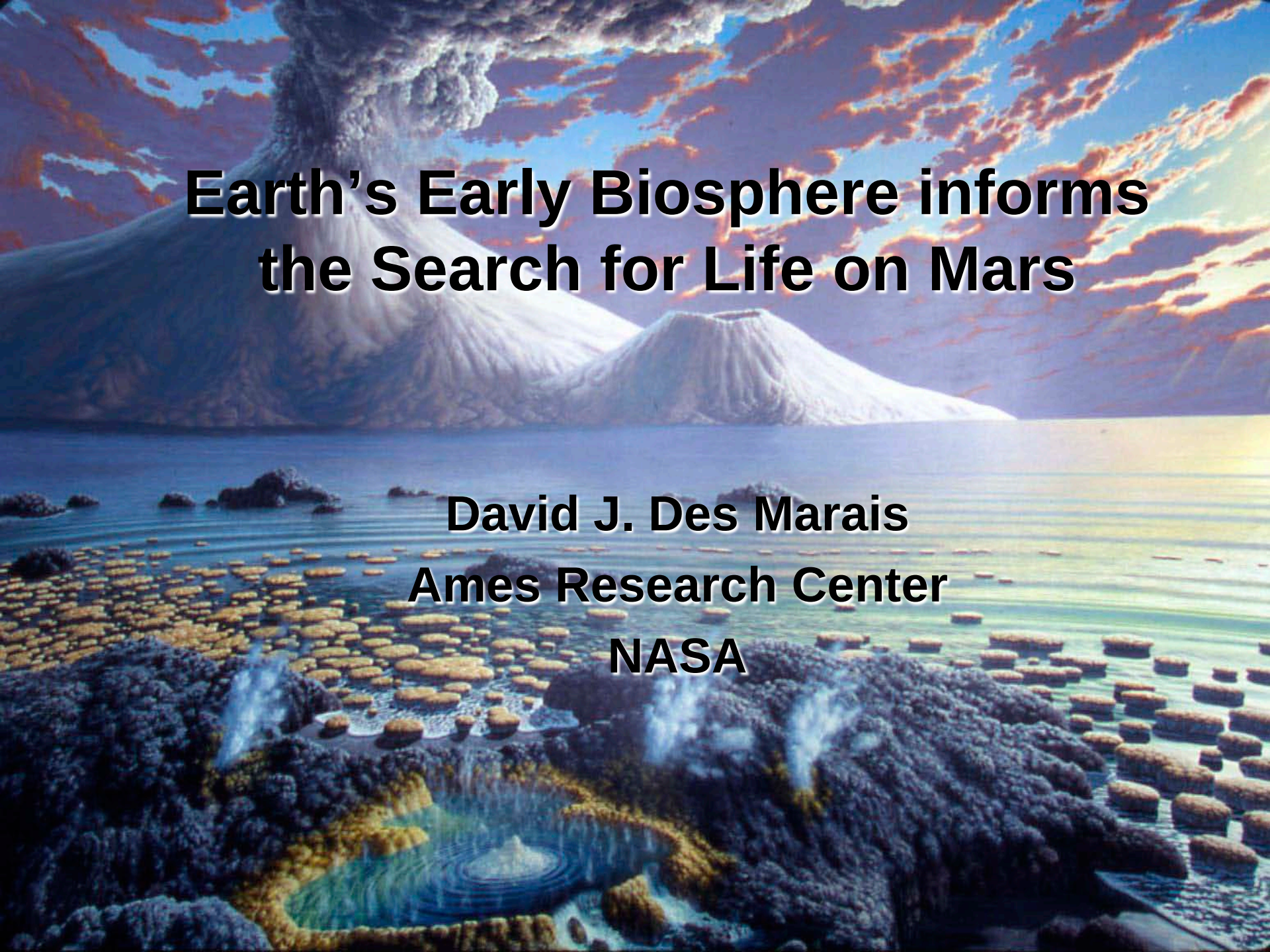


Earth's Early Biosphere informs the Search for Life on Mars

David J. Des Marais

Ames Research Center

NASA

Extending our Concepts of Life

- Origins on Earth
  - What environments and evolutionary paths allowed the key components of living system(s) to develop?
  - What evolutionary paths led to the array of attributes shared by all modern organisms?
- Determinism
  - Do “nurturing” environments usually lead to life?
  - To what extent do physical and chemical factors cause life elsewhere to resemble our own?
- Diversity
  - Does Earth’s biosphere represent a subset of the (<u>much</u> greater?) diversity of life in the universe?
  - What are the ultimate environmental limits of life?

A Definition of Life

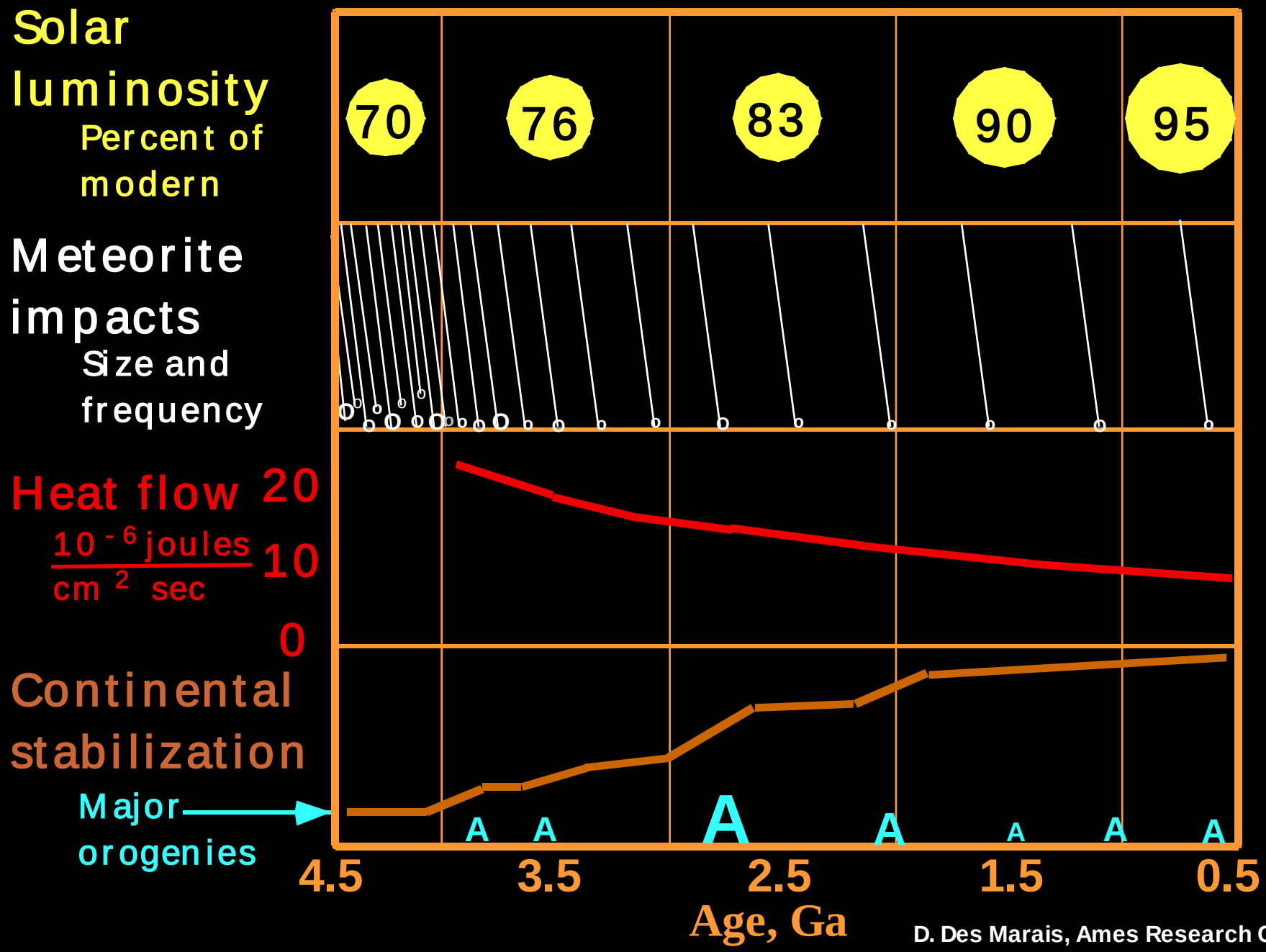
Life is the harnessing of free energy
to sustain and perpetuate,
by molecular replication and evolution,
a high density of information
in the form of complex molecules
& functionally-related larger structures

Earth & Mars
Similar environments: water- & C-based life

Topics in this Talk

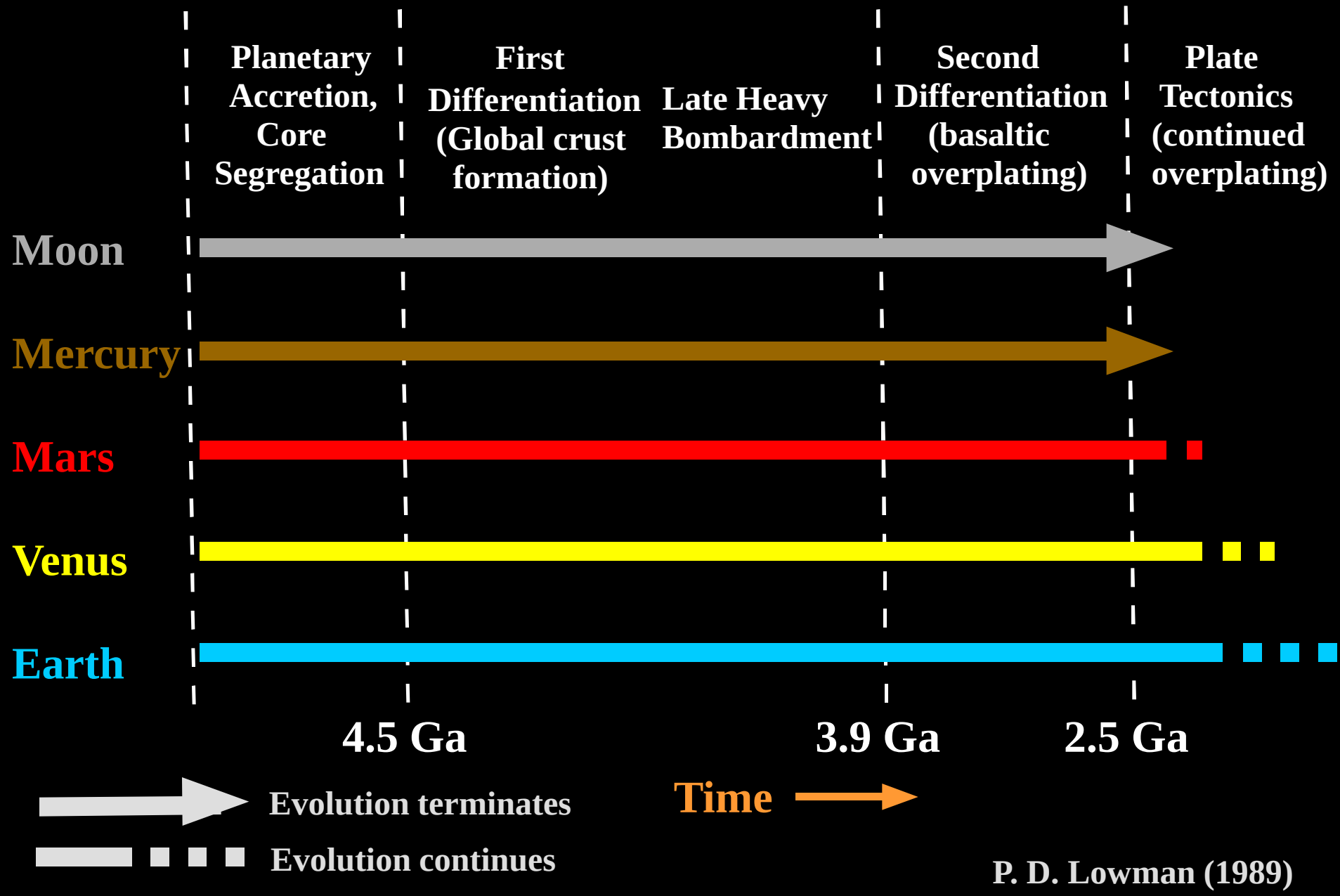
- Evolution of Earth's early crust
- Early (bio)geochemistry & bioenergetics
- Biosignature types & Archean biosphere
- Preservation of biosignatures & indicators of ancient environments

Evolution of Earth's Early Environment



D. Des Marais, Ames Research Center

Crustal Evolution in Silicate Planets



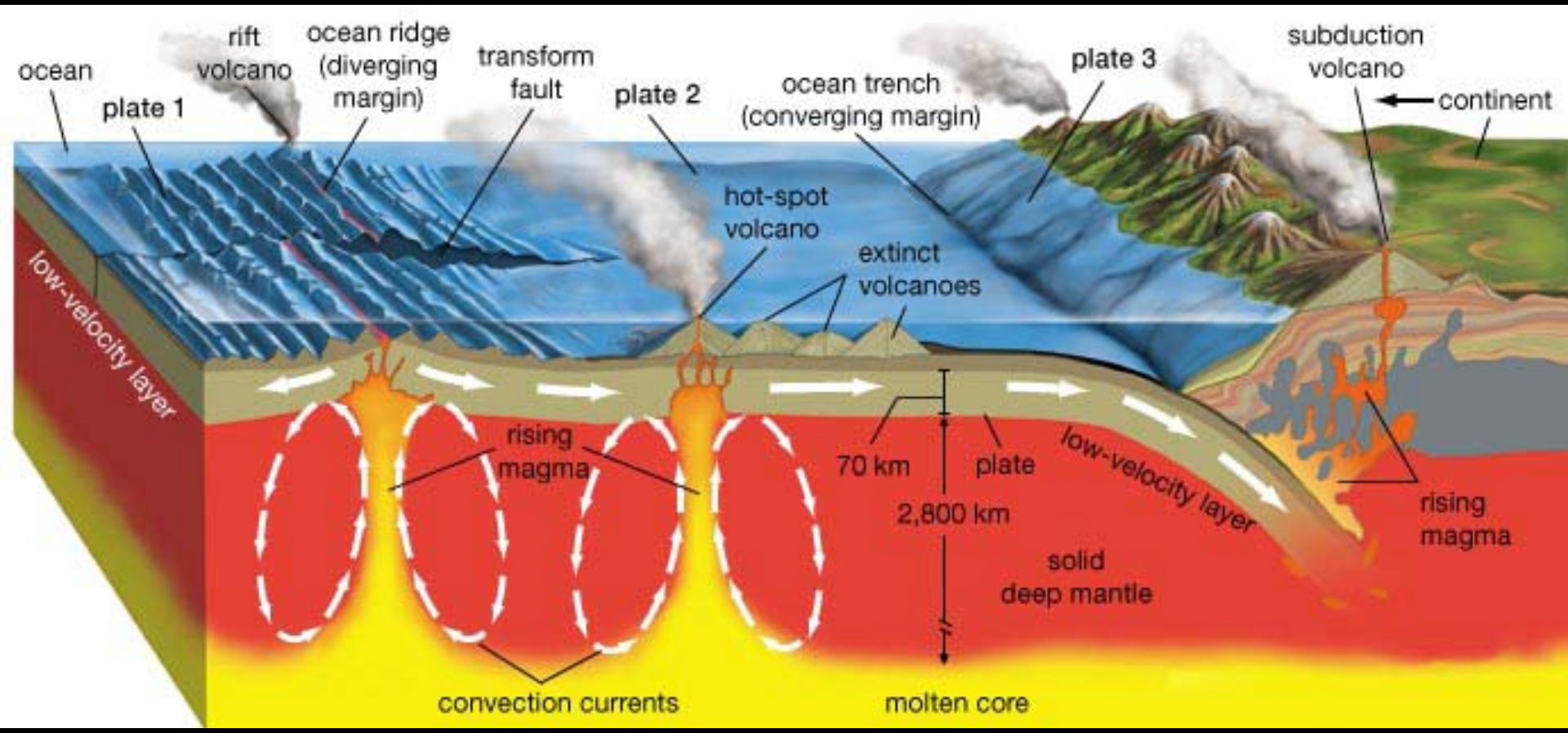
P. D. Lowman (1989)

Evolution of Earth's Continental Crust

- Initial differentiation
  - Protocontinental Hadean crust (analogy w lunar highlands)
  - Developed during accretion & its aftermath
  - Initial crustal enrichment of Na, K, Ca & Si
- "Vertical tectonics, platelet tectonics" (many interpretations!)
  - Early- to mid-Archean cratons & terrains
  - Formation of TTG domes & intervening basins with greenstone belts
- "Tertiary or modern" continental crust
  - High-Si rocks, more abundant granites, qtz & K
  - Late Archean & Proterozoic growth of cratons; assembly of "modern-size" continents
- *Water intimately involved in altering compositions*
- (Martian crustal evolution?)

Early Hadean (“artist’s concept”)

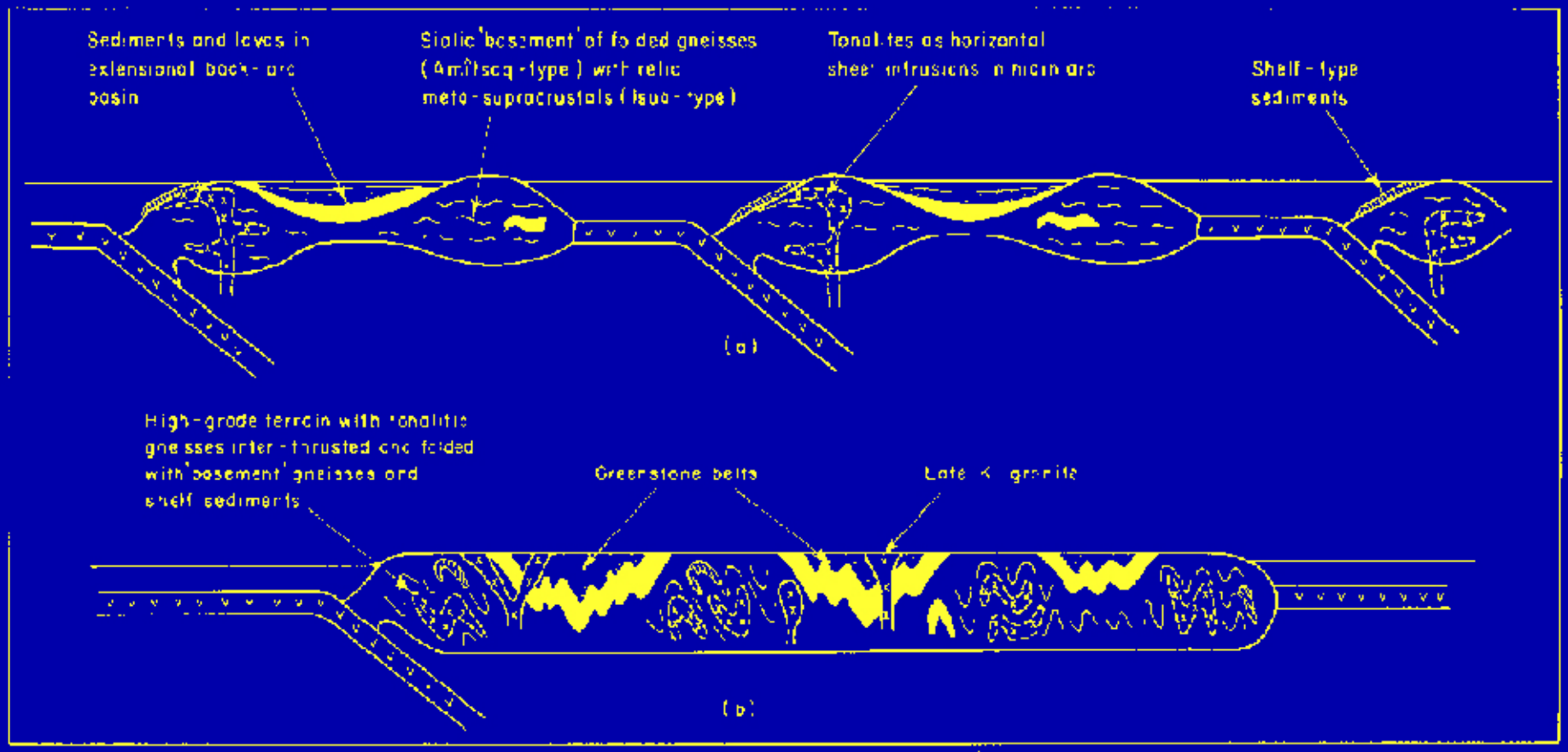
10 km



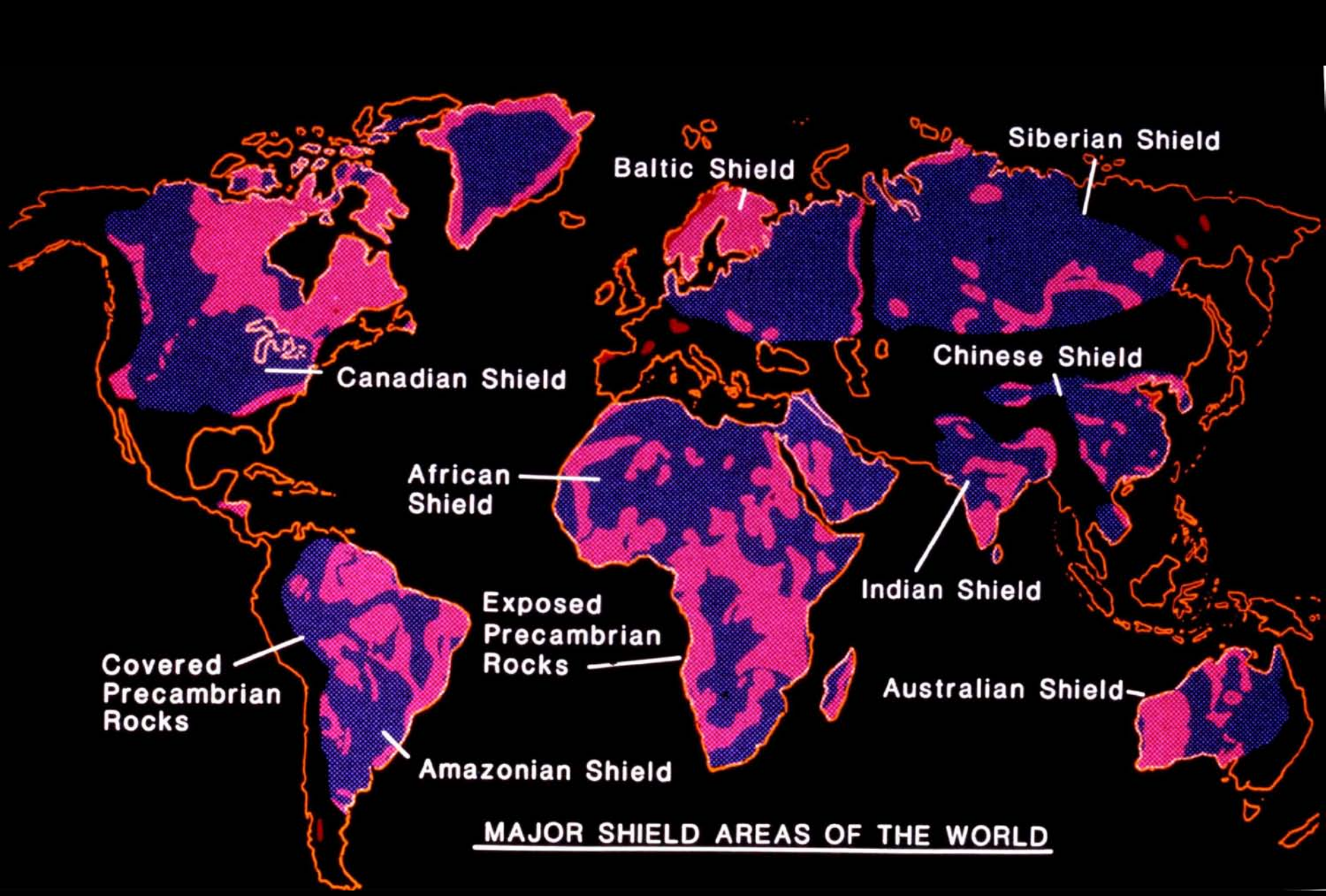
Crustal Plate Boundary Types

Stabilization of Archean Continental Crust

Windley (1984)

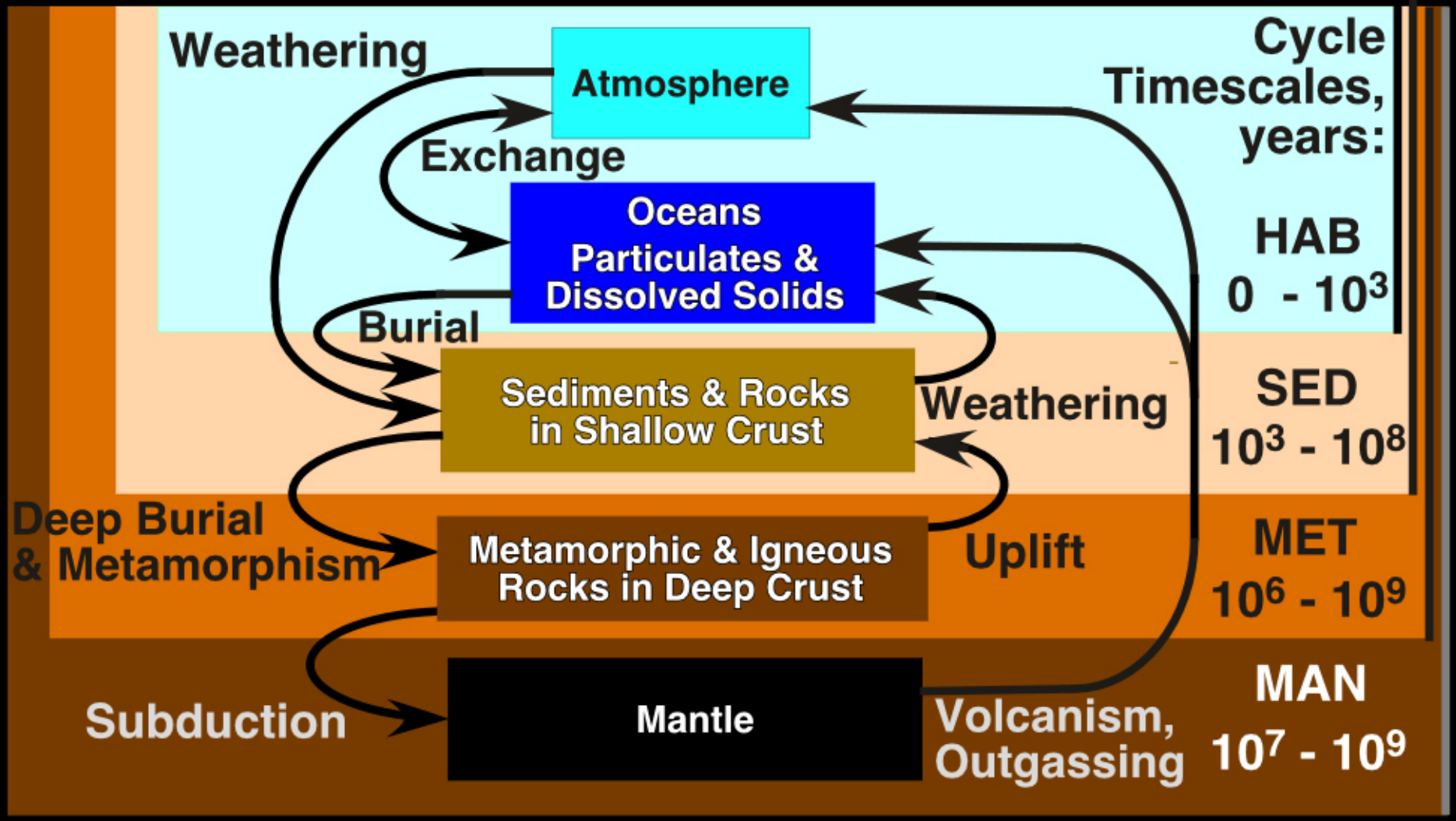


(stabilized via: plate tectonics? "platelet" tectonics? "vertical" tectonics?)



MAJOR SHIELD AREAS OF THE WORLD

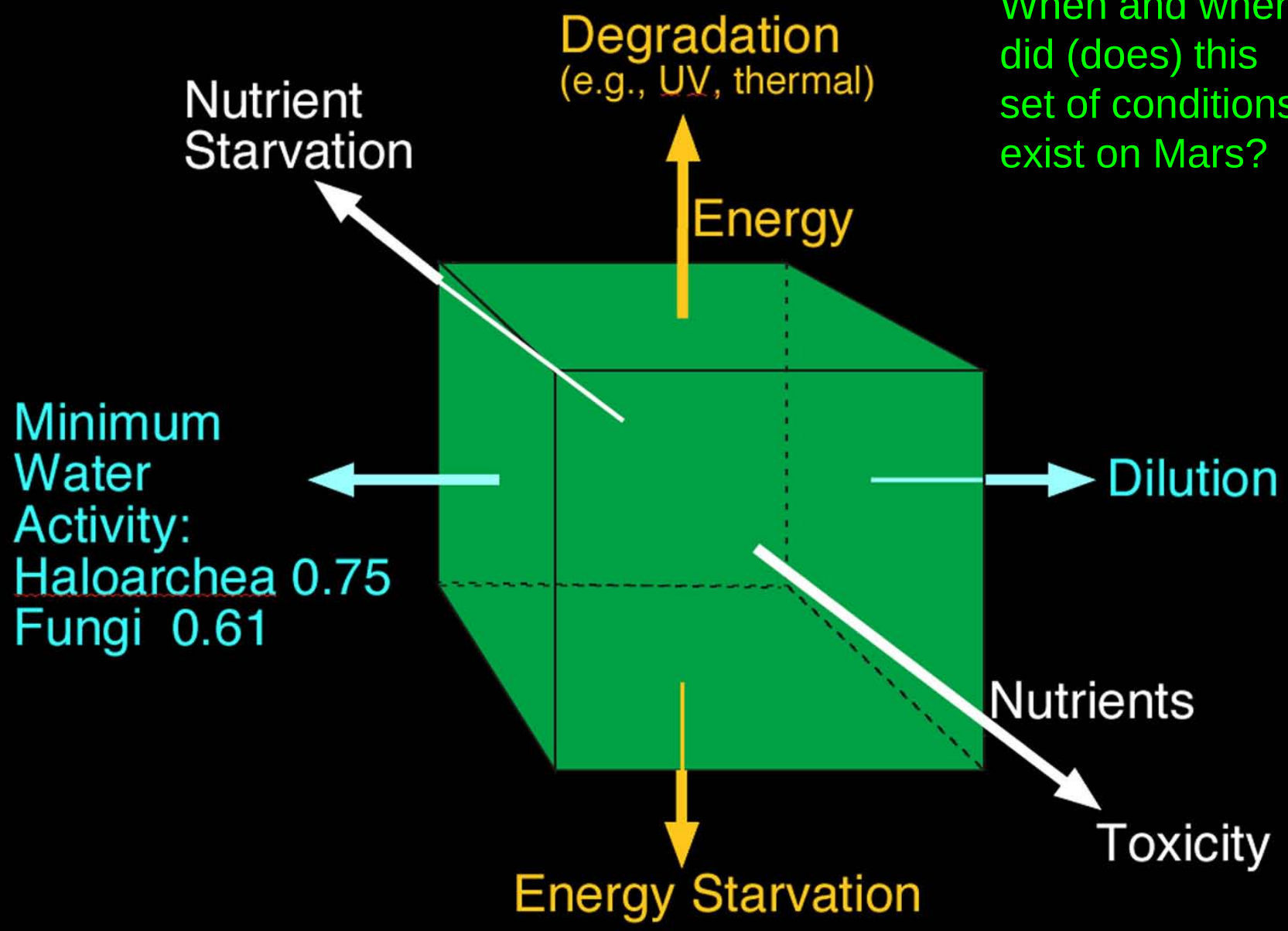
Geochemical Cycles



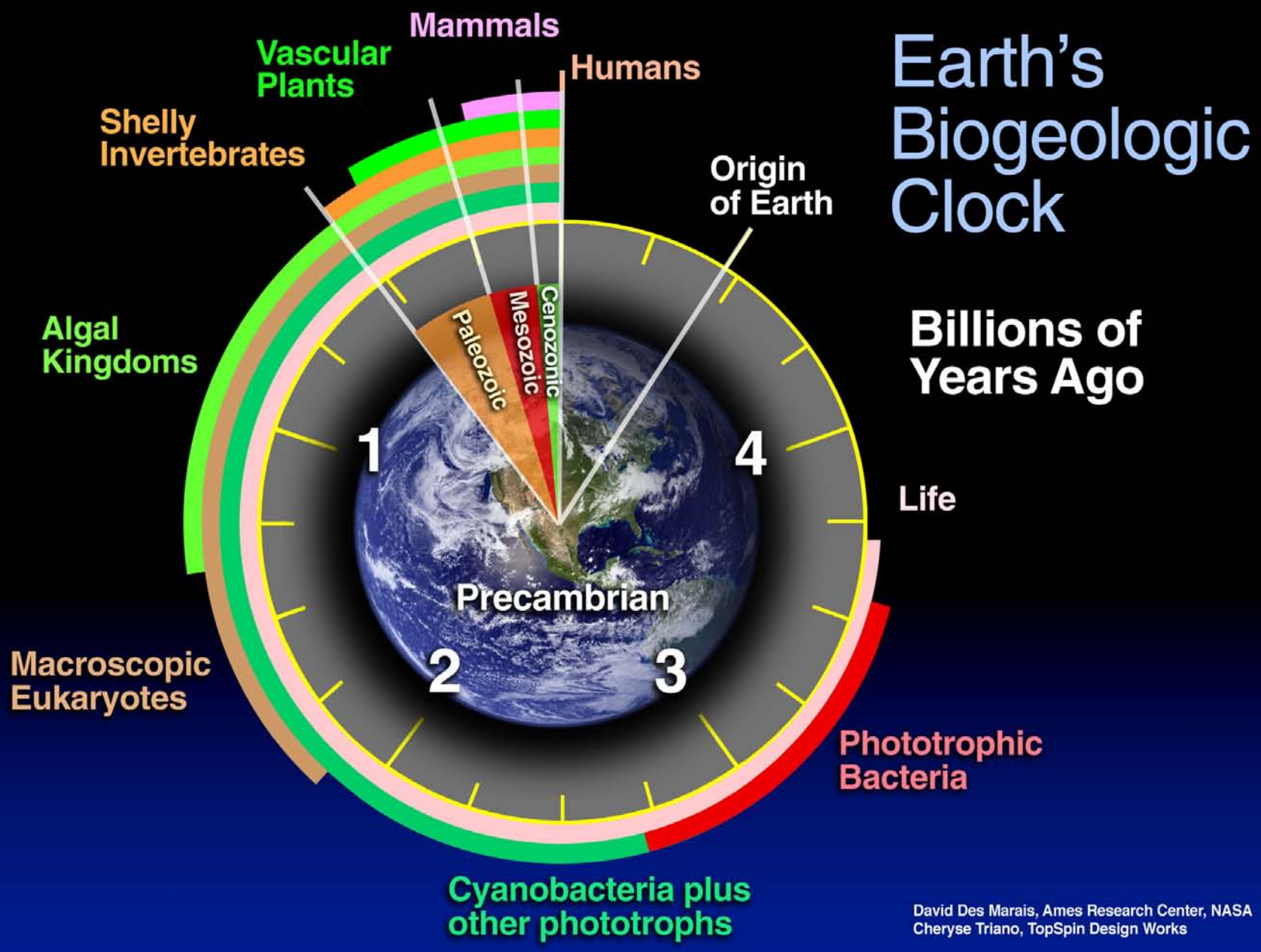
Sustain supplies of nutrients as well as reduced (H_2, S_{red}, Fe^{2+}) & oxidized (SO_x, Fe^{3+}) species for redox reactions

Range of Conditions that Sustains Life

When and where did (does) this set of conditions exist on Mars?



Earth's Biogeologic Clock



David Des Marais, Ames Research Center, NASA
Cheryse Triano, TopSpin Design Works

Topics in this Talk

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- Biosignature types & Archean biosphere
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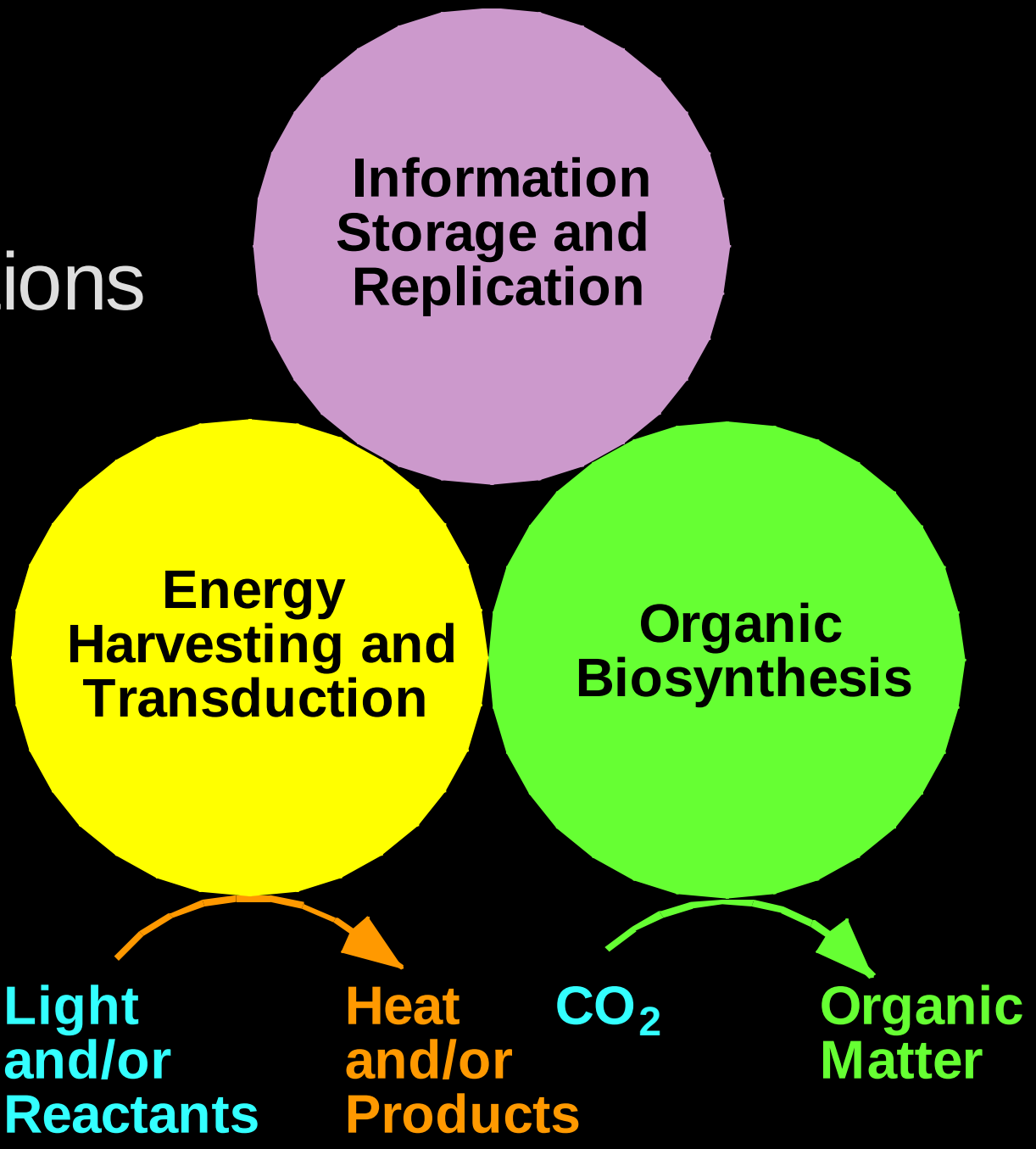
Life's Basic Functions



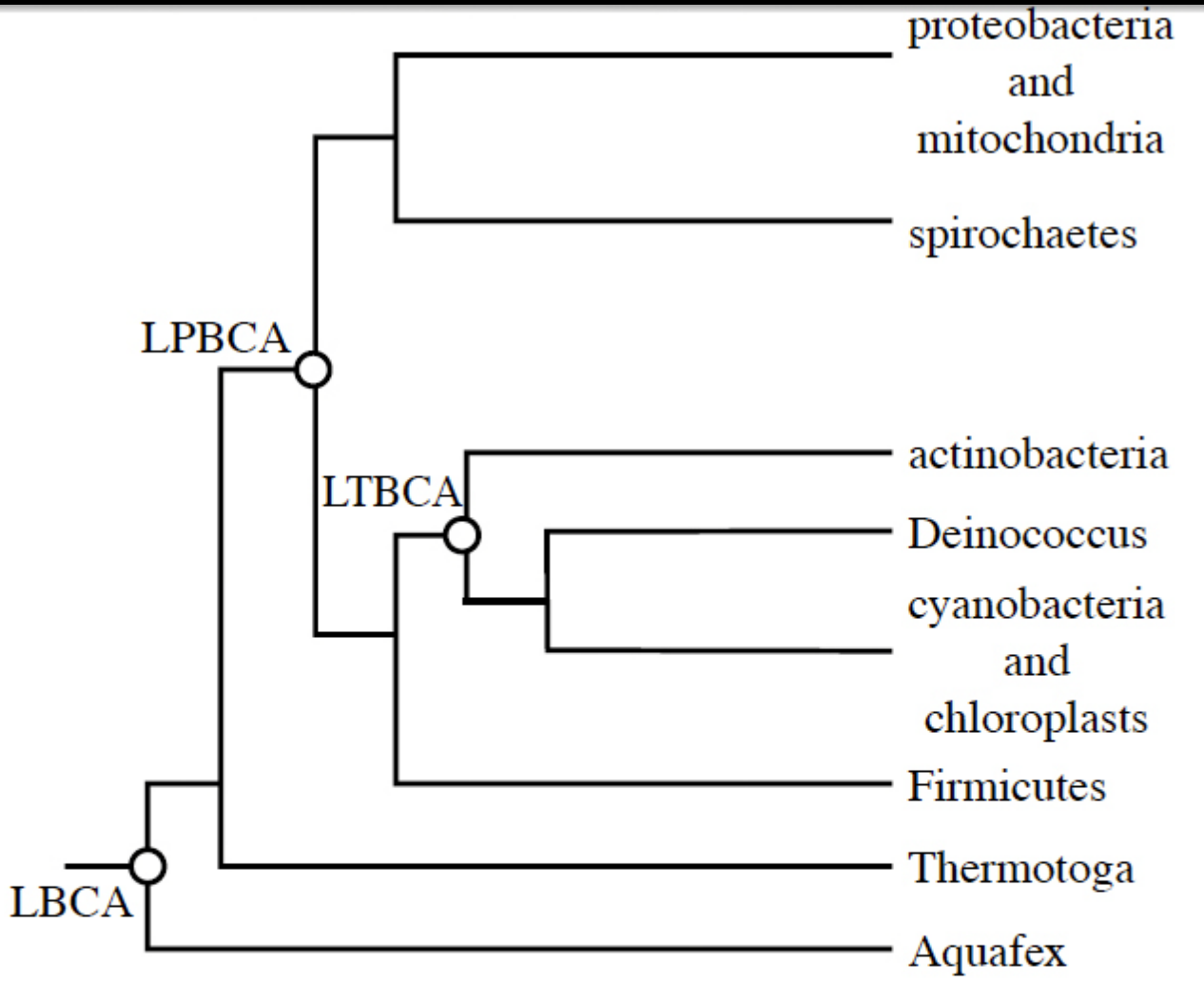


Figure 2. Tree of life for bacteria from the last bacteria common ancestor (LBCA) simplified from Battistuzzi *et al.* (2004). The last photobacterial common ancestor (LPBCA) developed efficient photosynthesis and evolved into the common clades of bacteria. The last Terrabacterial common ancestor (LTBCA) was a successful colonist on land.

Sleep & Bird

(2008)

Early Key Redox Reactions

(abiotic biotic) (Sleep & Bird, 2008)

$$3FeO_{rock} + H_20 \rightleftharpoons H_{2(aq)} + Fe_3O_4$$

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

$$2CO_2 + 4H_2 \longrightarrow 2CH_2O + 2H_2O$$

$$4SO_3^{2-} \longrightarrow S^{2-} + 3SO_4^{2-}$$

$$CH_4 + CO_2 + h\nu \longrightarrow 2CO + 2H_2$$

$$CH_4 + h\nu \longrightarrow C_{haze} + 2H_2$$

major abiotic sources

Estimated global productivity: 0.06 x 10^{12} mole C / year (Sleep & Bird, 2007)

(Modern global productivity: 9000 x 10^{12} mole C / year)

Redox Reactions for Early S & Fe Phototrophy

$$2CO_2 + S^{2-} + 2H_2O + h\nu \longrightarrow 2CH_2O + SO_4^{2-}$$

$$CO_2 + 4FeO + H_2O + h\nu \longrightarrow CH_2O + 2Fe_2O_3$$

Estimated global productivity: ~ 100 x 10^{12} mole C / year?
(Modern global productivity: 9000 x 10^{12} mole C / year)

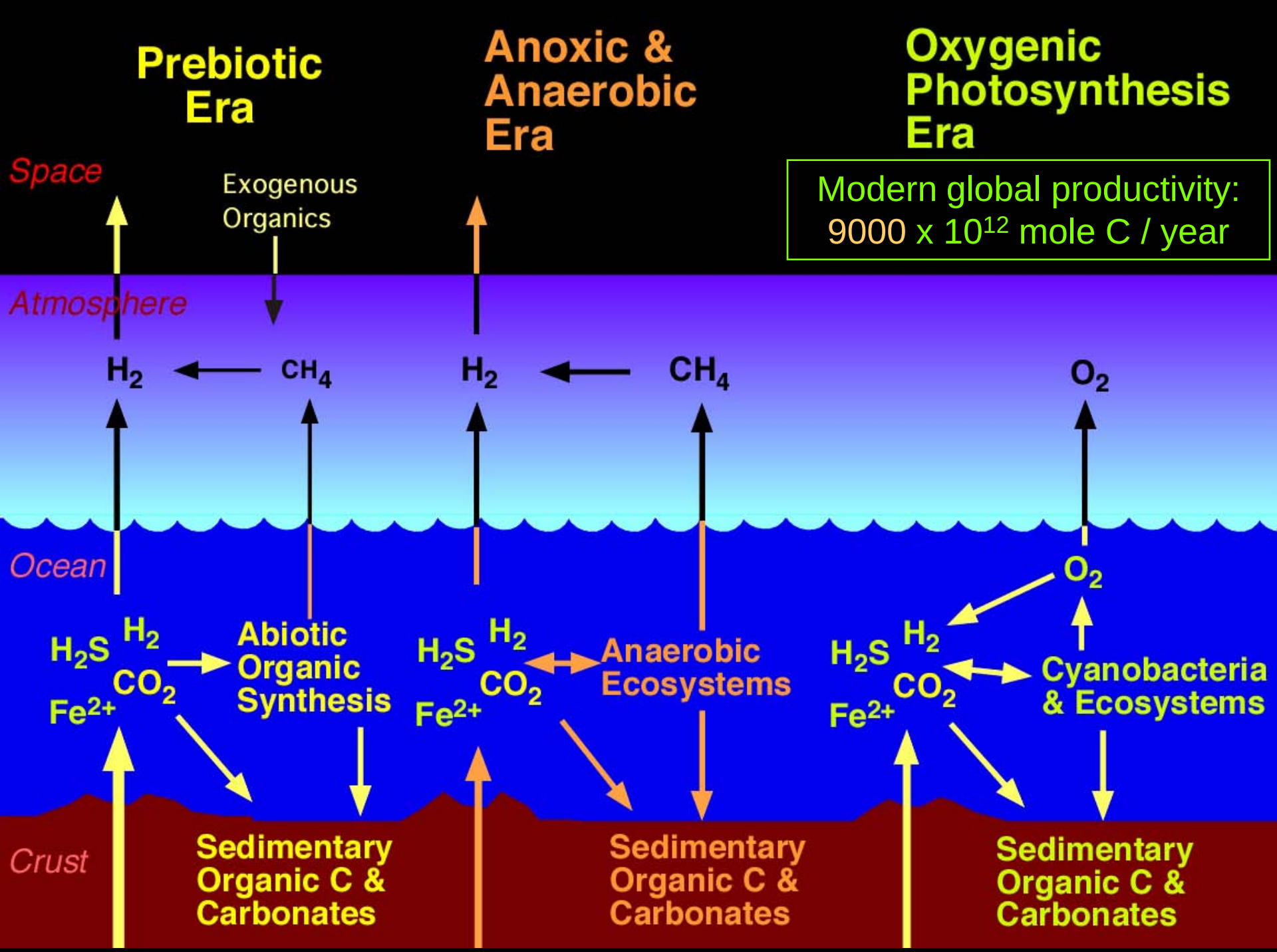
Coupled Sulfur Reactions

$$H_2S + 2CO_2 + 2H_2O \longrightarrow$$

$$S^0 \longrightarrow SO_4^{2-} + 2CH_20 + 2H^+$$

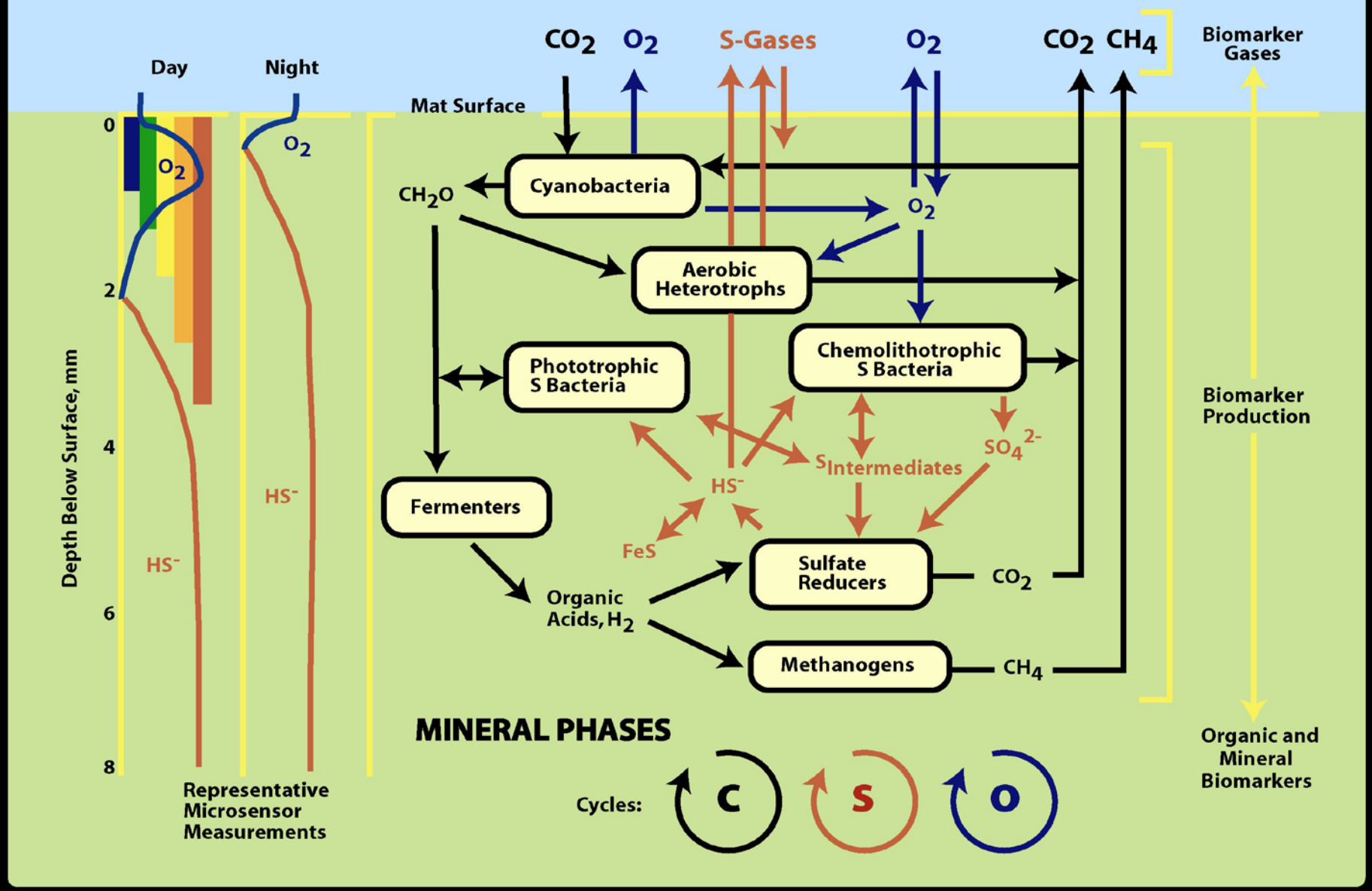
$$H_2S + 2HCO_3^- \longleftarrow SO_4^{2-} + 2CH_2O$$

Estimated global productivity: $\geq$ 1000 x 10^{12} mole C / year?
(Modern global productivity: 9000 x 10^{12} mole C / year)


Prebiotic Era
Anoxic & Anaerobic Era
Oxygenic Photosynthesis Era
Modern global productivity: 9000 x 10^12 mole C / year
Space
Exogenous Organics
Atmosphere
H2
CH4
H2
CH4
O2
Ocean
O2
H2S H2 CO2 Fe2+
Abiotic Organic Synthesis
H2S H2 CO2 Fe2+
Anaerobic Ecosystems
H2S H2 CO2 Fe2+
Cyanobacteria & Ecosystems
Crust
Sedimentary Organic C & Carbonates
Sedimentary Organic C & Carbonates
Sedimentary Organic C & Carbonates

20 microns
R. Ley

MICROBIAL MAT BIOGEOCHEMISTRY



Smithsonian Institution Mural Depicting Archean Earth

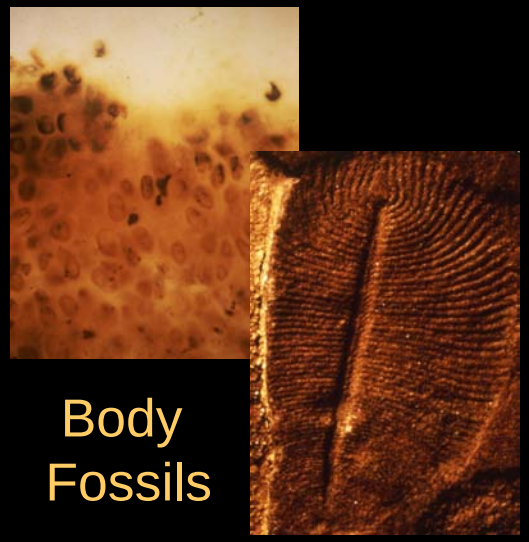
Topics in this Talk

- Evolution of Earth's early crust
- Early (bio)geochemistry & bioenergetics
- Biosignature types & Archean biosphere
- Preservation of biosignatures & indicators of ancient environments

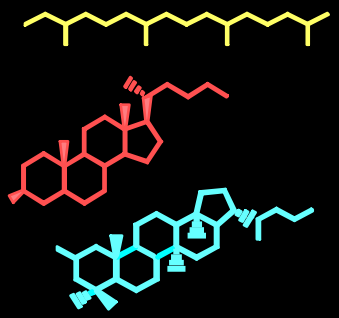
Biosignatures / Biomarkers

- A biosignature is an object, substance and/or pattern whose origin specifically requires a biological agent
- The principal value of a biosignature arises, not from the probability that it was made by life, but rather from the <u>improbability</u> that it was made by nonbiological processes
- Astrobiological exploration is founded upon the premise that biosignatures encountered beyond Earth will be recognizable

Fossil Biosignatures: What We Look For…

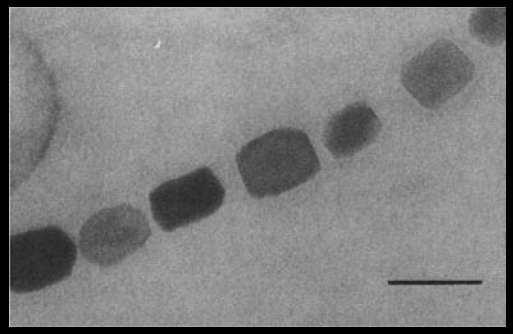


Body Fossils

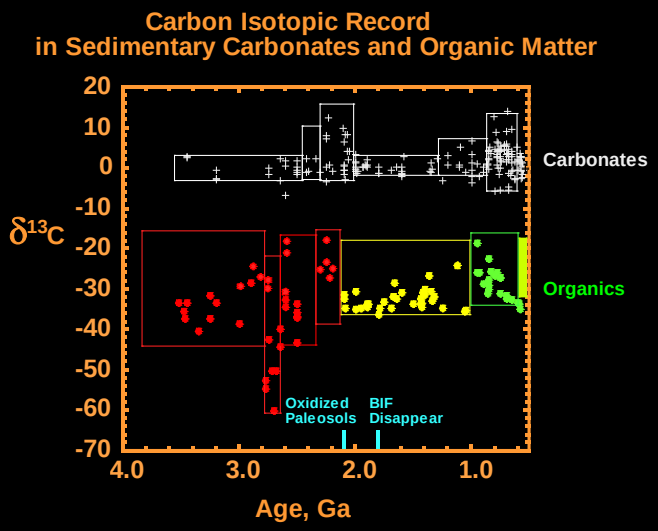


Chemical Fossils (Biomarkers)

Biofabrics



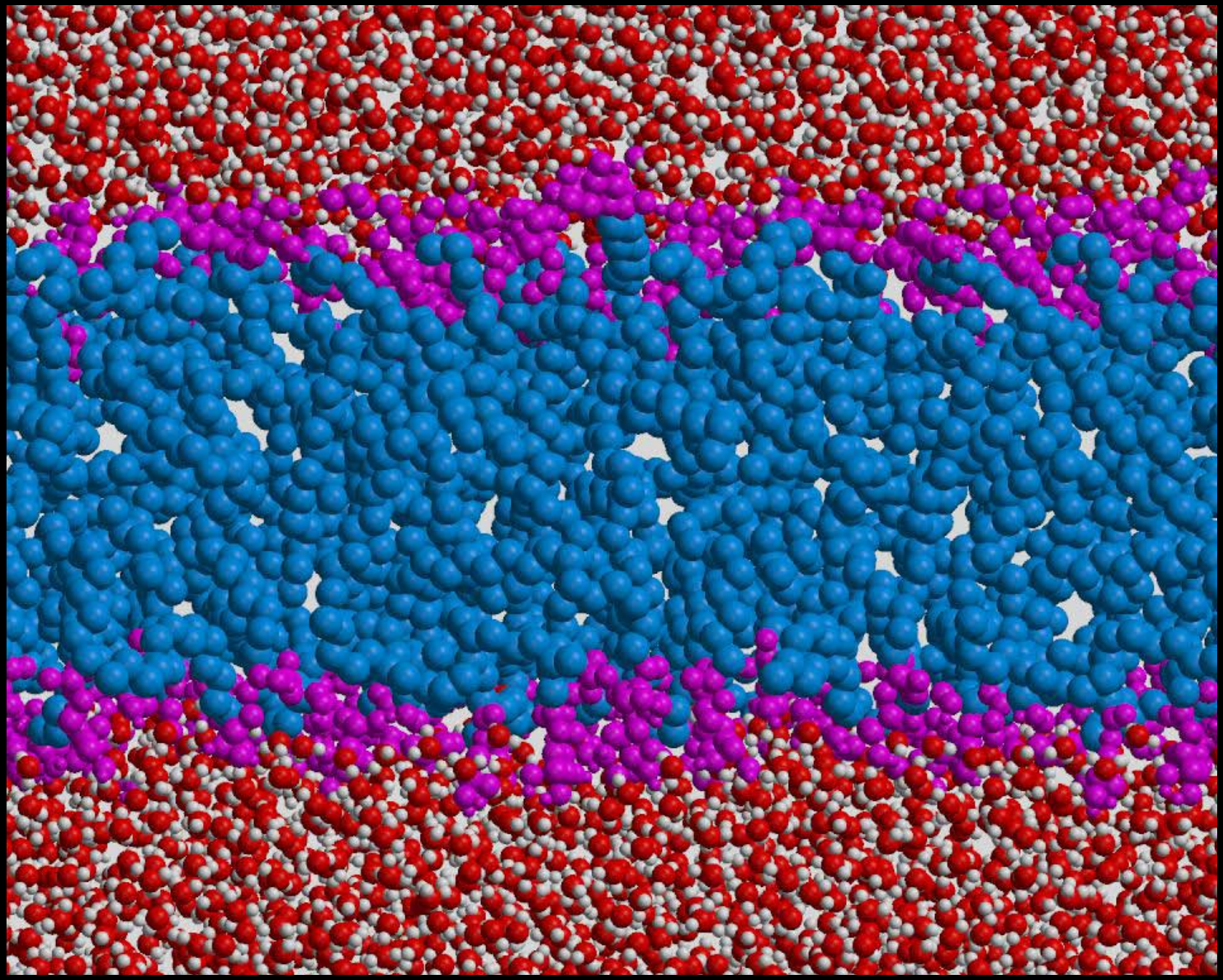
Biominerals



Stable Isotopes

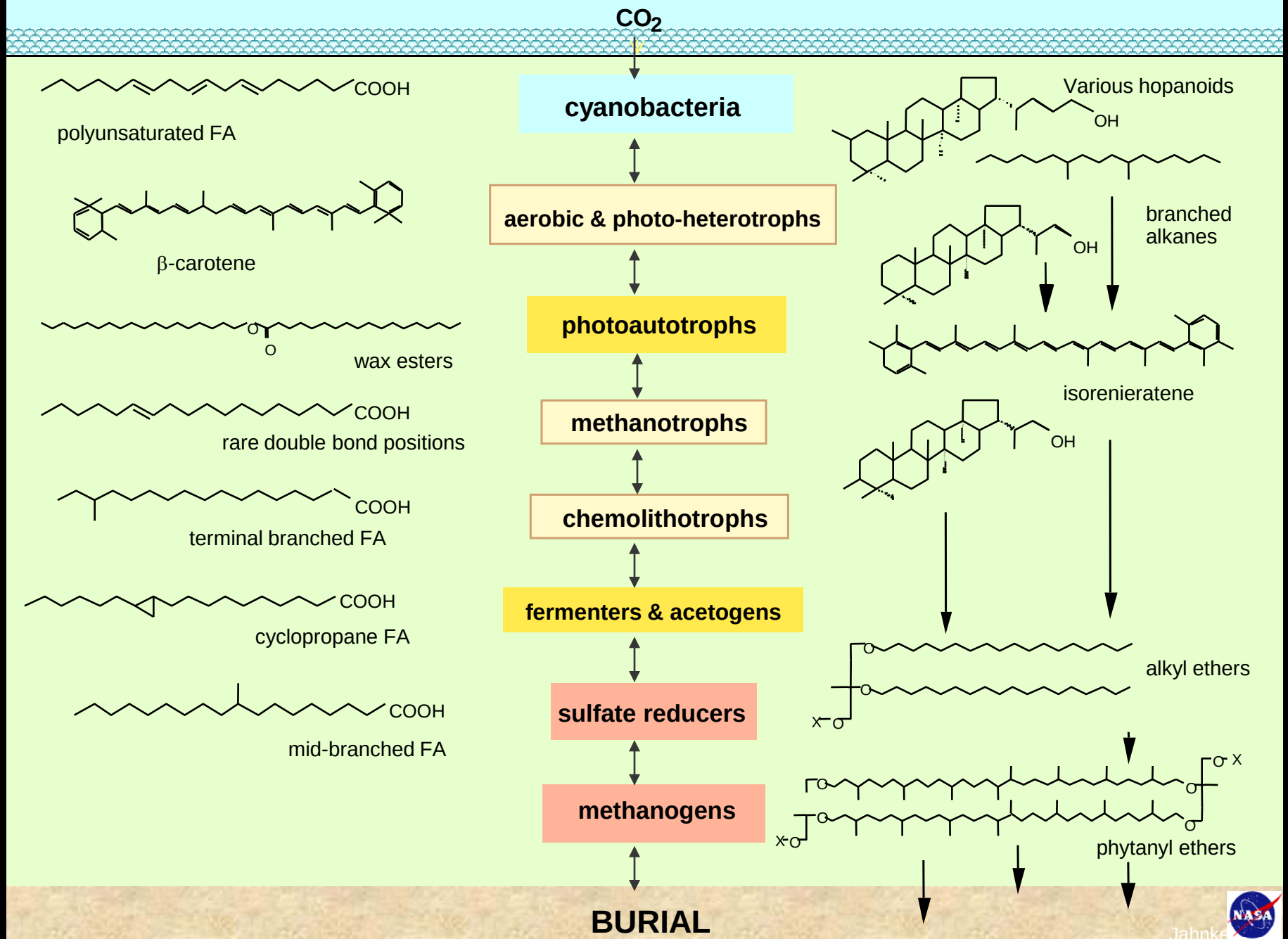
Molecular (Biomarker) Structures

- Best molecular biomarkers have known biological functions & are diagnostic for specific biota
- Can indicate: presence of life, microbial physiology & activity, paleoenvironmental conditions
- Labile (e.g., RNA) & stable (e.g., certain lipids) are suitable for modern or ancient samples, respectively
- Large, complex molecules (e.g., RNA, lipids, proteins) can be highly diagnostic for specific biota
- Biomarkers in sediments are altered by microbial & geological processes: thus durable (hydrocarbon) structures are more durable & better-preserved
- Environmental context (rock type, mineralogy, environmental history, etc.) is crucial



A. Pohorille, Ames Research Center

BIOMARKERS ARE COMMUNITY SIGNATURES

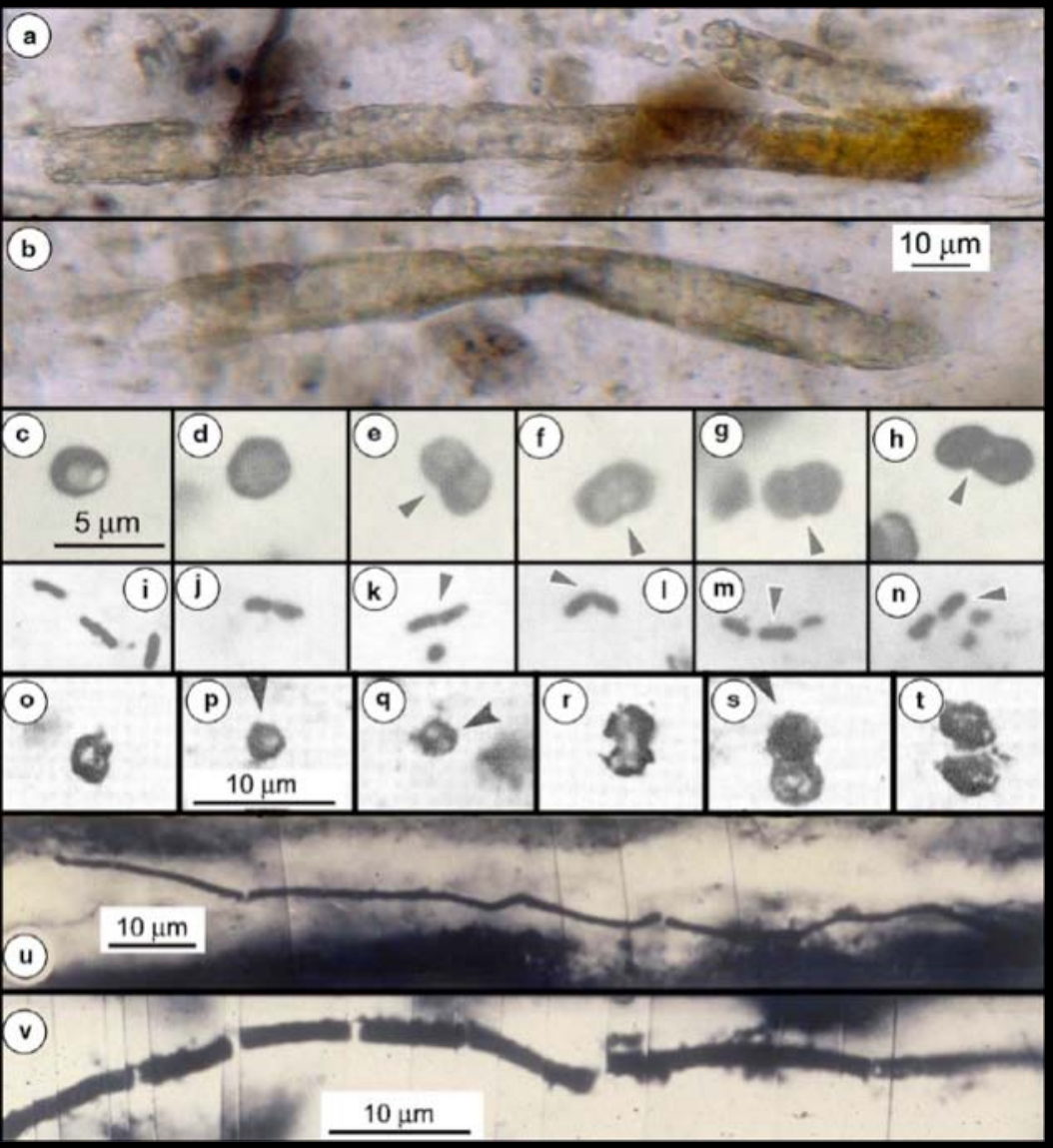


Jahnke

Cellular and extracellular morphologies

- Microbial cell populations can have characteristic size and shape distributions
- Physical forces dominate the shapes of objects smaller than ~1 micron
- Typically difficult to infer function from shapes, although associations among objects can be diagnostic
- Compositions of objects (e.g., organic?) offer critical information
- Environmental context (rock type, mineralogy, environmental history, etc.) is crucial for proper interpretation

Precambrian Microfossils

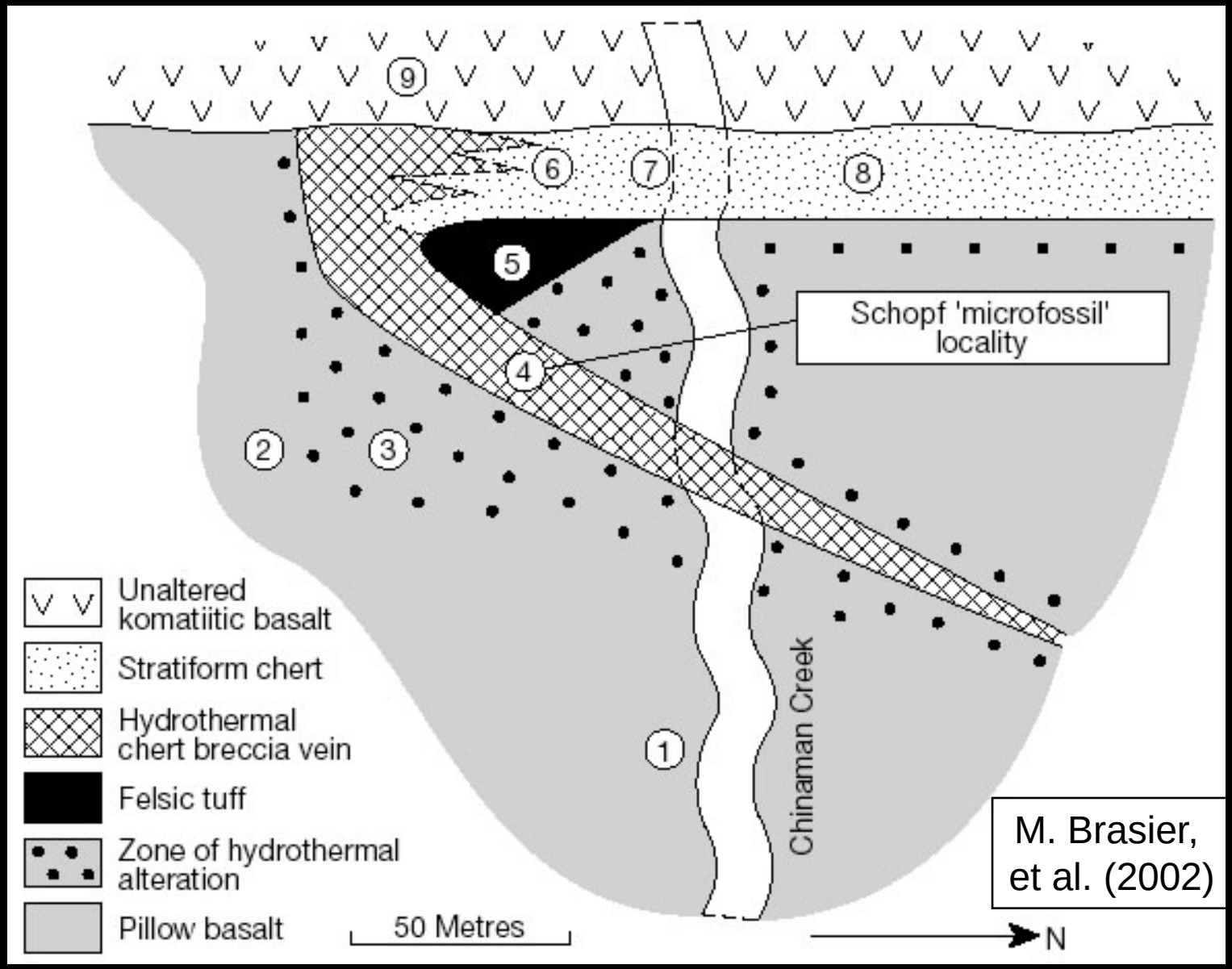


Apex Basalt (age: 3400 Ma)
Warrawoona Gp., Australia

HYC Pyritic Shale (age: 1500 Ma)
Barney Creek Fm., Australia

Apex Basalt sampling site

Environmental context of the fossiliferous chert

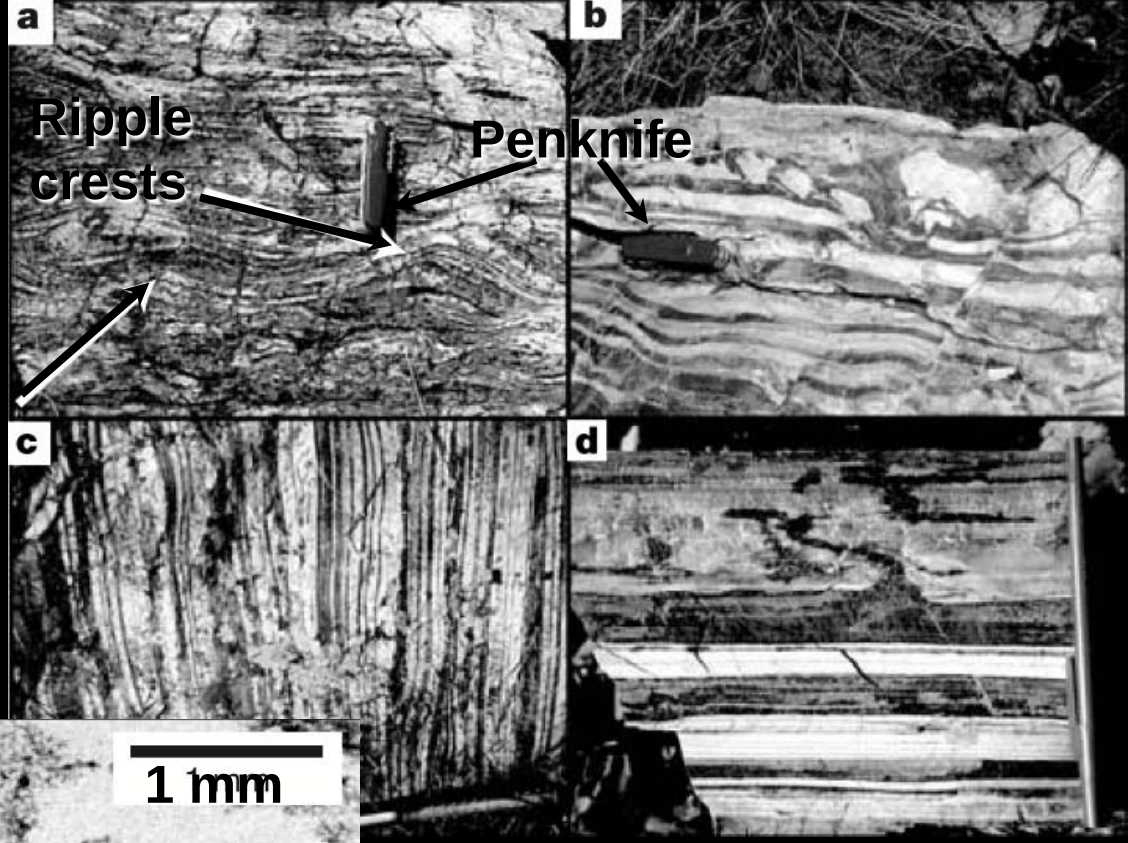


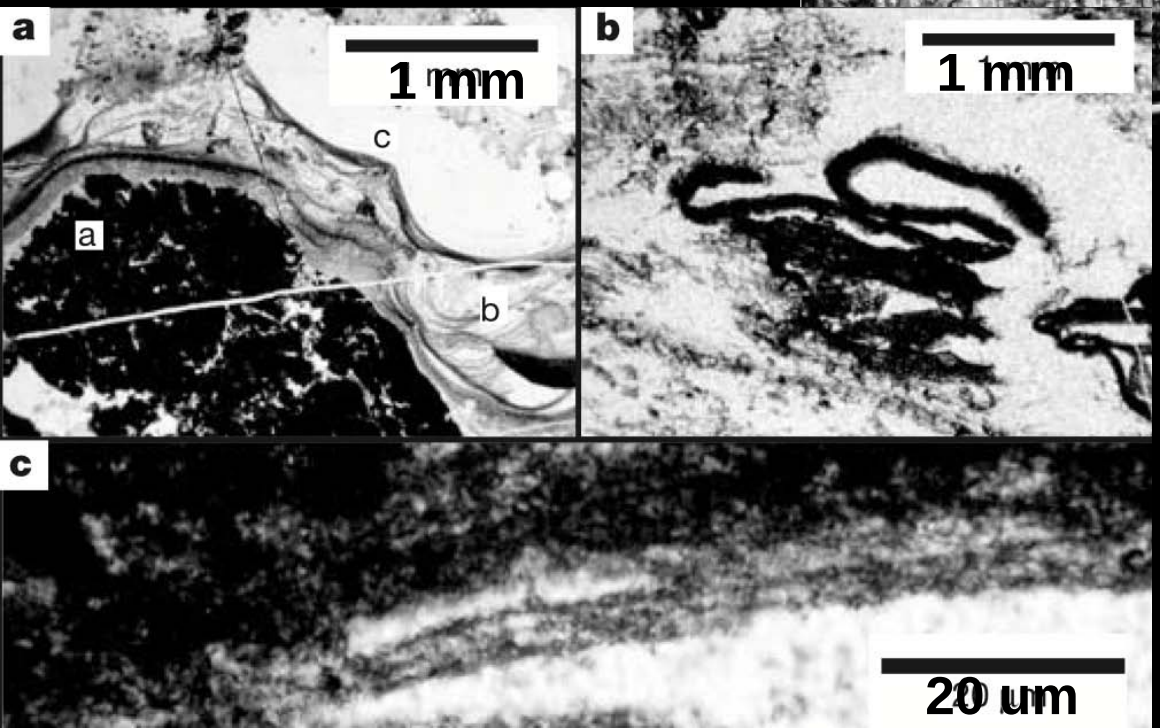
Biofabrics & Community Structures

- Can reflect shapes of microbes, motility, community structure, exudates & biominerals
- Architectures reflect interactions between biota & their environment
- Environmental changes can alter the biofabrics that are integrated into larger, community level structures (e.g., biolaminae & stromatolites)
- Abiotic processes can mimic community structures; must document morphology & paleoenvironment to demonstrate biogenicity
- Environmental context (rock type, mineralogy, environmental history, etc.) is crucial to interpretation

Photosynthetic Microbial mats in 3,416 Ma coastal environments

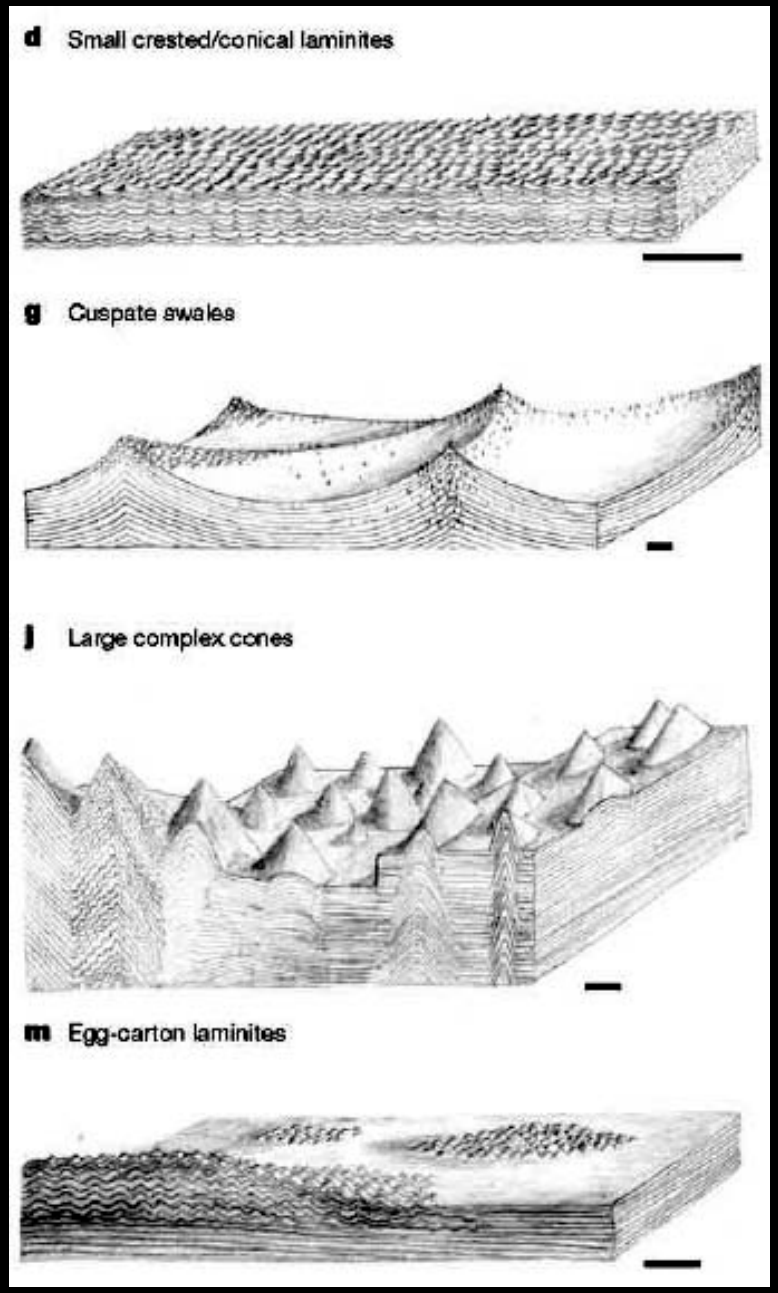
M. Tice & D. Lowe
Nature, 431 (2004)

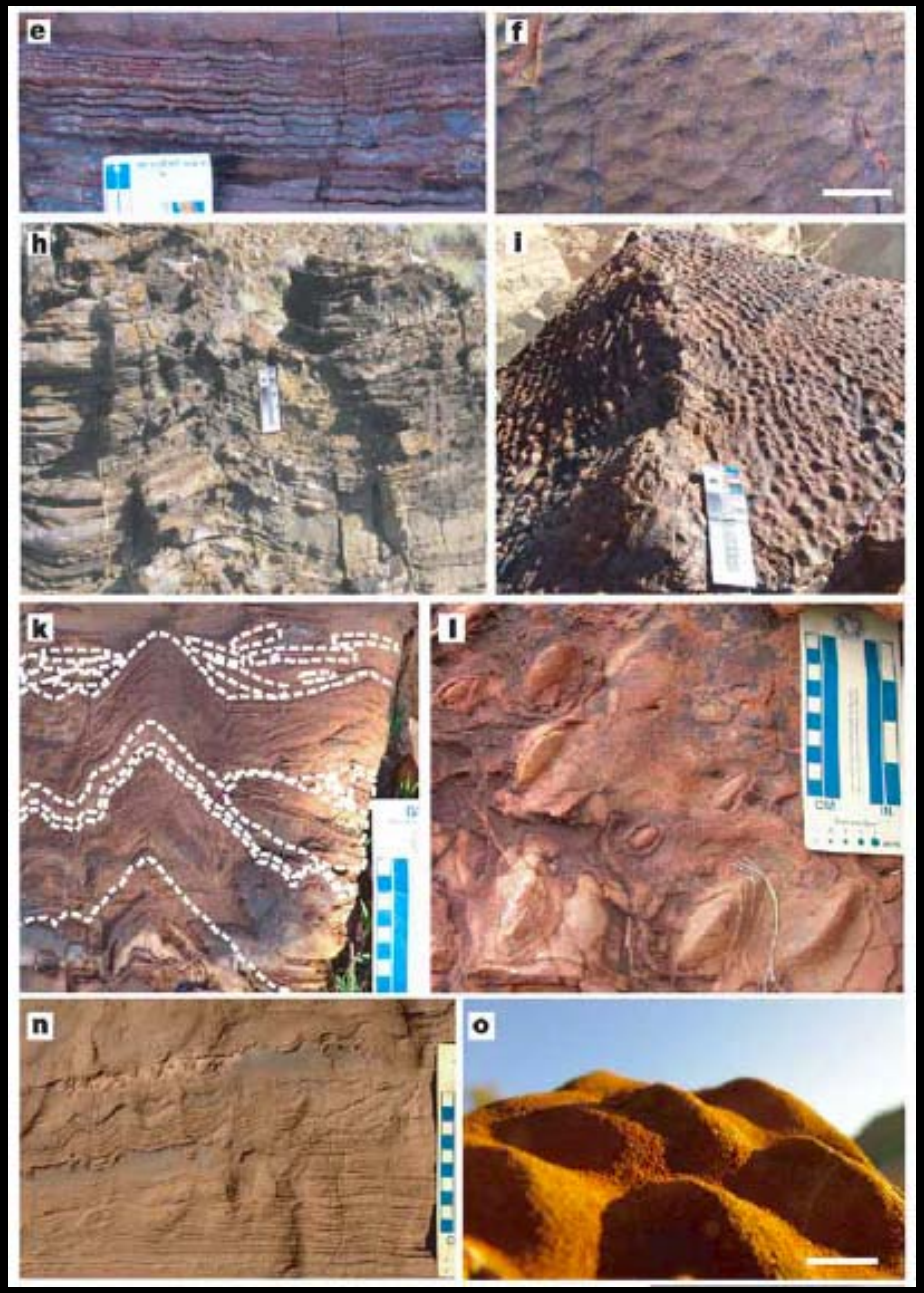




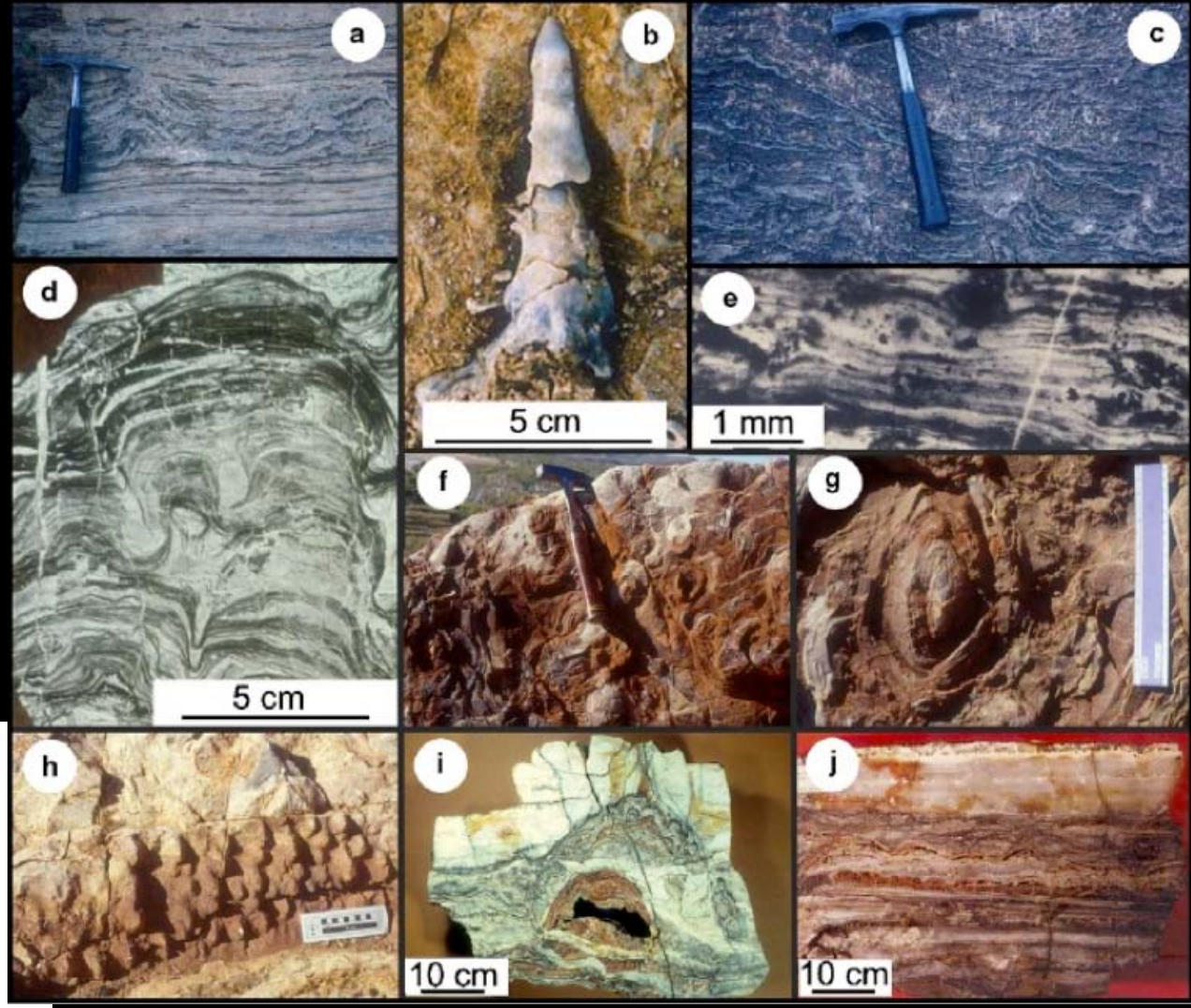
Organic photosynthetic biofilms preserved in coastal sediments (also in 3.2 Ga sands; Noffke et al., 2006). Minimal evidence of hydrothermal activity .

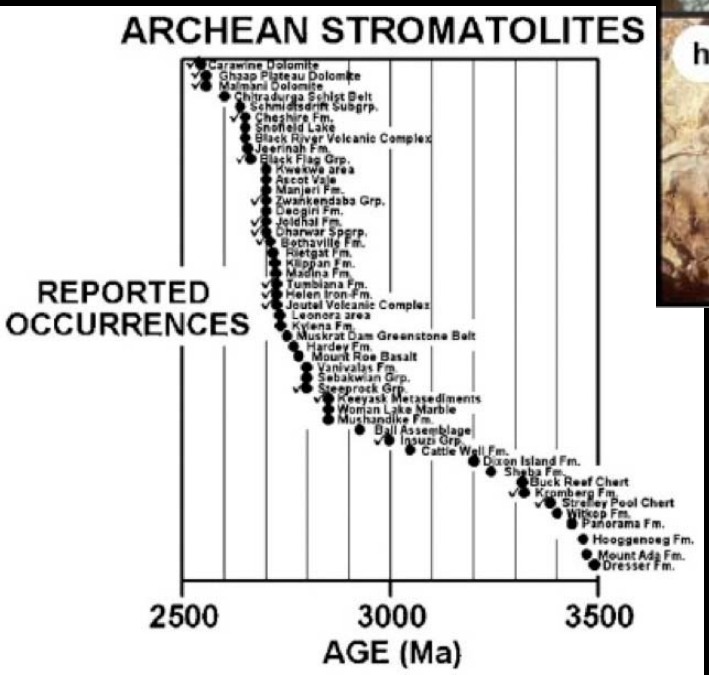
Stromatolitic Reef, 3.43 Ga Strelley Pool Chert (Allwood et al., 2006)



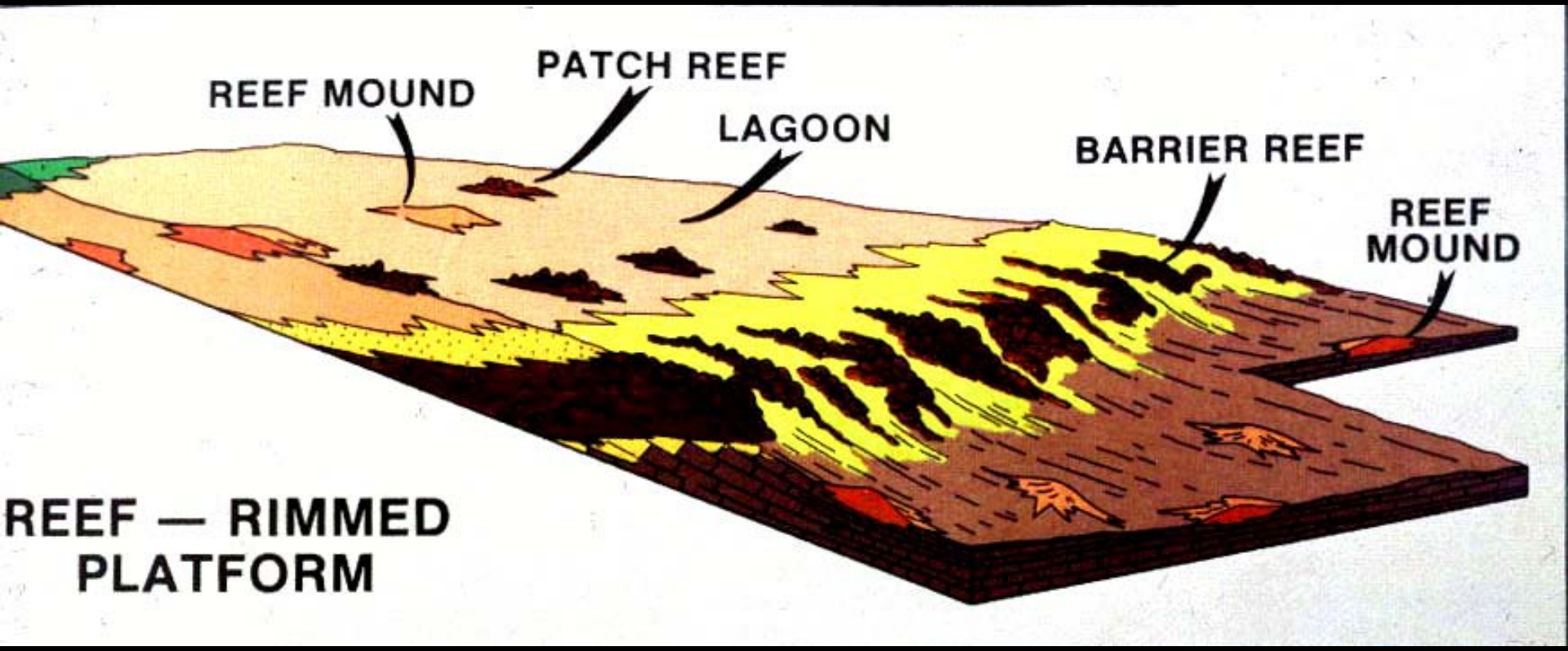


Archean Stromatolites

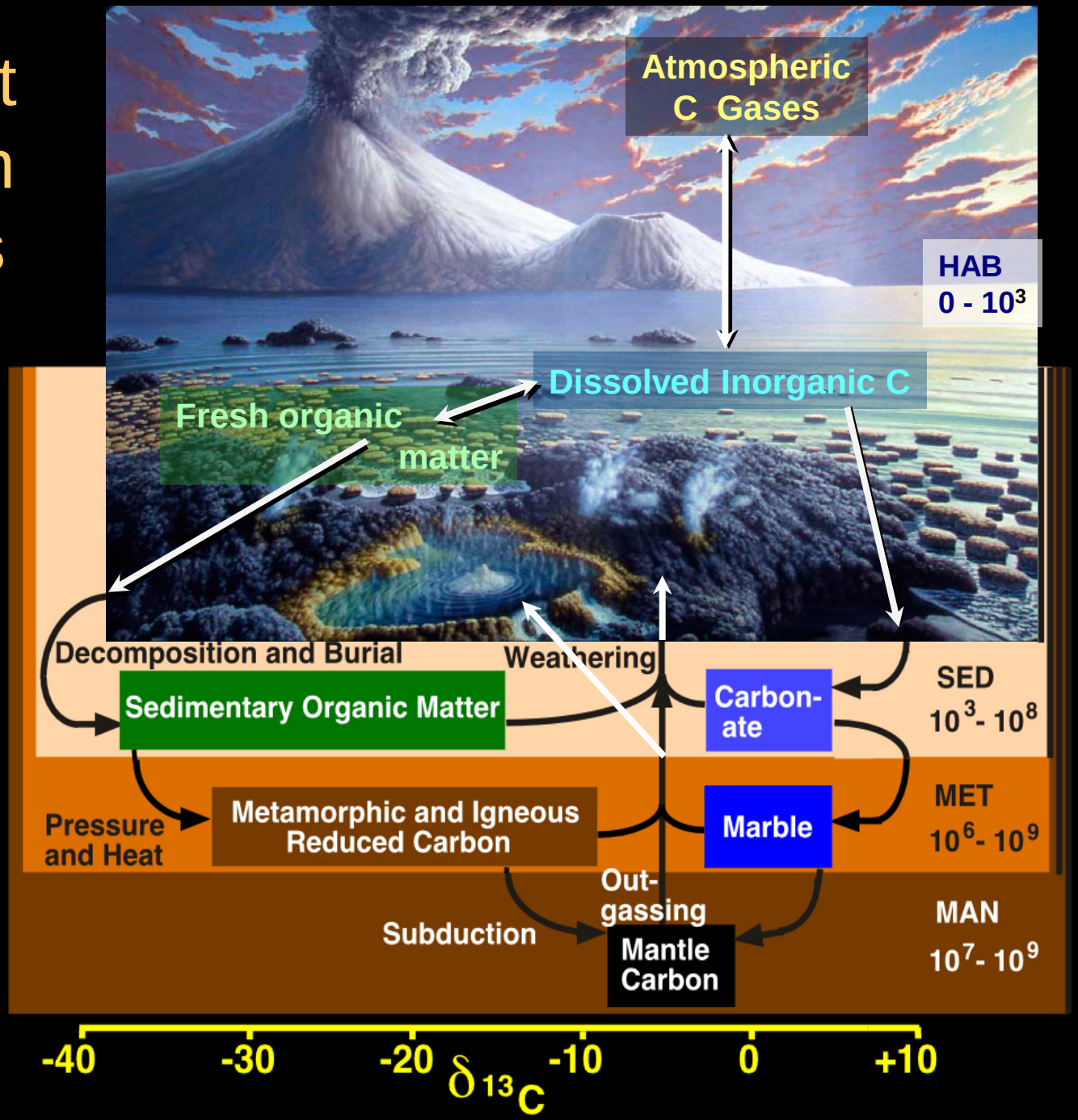




J. W. Schopf, et al. (2007)


REEF MOUND
PATCH REEF
LAGOON
BARRIER REEF
REEF MOUND
REEF — RIMMED PLATFORM

Ancient Carbon Cycles



Productivity, Organic Burial, and Redox Reservoirs

C flux,
x 10^{12} mol/yr

9000

$CO_2 + H_2O \rightleftharpoons CH_2O + O_2$

Photosynthesis

Respiration

8999

Atmospheric O_2

Erosion, Thermal Destruction

Sedimentation

10

Fe^{2+}

S

Biological Redox Reactions
Sedimentation

Buried Organic Carbon

Plus Sulfide from Sulfate Reduction

Reduced

Buried Ferric Iron

Sulfate in Seawater & Sediments

Oxidized

(Des Marais, 2002)

Attributes of Archean Biosphere (~ 3.4 Ga)

- Microfossils & associated reduced carbon in formerly habitable environments (e.g., Apex Basalt)
- Widespread reduced C in coastal environments
- "Life-like" carbon isotopic discrimination
- Biofilms in energetic (migrating sands) sedimentary environments (Moodies Group, S. Africa)
- Stromatolitic reefs with diverse (photosynthetic?) mat morphologies (e.g., Strelley Pool chert, W. Australia)
- Endoliths? (Barberton Belt, S. Africa, pillow basalts)
- Benthic life was resilient & diverse; plankton TBD

Topics in this Talk

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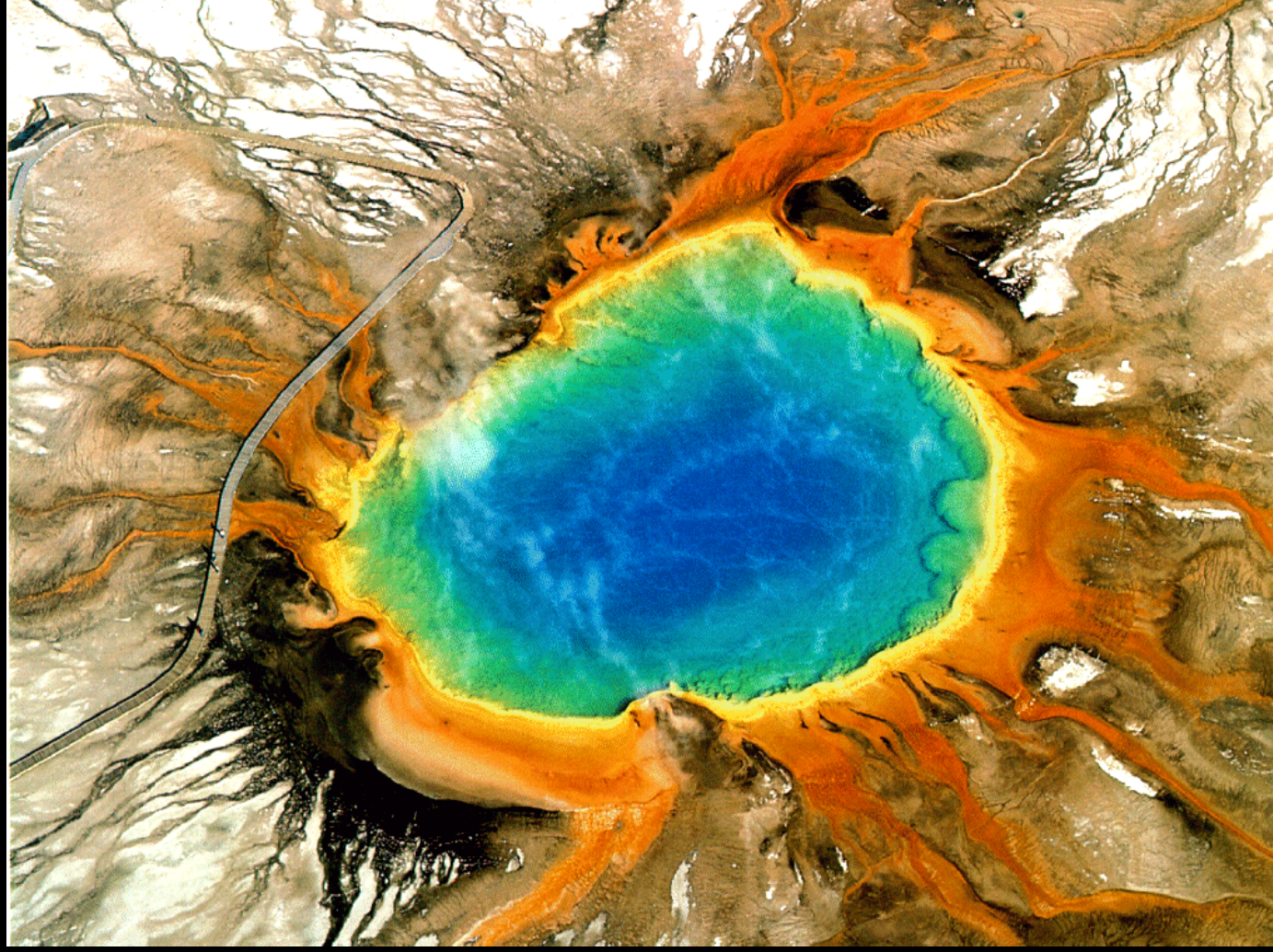
Minerals & Rocks that Preserve Fossil Records

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)

Thermal spring sites are ideal to search for evidence of life on Mars



“Oases”: sources of near-surface water
Reduced chemical species provide sources of energy for life
Mineral deposits preserve evidence of environment and life
Range of conditions sustains large diversity of biota
Sites of ancient spring deposits may already have been found

Buried Alive

Excelsior Geyser's rugged crater was created by rare massive geyser eruptions. Surprisingly, it also preserves a record of early life.

For thousands of years, microbes have grown in the runoff channels extending from nearby Grand Prismatic Spring. These vast communities were buried alive as the flowing hot water deposited a crust of silica minerals. The resulting deposit, called sinter, preserves the shape of the microbial mat it entombed. As new mats grew, more layers developed. Today's formation is the result of this interplay between its living and nonliving components.

Yellowstone's hydrothermal features provide a glimpse into the distant past when intense volcanism was widespread on the young Earth. The lifeforms found here help scientists understand the type of life that likely arose and diversified billions of years ago on our planet.

Layers of sinter (above) form the geyser wall and are the preserved remains of ancient microbial communities.

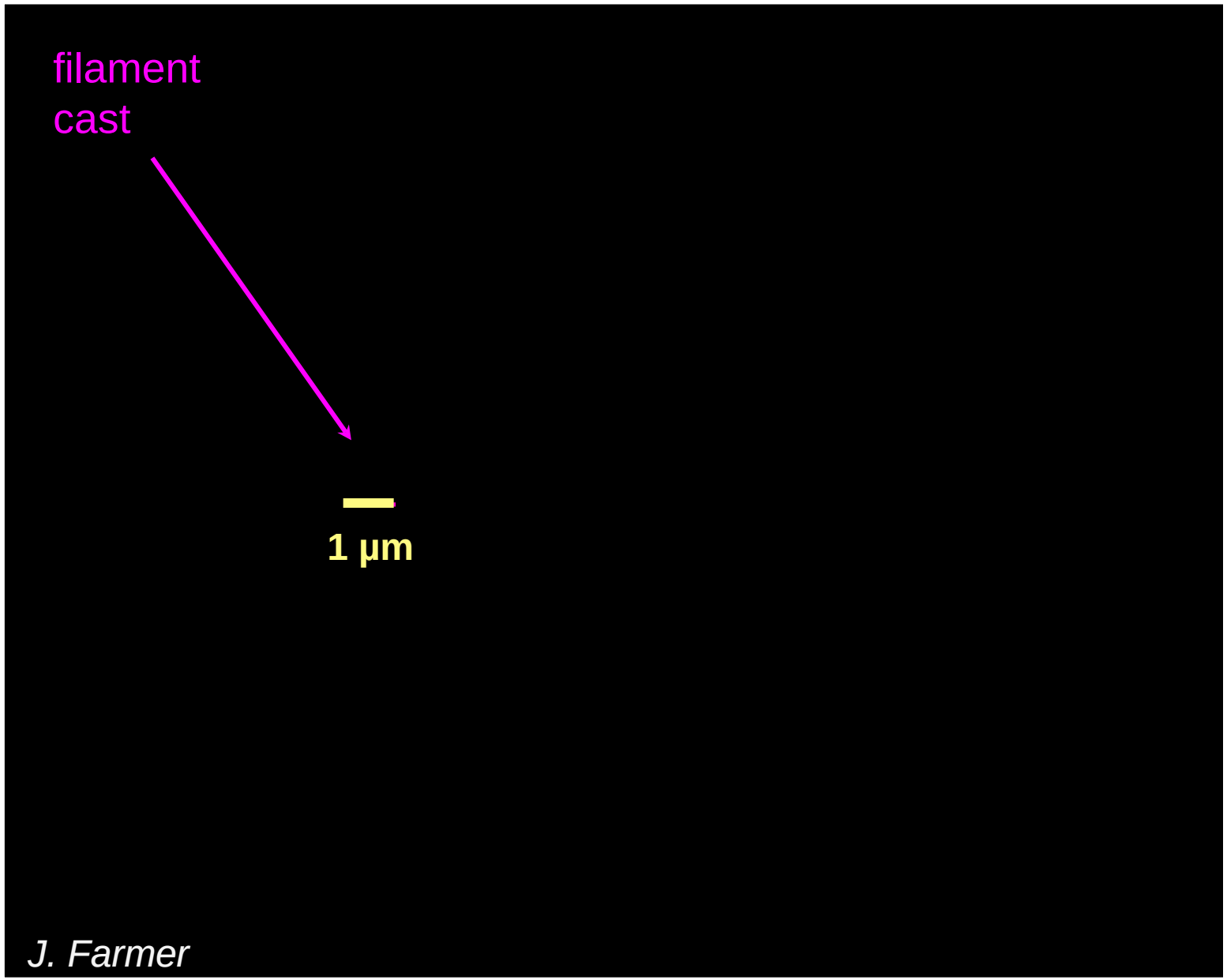
Life Beyond Earth?

- Formations that entomb microbes in Yellowstone's geysers and hot springs may offer clues in the search for life on other worlds.
- Volcanic hot spring systems are believed to have existed on other planets in our solar system.
- If similar formations are found, they may contain evidence that life existed elsewhere in the universe.

This exhibit made possible by a generous grant to the Yellowstone Park Foundation from the NASA Astrobiology Institute and Lockheed Martin Space Operations

SEM Image of Silica Encrusted *Phormidium* Filaments

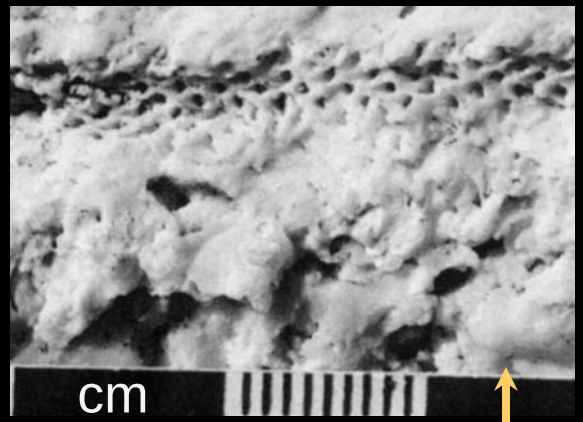
Fountain Paint Pots



Wobegong Thermal Spring Deposit, ~400 Myr old
Drummond Basin, Queensland, Australia

FIGURE 5—Outcrop of the "Wobegong North" sinter.

Yellowstone
Angel Terrace
Tree Branches

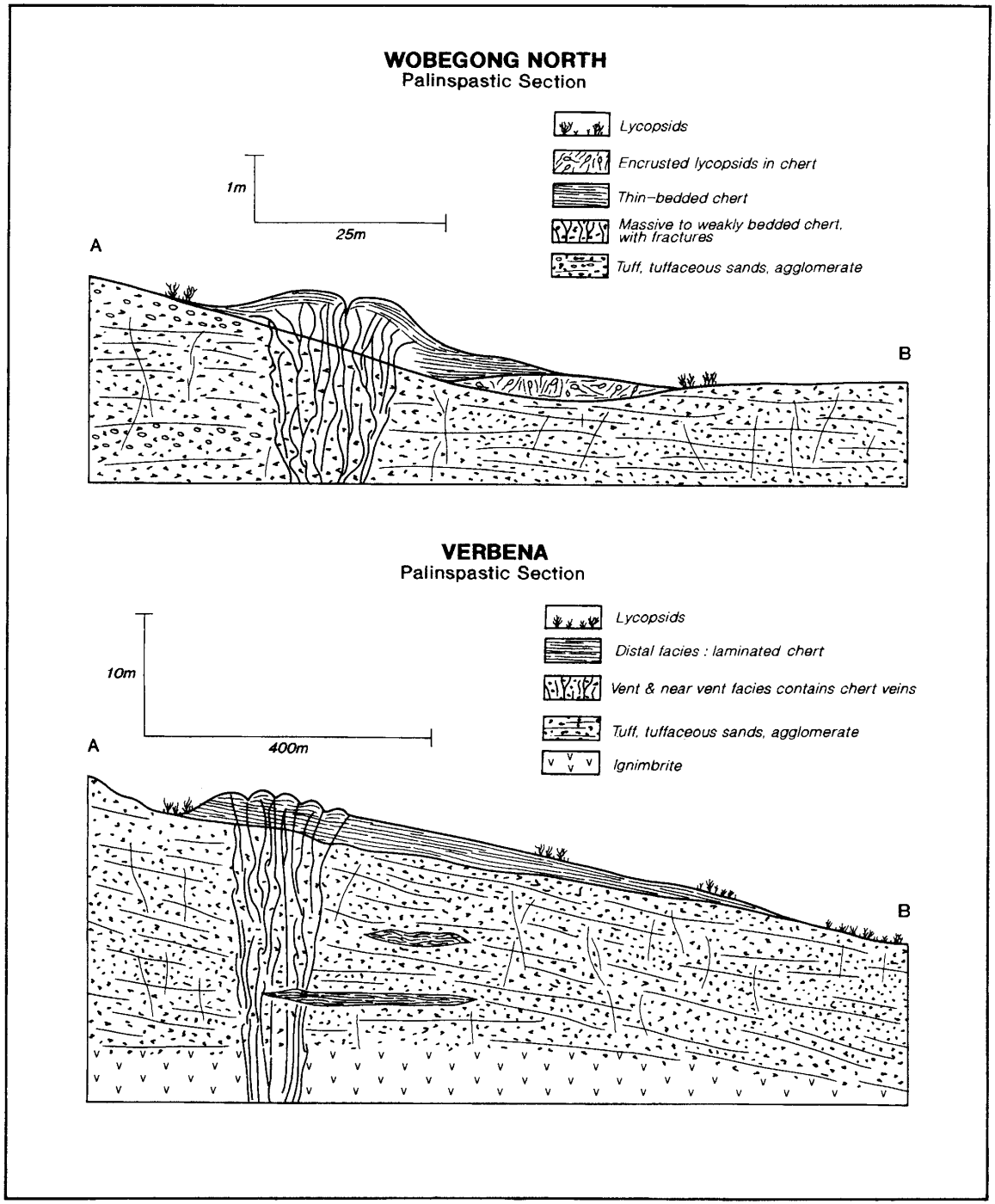


Drummond Basin
Wobegong Sinter

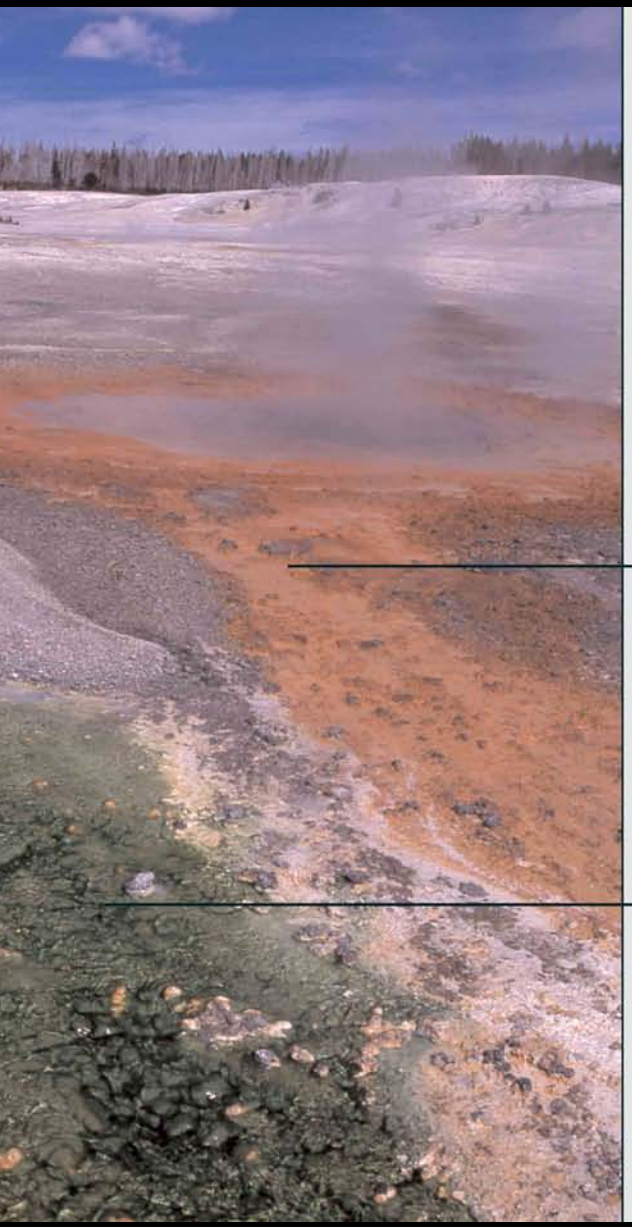
Yellowstone Analogs: Paleozoic Thermal Spring Sinters

Drummond Basin, Queensland, Australia ~400 Ma

Walter, Des Marais, Farmer and Hinman, **Palaios 11**, 497-518 (1996)



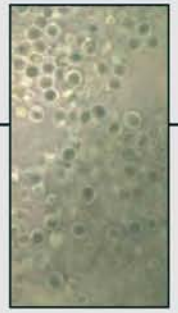
Whirligig Geyser, Norris Geyser Basin



Living Thermometer

Can you imagine living in a geyser? Thermophiles—microorganisms that thrive in heat—are perfectly adapted to living in geysers and their runoff channels. Some live where temperatures are hottest, while others reside in cooler areas. As you look at the colors in and around Whirligig Geyser, you are looking at a "living thermometer."

At 122–140˚F (50–60˚C), Whirligig's runoff channel is hot enough to burn you. Thermophiles living here use iron for energy from Whirligig's iron-rich water, and become coated with rust. These chemical-users are called "chemotrophs."



Thermophilic algae, including *Cyanidium*, inhabit the green channel. Like plants, these tiny single-celled organisms photosynthesize, or use sunlight for energy. These "phototrophs" live where temperatures range from 100–133˚F (38–56˚C).

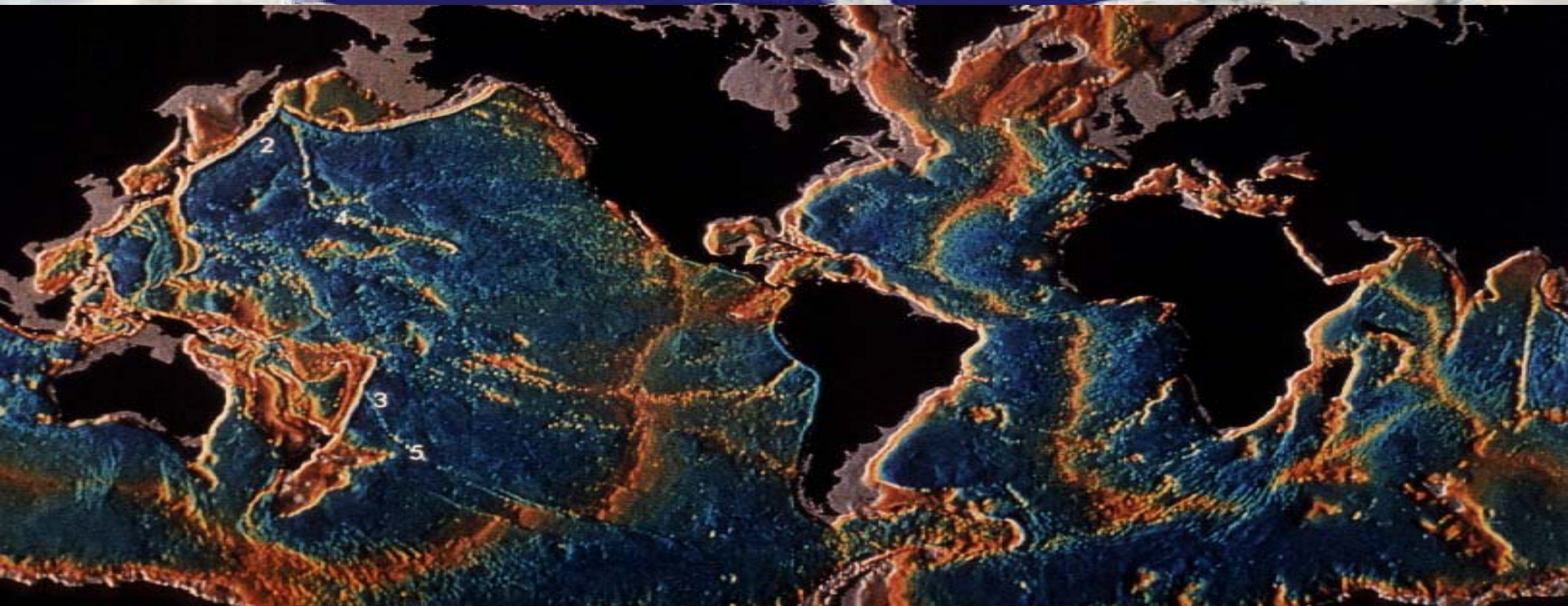
Communal Life

- Norris Geyser Basin is highly acidic. Amazingly, thermophiles living here thrive in heat *and* acid.
- Thermophiles are too small to see without a microscope, but their vast communities are clearly visible.
- The number of thermophiles living beneath a ten-inch square may exceed the number of people on Earth!

Did You Know?

- Scientists study these thermophiles to learn how life has adapted to iron-rich, acidic conditions.
- Mineral deposits here record one of Earth's most extreme habitats. Scientists use this record to aid their search for similar deposits and possible life on Mars.

This exhibit made possible by a generous grant to the Yellowstone Park Foundation from NASA Astrobiology Institute and Lockheed Martin Space Operations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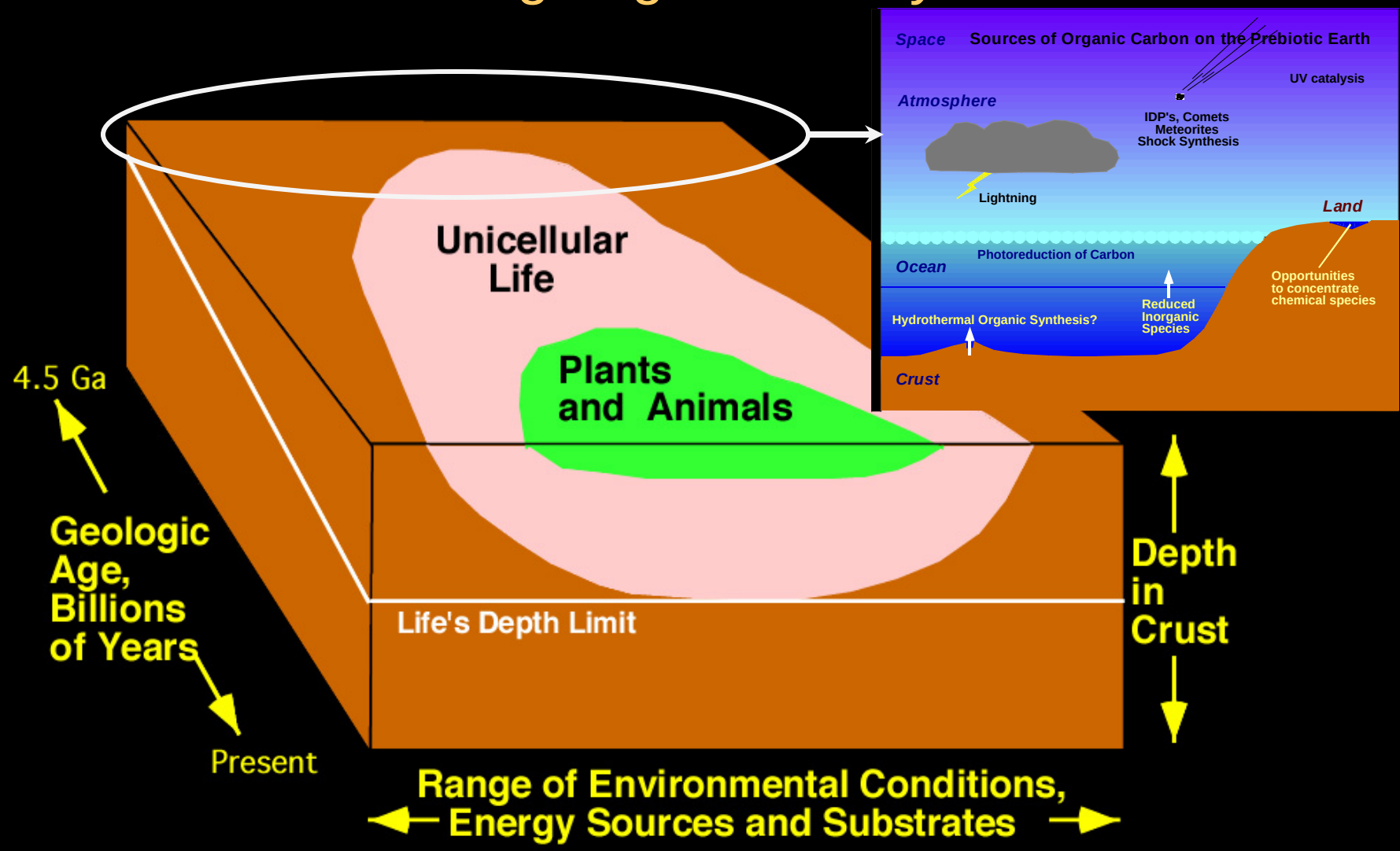
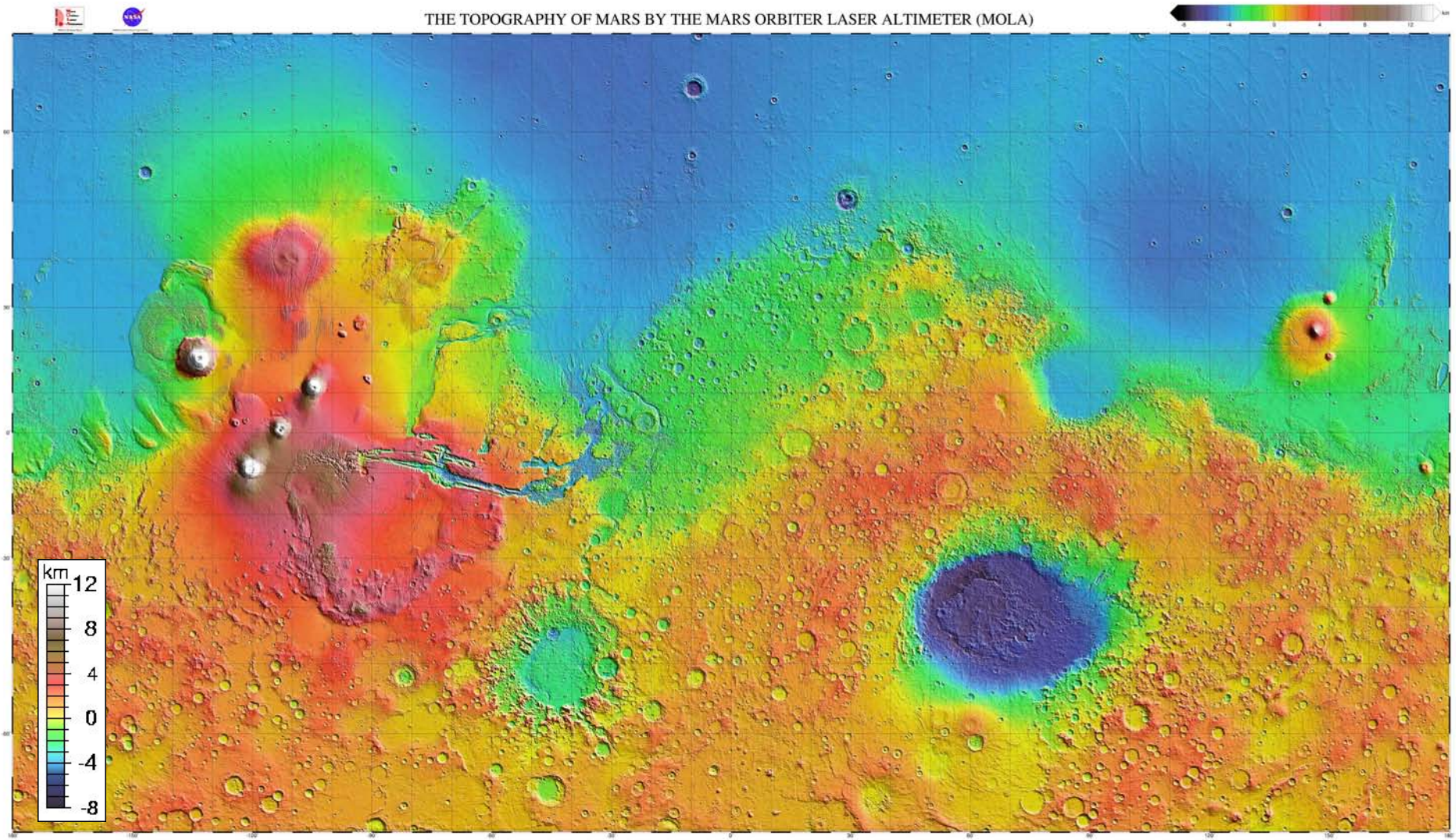
Knowledge of early planetary environments is critical to understanding origins & early evolution of life



BUT: Earth's earliest record has been largely obliterated..


THE TOPOGRAPHY OF MARS BY THE MARS ORBITER LASER ALTIMETER (MOLA)
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