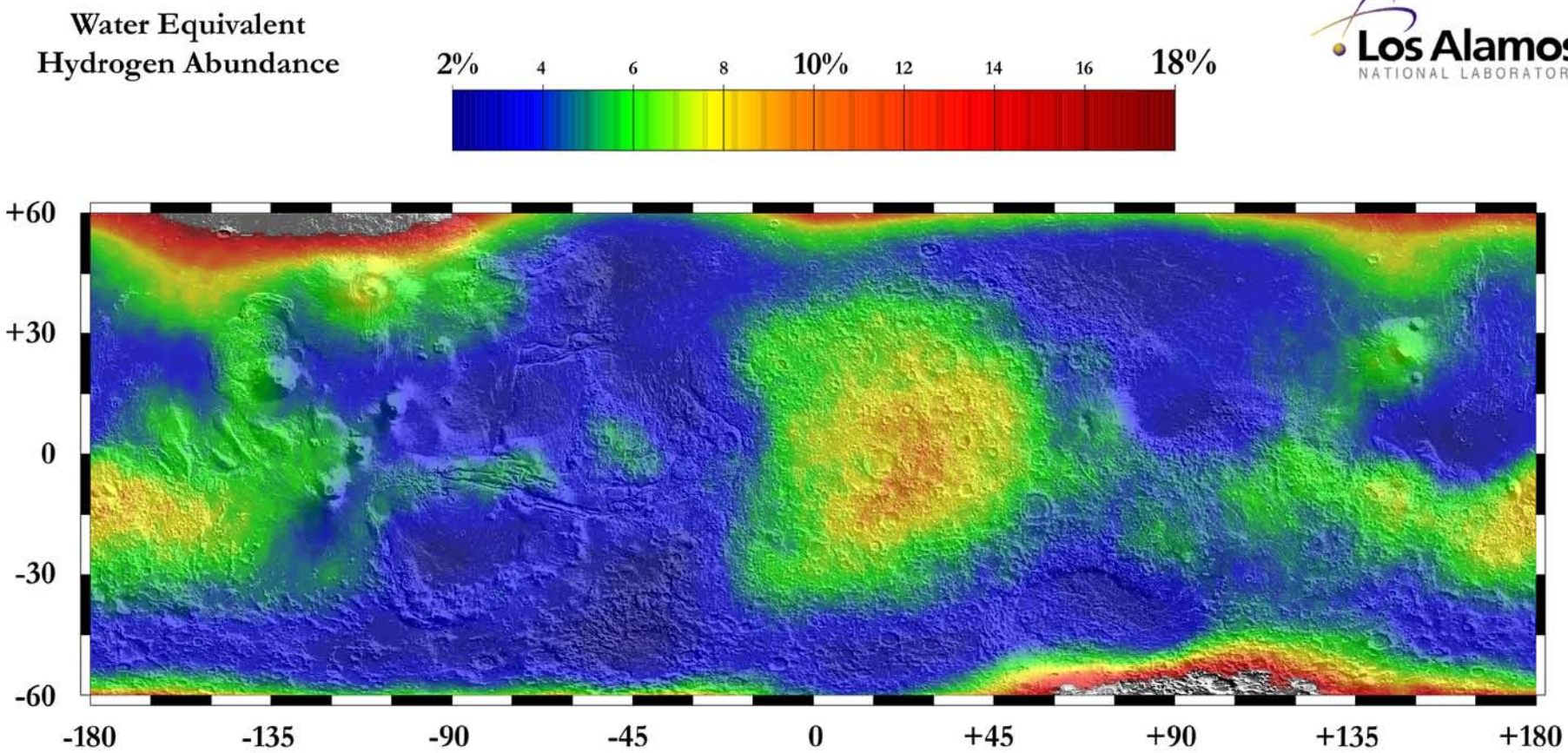
OTHER

Goal III sub-objectives (MEPAG Goals Document, 2010)

- Characterize the spectral properties of the regolith, since it is a filter through which we view most of the Martian surface by remote sensing.
- Interpret the history of surface conditions and processes.

Source: MEPAG Goals Document

Gamma Ray Spectrometer, Mars Odyssey orbiter, launched 2001



Distribution of Water on Mars: Overlay of water equivalent hydrogen abundances and a shaded relief map derived from MOLA topography. Mass percents of water were determined from epithermal neutron counting rates using the Neutron Spectrometer aboard Mars Odyssey between Feb. 2002 and Apr. 2003.

Reference: Feldman W. C., T. H. Prettyman, S. Maurice, J. J. Plaut, D. L. Bish, D. T. Vaniman, M. T. Mellon, A. E. Metzger, S. W. Squyres, S. Karunatillake, W. V. Boynton, R. C. Elphic, H. O. Funsten, D. J. Lawrence, and R. L. Tokar, The global distribution of near-surface hydrogen on Mars, *JGR-planets*, submitted July 2003.

These data were generated by the Planetary Science Team at Los Alamos: B. Barraclough, D. Bish, D. Delapp, R. Elphic, W. Feldman, H. Funsten, O. Gasnault*, D. Lawrence, S. Maurice*, G. McKinney, K. Moore, T. Prettyman, R. Tokar, D. Vaniman, and R. Wiens. * Also at Observatoire Midi-Pyrenees, France

The neutron spectrometer aboard Mars Odyssey, a component of the Gamma-ray Spectrometer suite of instruments, was designed and built by the Los Alamos National Laboratory and is operated by the University of Arizona in Tucson. The Mars Odyssey mission is managed by the Jet Propulsion Laboratory.

Relationship between gas questions and gas samples

QUESTIONS

origin and evolution of the martian atmosphere?

- **Paleo-atmosphere**
- **Loss of atmosphere** (N, Ne, Ar isotopes, $^{129}Xe/^{132}Xe$)
- **Age of atmosphere** (escape rate: e.g. $^{14}N/^{15}N$, $^{12}C/^{13}C$)
- **Loss of water**: How, when = climate evolution (D/H ratio)
- **Volcanic outgassing** (e.g. radiogenic isotopes ^{40}Ar, ^{129}Xe)

SAMPLES

Present-day atmosphere sample
High precision data on atmospheric noble gases + other volatile elements (e.g. Xe isotopic composition)

Paleoatmosphere samples and proxies

- **Chemical sediments** Mineralogy gives insight to volatile content of planet
- **Igneous rocks** Gas inclusions (noble gases, CO_2) → insight to magmatic volatile content, outgassing efficiency

Pre-decisional: for discussion purposes only

Extant Life Objective

It would be mandatory to analyze the returned samples for extant life: (a) in order to meet Planetary Protection requirements and (b) because of the scientific importance of detecting extant life, if any is present.

However the search for extant life is given low priority when it comes to sample and site selection because:

- There is an extremely low probability of extant life in any surface samples (low water activity, high UV, low temps, etc.)
- More hospitable environments that existed in the past, such as hydrothermal vents or lakes, are not active on Mars today.
- If organisms (resistant, dormant forms) are present near the surface, the criteria are unclear whereby sites and samples most likely to contain such forms could be identified.

In concurrence with MRR-SAG (2009), it is thought that the likelihood of life's existence near the martian surface is much greater in the past than the present, and that there are ways to locate high priority targets in ancient terranes. Therefore the focus for exploration should be on ancient rocks rather than modern environments.

DRAFT FINDING #1: Analyses of returned samples for extant life will be a high priority science objective, but we don't have a logical way to effectively incorporate this into sample selection on Mars.

Pre-decisional: for discussion purposes only

MEPAG Goal 1: Determine if life ever arose on Mars

Objective B. Characterize present habitability and search for evidence of extant life

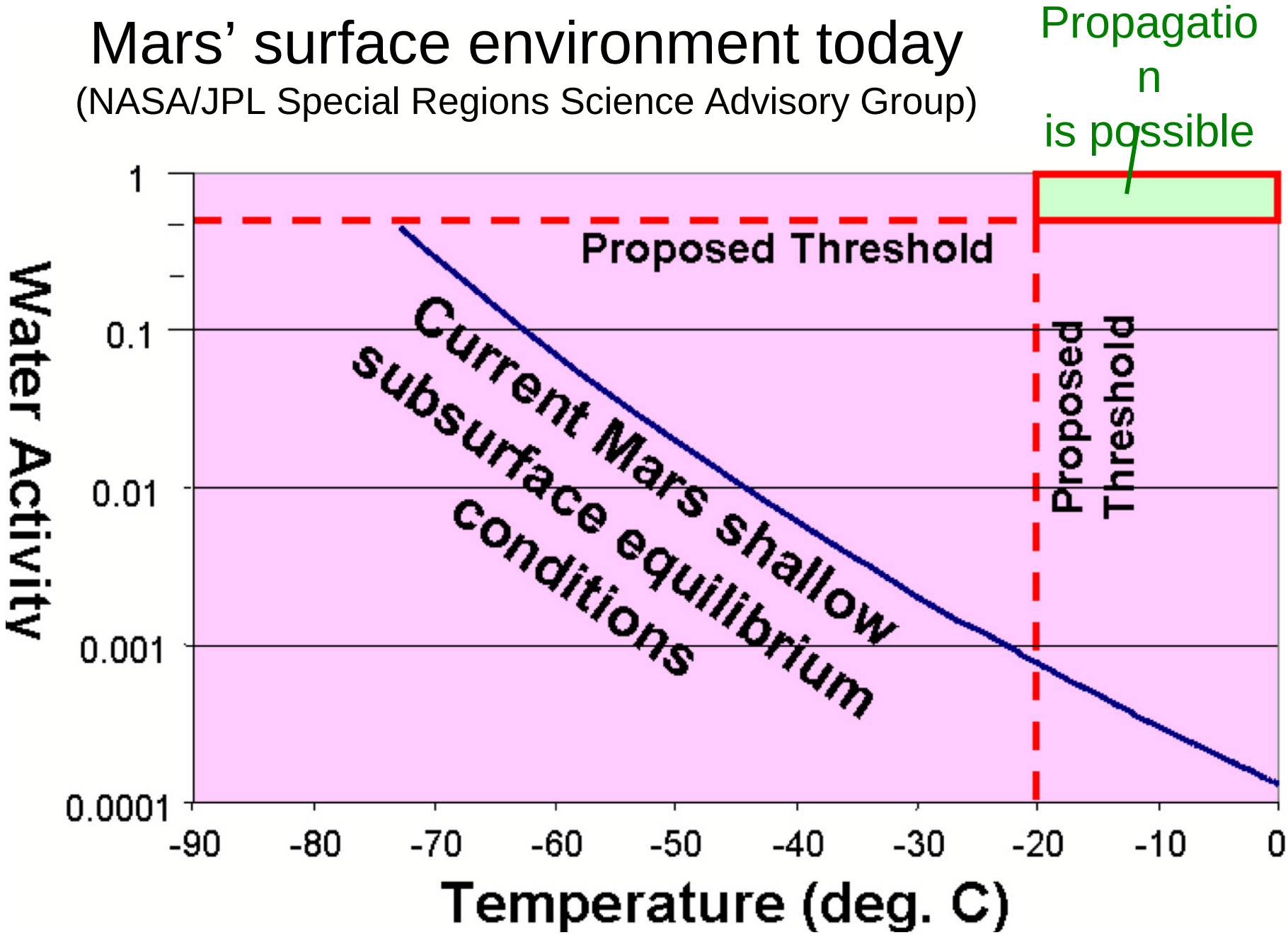
1. Identify and characterize any presently habitable environments (establish geologic context, water availability, energy sources, bioessential elements, physicochemical conditions over time)

2. Assess the potential of various environments to enhance preservation or hasten degradation of biosignatures of extant life (determine processes that degrade or preserve types of biosignatures in surface regolith/rocks, evaluate conditions at depth with respect to biosignature degradation or degradation)

3. Search for evidence of ancient life in environments having high combined potential for habitability and preservation of biosignatures (e.g., seek evidence of ongoing metabolism, organic compounds, bioessential elements, stereochemistry, and bio-organic or biomineral structures)

Mars' surface environment today

(NASA/JPL Special Regions Science Advisory Group)



ExoMars 2018 Instruments (1)

PanCam - The **Pan**oramic **Cam**era

To perform digital terrain mapping of Mars.

Principal Investigator: Andrew John Coates, MSSL/University College London, London, United Kingdom
Co-Principal Investigator (High Resolution Camera): Ralf Jaumann, DLR/IPF, Berlin, Germany
Co-Principal Investigator (Wide Angle Cameras): Jean-Luc Josset, Institute for Space Exploration, Neuchâtel, Switzerland.

MOMA – **M**ars **O**rganic **M**olecule **A**nalyser

It will target biomarkers to answer questions related to the potential origin, evolution and distribution of life on Mars.

Principal Investigator: Fred Goesmann, Max-Planck-Institute for Solar System Research, Lindau, Germany
Co-Principal Investigator: Paul Mahaffy, Goddard Space Flight Center, Washington, United States of America
Co-Principal Investigator: Francois Raulin, University of Paris 12 and 7, Paris, France.

MicrOmega

A micro-imaging system designed to identify the mineralogical and the molecular composition of Martian samples.

Principal Investigator: Jean-Pierre Bibring, Institut d'Astrophysique Spatiale, Orsay, France
Co-Principal Investigator: Frances Westall, Centre de Biophysique Moléculaire, Orléans, France
Co-Principal Investigator: Nicolas Thomas, University of Bern, Switzerland.

MARS-XRD - **MARS X-R**ay **D**iffractometer

A combined X-ray diffractometer and fluorescence spectrometer to analyse the mineralogy and chemical composition of the Martian rocks and soil.

Principal Investigator: Lucia Marinangeli, IRSPS Universitá d'Annunzio, Pescara, Italy
Co-Principal Investigator: Ian Brian Hutchinson, University of Leicester /University of Brunel, United Kingdom.

Raman Spectrometer

To provide context information for the identification and characterisation of potential organic compounds that can be related with present or past signatures of life on Mars.

Principal Investigator: Fernando Rull Perez, Centro de Astrobiología, Unidad Asociada (CSIC-UVA), Spain
Co-Principal Investigator: Sylvestre Maurice, Laboratoire d'Astrophysique - Observatoire Midi-Pyrénées (LAOMP), France

ExoMars 2018 Instruments (2)

WISDOM - **W**ater **I**ce and **S**ubsurface **D**eposit **O**bservation **O**n **M**ars

To provide a detailed view of the subsurface structure of the Red Planet by imaging the upper layers of the Martian crust.

Principal Investigator: Valérie Ciarletti, LATMOS, France
Co-Principal Investigator: Svein-Erik Hamran, FFI, Norway
Co-Principal Investigator: Dirk Plettemeier, TU-Dresden, Germany.

Ma_MISS - **M**ars **M**ultispectral **I**mager for **S**ubsurface **S**tudies

Located inside the drill, it will contribute to the study of the Martian mineralogy and rock formation.

Principal Investigator: Angioletta Coradini, Institute for Interplanetary Space Physics, IFSI, Italy.

CLUPI - **Cl**ose - **UP** **I**mager

A camera system to acquire high-resolution colour close-up images of rocks, outcrops, drill fines and drill core samples.

Principal Investigator: Jean-Luc Josset, Space Exploration Institute, Neuchâtel, Switzerland
Co-Principal Investigator: Frances Westall, Centre de Biophysique Moléculaire, Orléans, France
Co-Principal Investigator: Beda Hofmann, Natural History Museum, Bern, Switzerland.

LMC - **L**ife **M**arker **C**hip

To detect specific molecules that may be associated with past or present life on Mars.

Principal Investigator: Mark R. Sims, University of Leicester, United Kingdom
Co-Principal Investigator: David C. Cullen, Cranfield University, United Kingdom.

MEPAG Goal 1: Determine if life ever arose on Mars

Objective C. Determine how the long-term evolution of Mars affected prebiotic chemistry and habitability

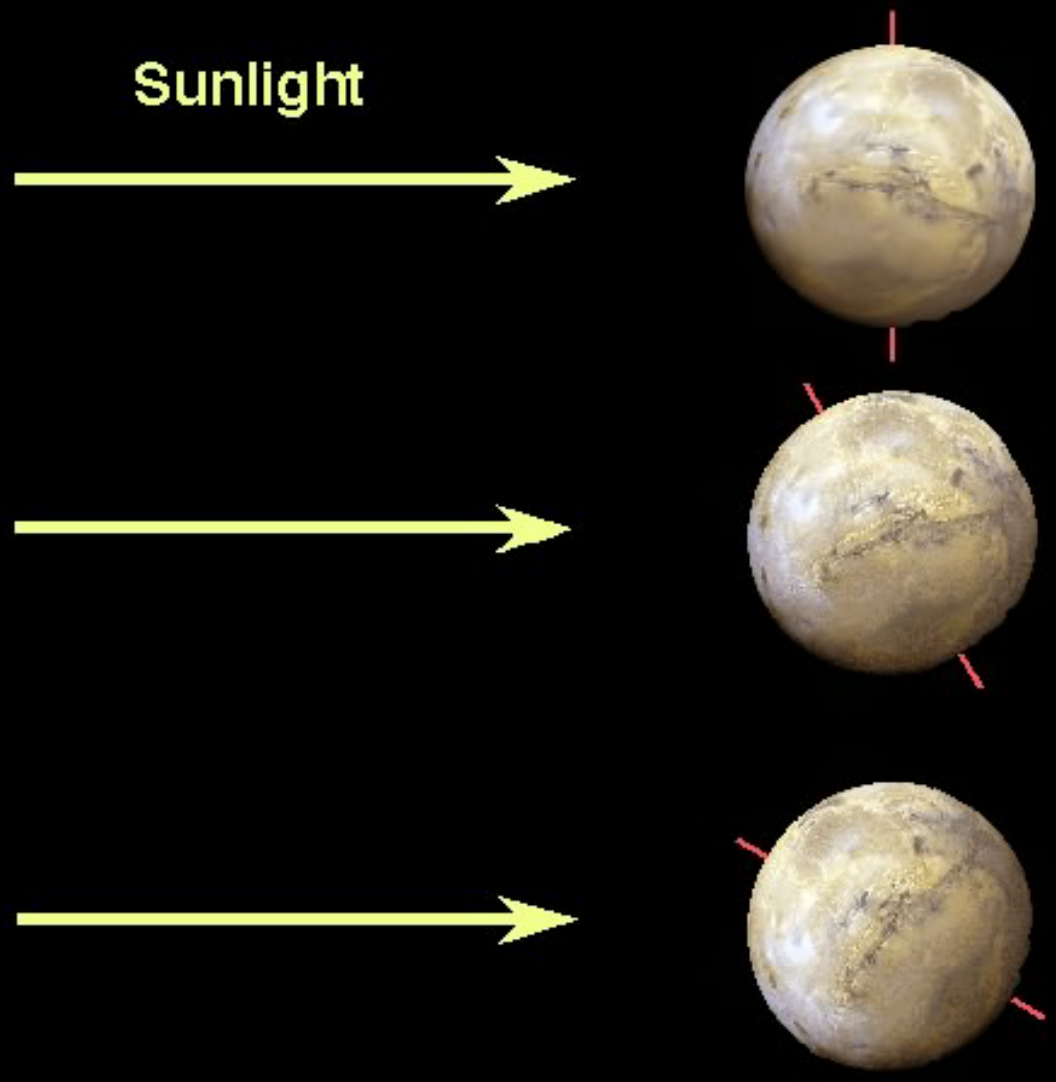
1. Characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs

2. Constrain evolution in the geological, geochemical, and photochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly as it bears on provision of chemical energy and … bioessential elements

3. Constrain the nature and abundance of possible energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions

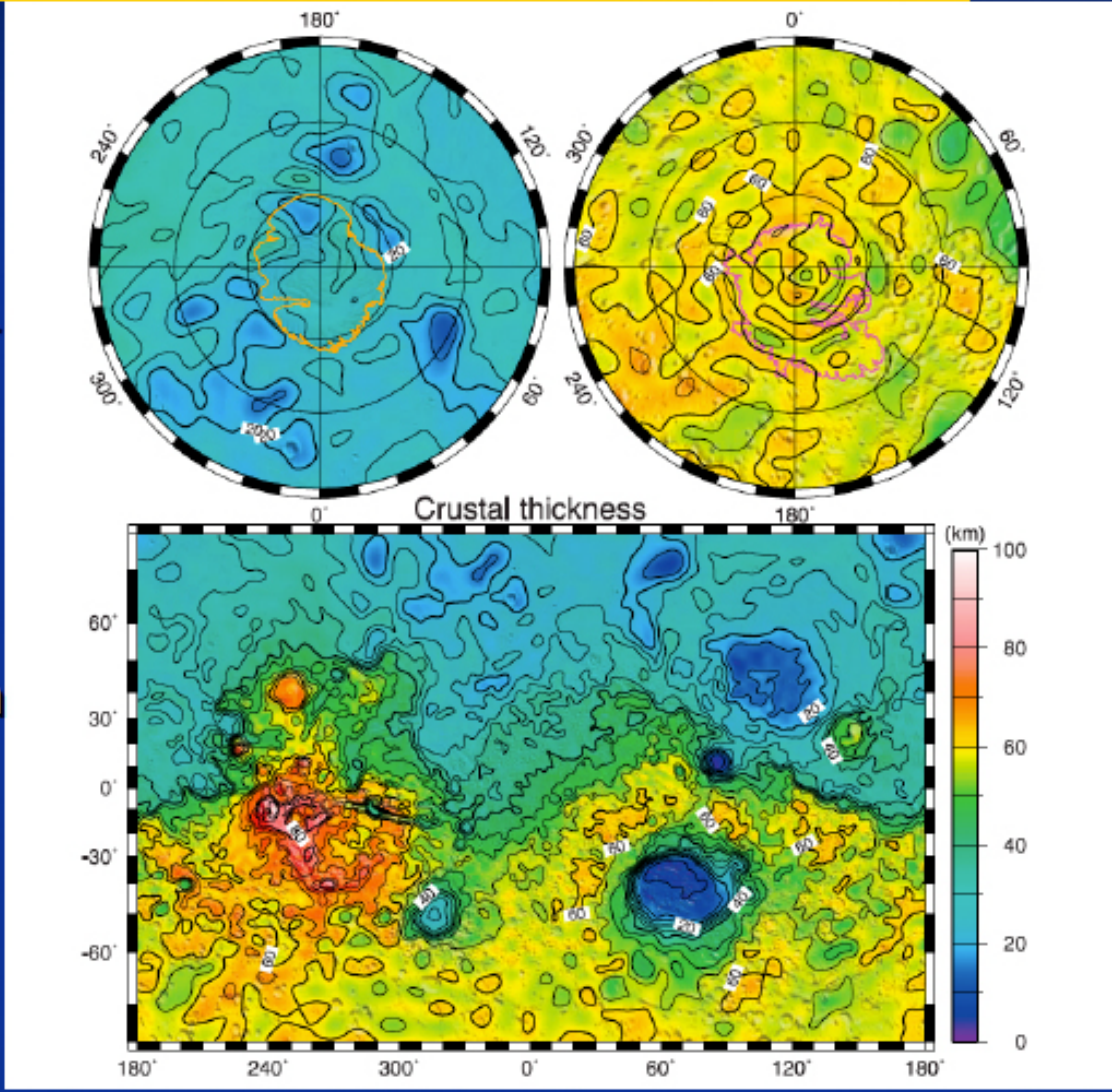
4. Evaluate the presence and magnitude of oxidative or radiation hazards at the surface and in the shallow crust

Obliquity changes can exert major effects upon the abundance and global distribution of water in the surface environment



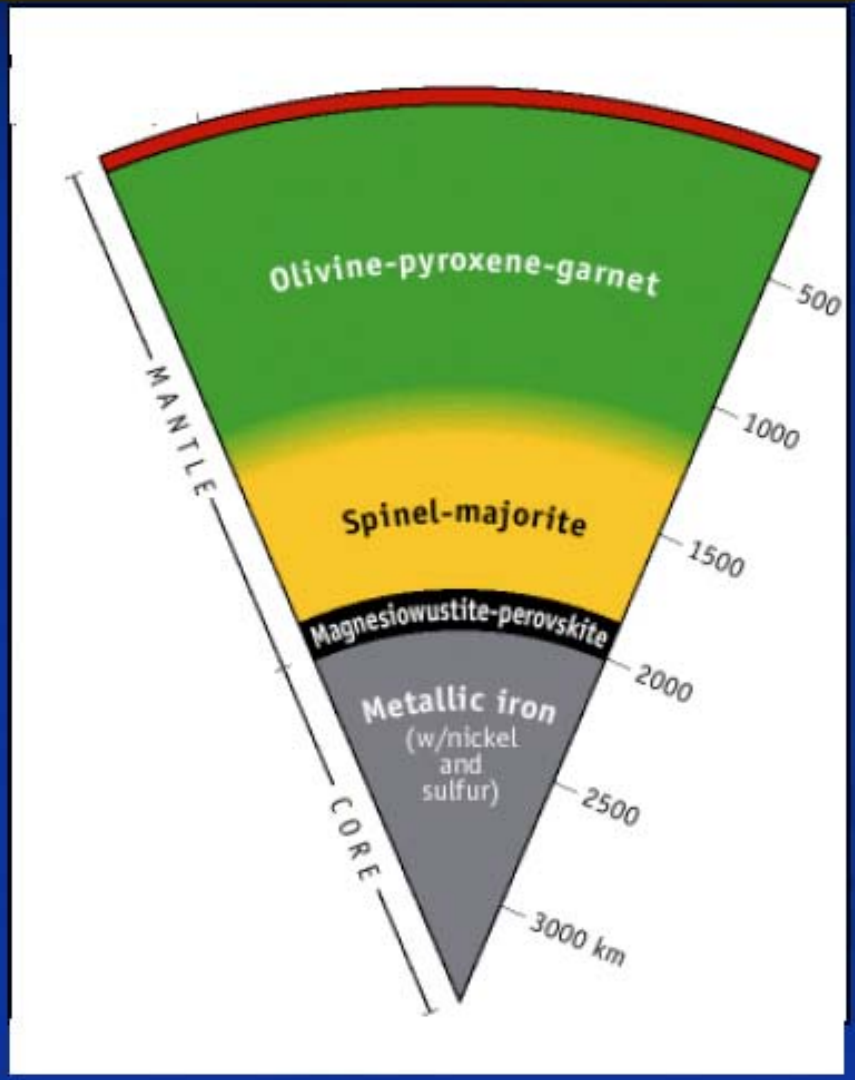
Crustal Questions

- **The volume of the crust is unknown to within a factor of two.**
- Does Mars have a layered crust? Is there a primary crust beneath the secondary veneer of basalt?
- To what extent were radiogenic elements concentrated in the crust? Is there a difference in composition between the north and the south?
- Is the crust a result of primary differentiation or of late-stage overturn? How much of it is secondary?



Mantle Questions

- What is the actual mantle composition (e.g., Mg#, mineralogy, volatile content oxidation state)?
- To what degree is it compositionally stratified? What are the implications for mantle convection?
- Are there polymorphic phase transitions?
- What is the thermal state of the mantle?



Questions About Core Structure

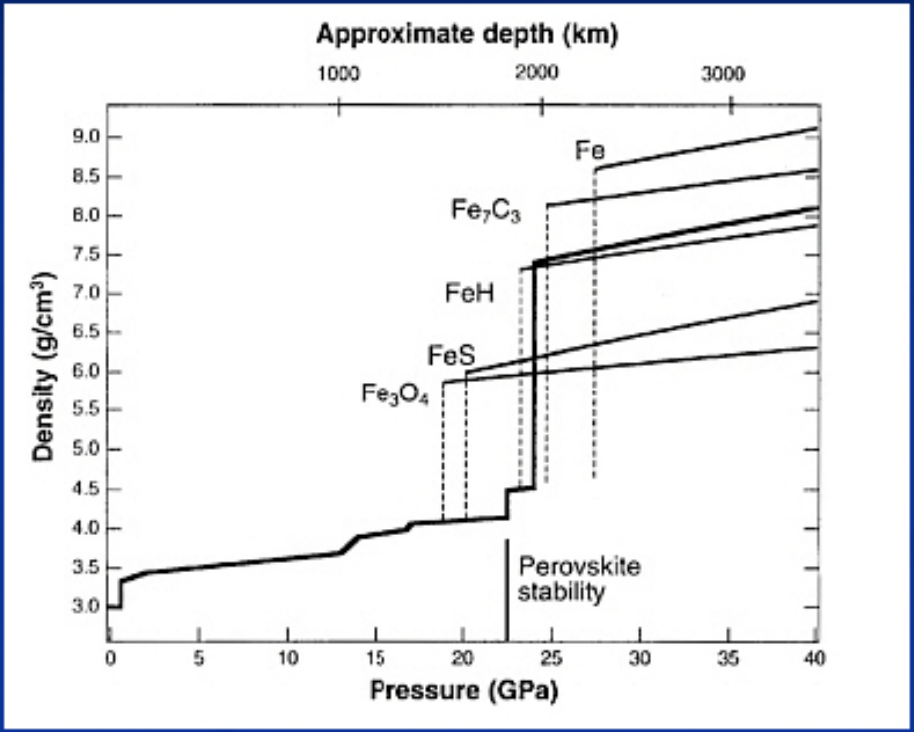
Radius is 1600 ±150 km, so density is uncertain to ±20%

Composed primarily of iron, but what are the lighter alloying elements?

At least the outer part appears to be liquid; is there a solid inner core?

How do these parameters relate to the initiation and shut down of the dynamo?

Does the core radius preclude a lower mantle perovskite transition?

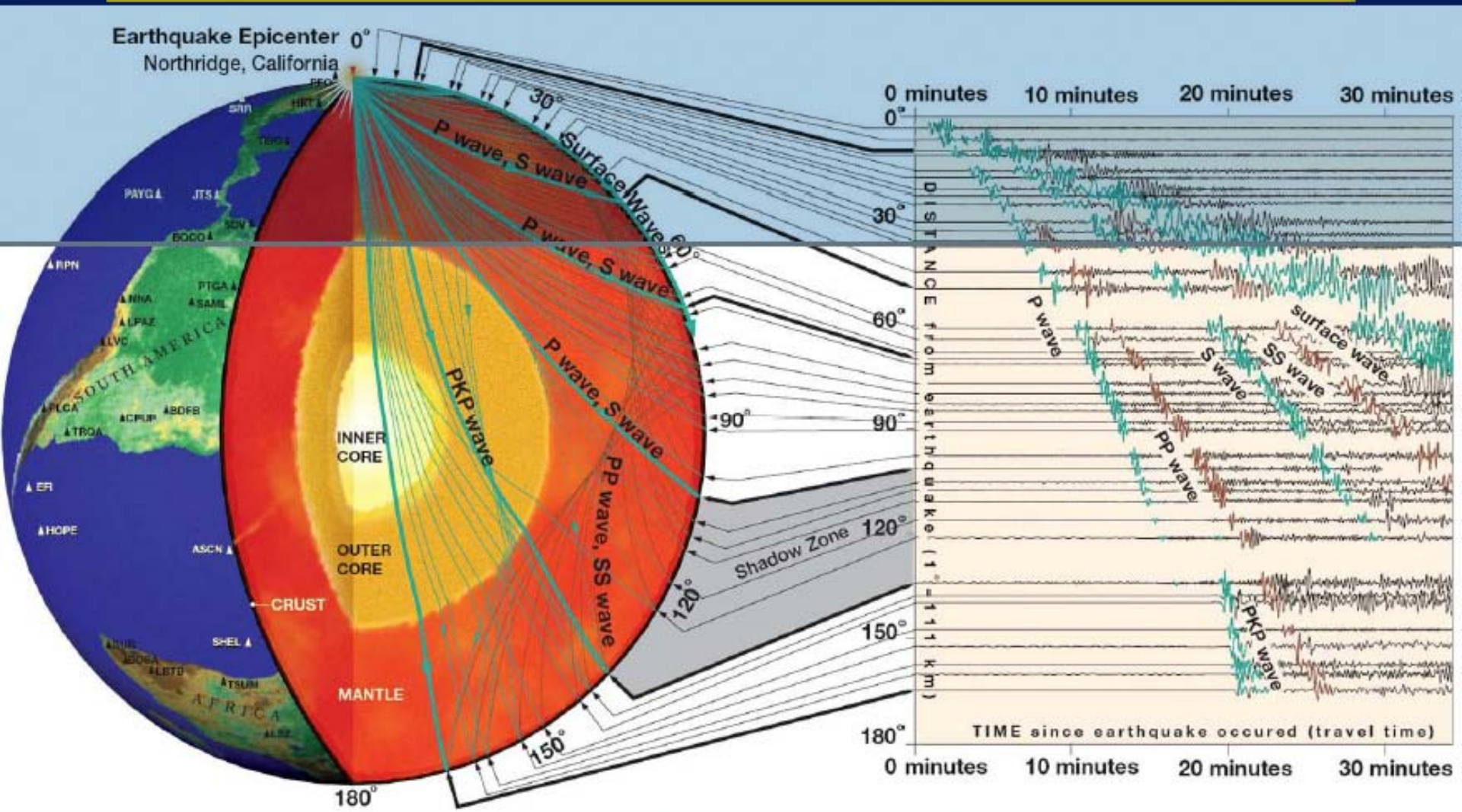


Our only constraints on the core are the moment of inertia and total mass of Mars. But since we have three parameters (mantle density, core radius and density), we are stuck with a family of possible core structures, each with significantly different implications for Mars' origin and history.

Highest Priority Science Goals

- Determine the thickness of the crust at several geologically interesting locations. Determine crustal layering at these locations.
- Determine the depths to mantle phase transition boundaries or compositional boundaries.
- Determine the radius of the core .
- Determine the state of the core and the radius of a potential inner core.
- Determine the additional details of the radial seismic velocity profile of the planet interior.
- Determine the global planetary heat flow.

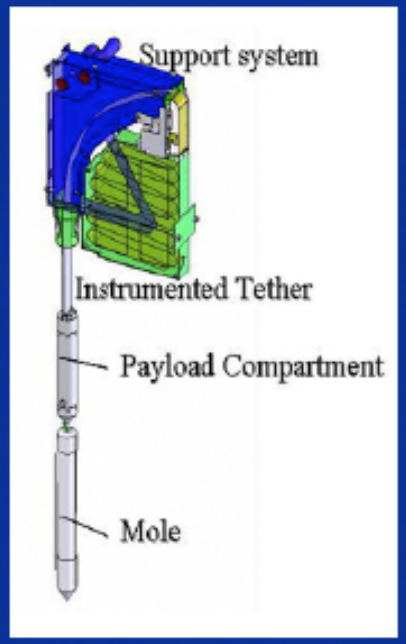
Travel Time Analysis



Planetary Heat Flow

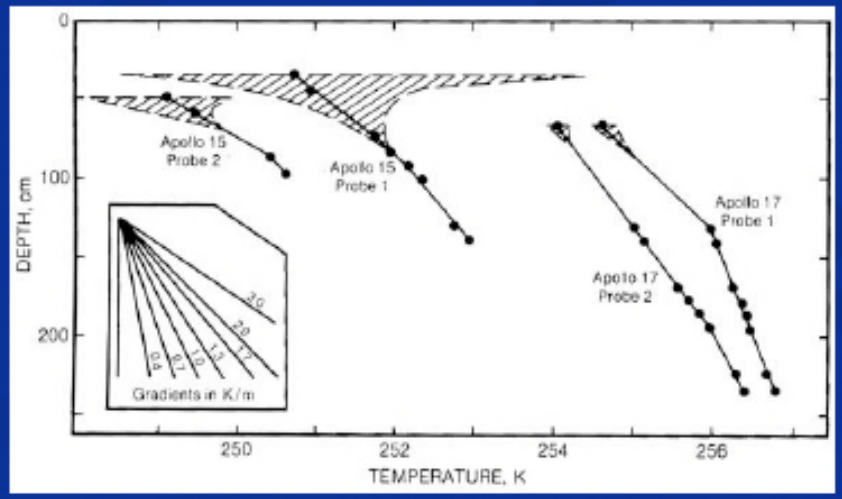
Constrains:

- Thermal and volatile history
- Distribution of radiogenic elements
- Thickness of lithosphere
- Subsurface environment, energy source for chemoautotrophic life forms



Key challenges:

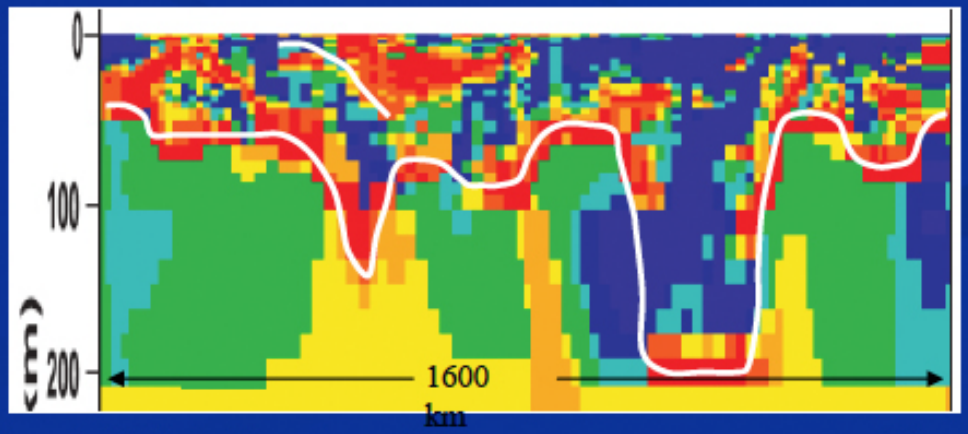
- Measuring the thermal gradient beneath the annual thermal wave, at 3-5 m depth.
- Accurately measuring the thermal gradient and conductivity in an extremely low conductivity environment where self-heating is an issue.
- Effects of local topography
- Long-term fluctuations of the surface temperature and insolation (climate variations, obliquity changes, etc.)

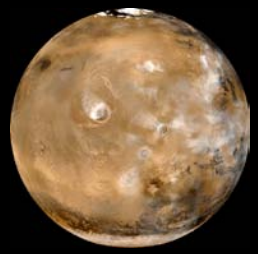


Electromagnetic Sounding

- **Uses ambient EM energy to penetrate the crust and upper mantle.**
- **Is widely used in terrestrial resource exploration and studies of the lithosphere and the deep mantle.**
  - Related methods used to detect subsurface oceans in Galilean satellites and to sound interior of the Moon.
- **Two measurement methods:**
  - Magnetotellurics (10^{-2}-10^{2} Hz). Form frequency-dependent EM impedance from orthogonal horizontal electric and magnetic fields
  - Geomagnetic Depth Sounding (10^{-5}-1 Hz). Form EM impedance from 3-component magnetic fields at 3 surface stations.

EM sounding can help determine:
Crustal thickness
Depth to ground water
Temperature profile in mantle lithosphere
Low frequency EM environment





Great Potential of a Fundamentally International Mars Exploration Program

Broad, deep science & engineering intellectual base

Promotes international collaborations in other areas

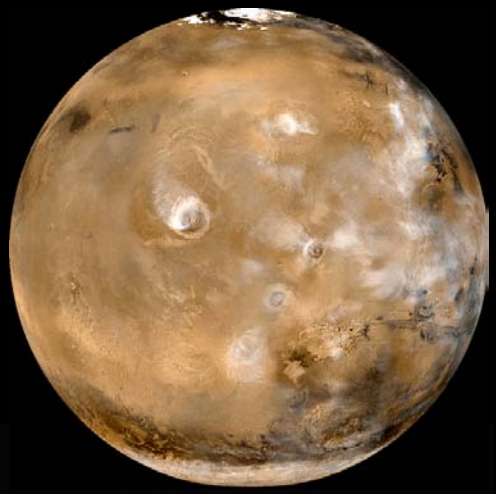
Continues cadence of orbiters, landers & synergies

Enables spacecraft portfolio for Mars sample return

Enables Mars network science:
multiple small geophysical & climate stations

Coordinated approach to future human exploration

The Martian environment has been more Earth-like than that of any other planet in our solar system.



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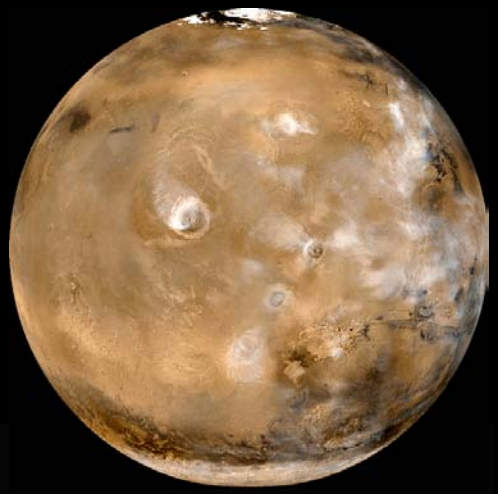
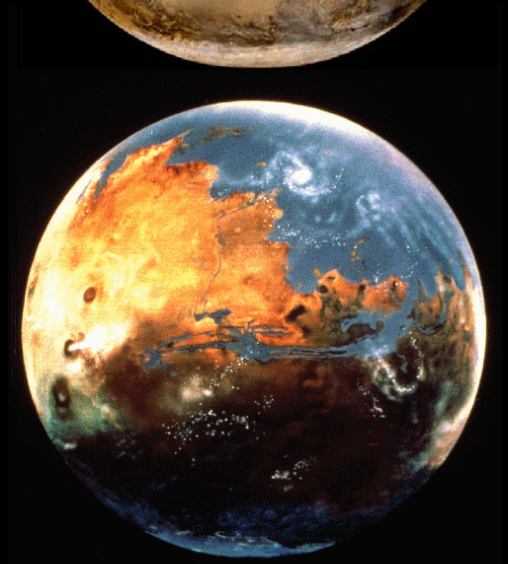
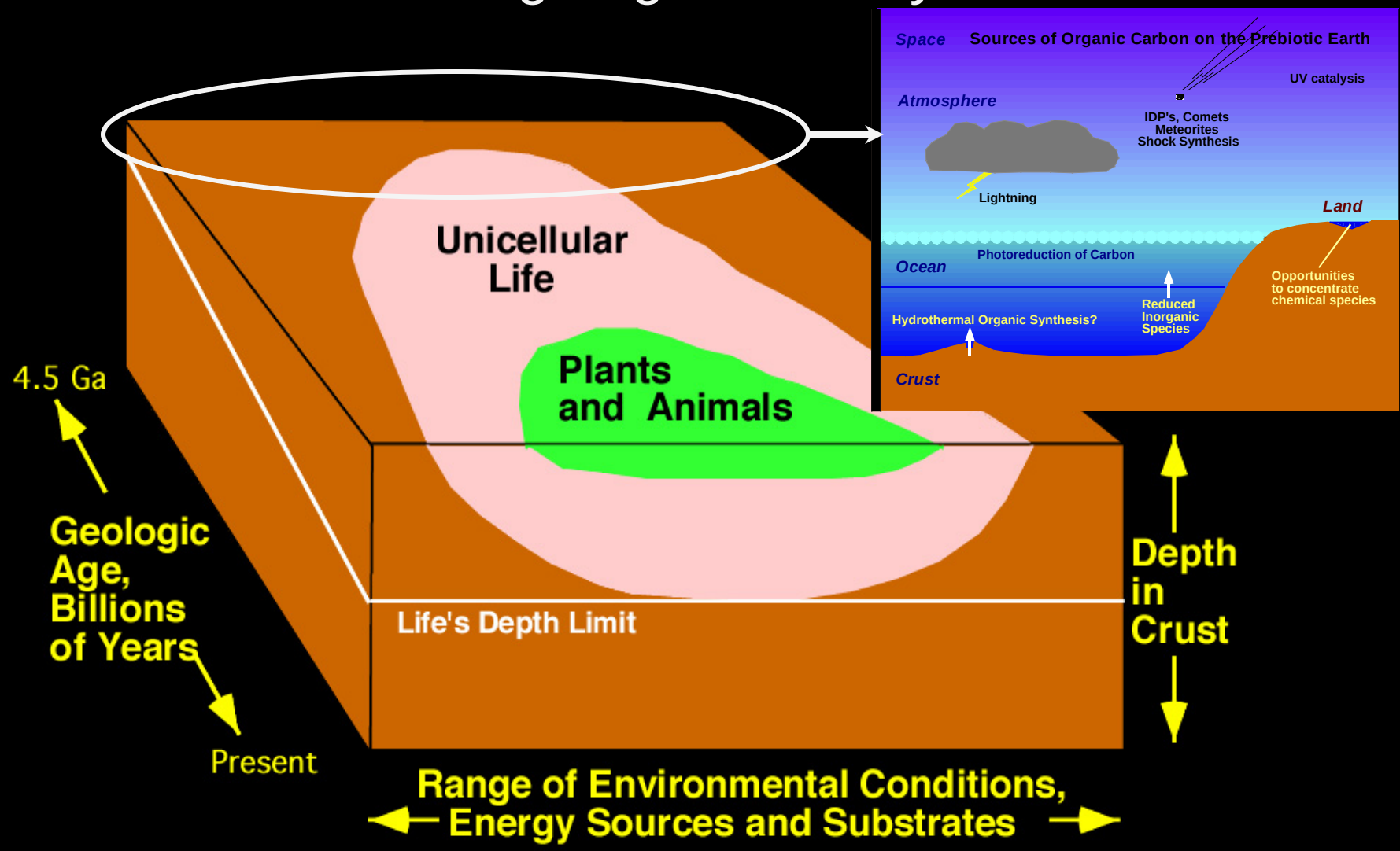




A planetary-scale exploration program is needed to understand the planetary-scale Martian system!

Knowledge of early planetary environments is critical to understanding origins & early evolution of life



But Earth's earliest record has been largely obliterated.
Mars' earliest record is probably still well-preserved!

Had T. S. Eliot lived in today's space age, he <u>might</u> advise:
"Explore our own origins and the depths of space
Then consider once again our own moment and place
And know it for the first time."

End…