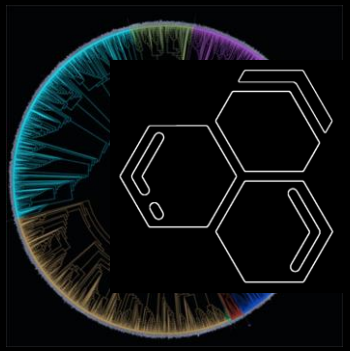


From Habitability to Life

An Ecosystem Approach to the Search for Life Beyond Earth

Presentation to the NAS/Astrobiology Science Strategy for the Search for Life in the Universe Committee – March 6, 2018

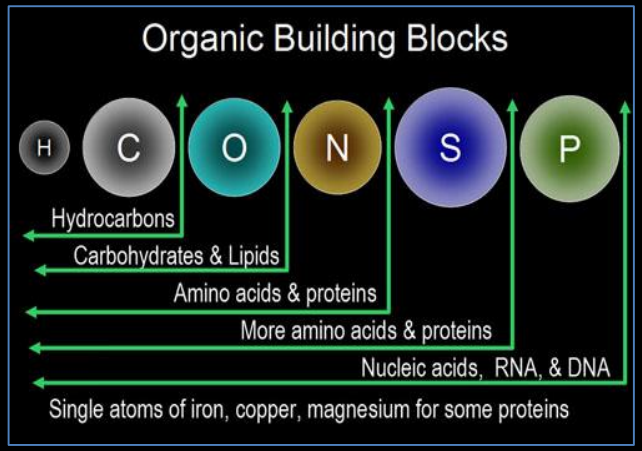
Nathalie A. Cabrol
SETI Institute Carl Sagan Center

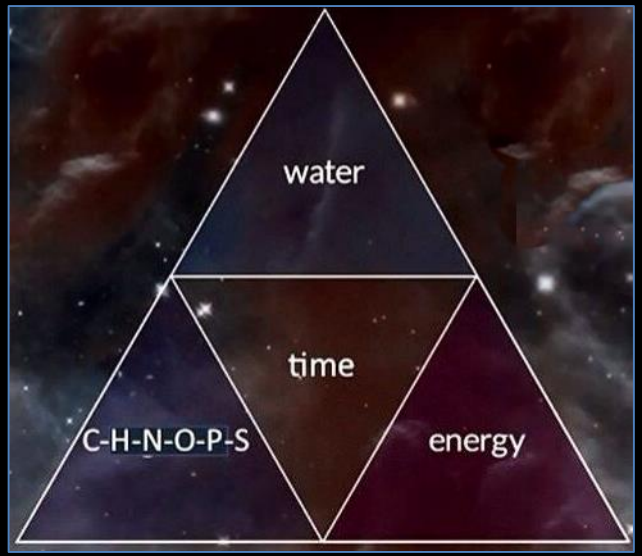
A Different Perspective on Exploration

- From habitability to biosignatures: *Transition in intellectual framework.*
- Change in the nature, perspective, and scale of exploration.
- New exploration tools and strategies.
- Missing links in missions.
- Exploring coevolution potential in the Solar System (Mars & Icy Moons).

Exploring Planetary Coevolutions: Key Questions

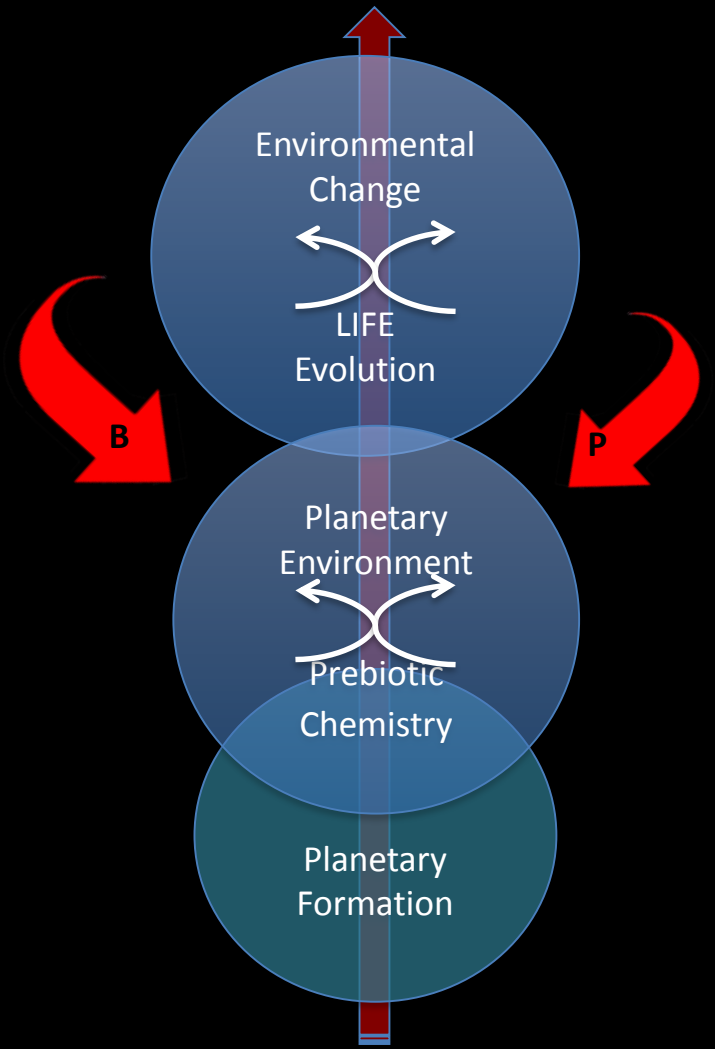
- What are the data available, how to work with them to build intellectual frameworks and generate reasonable ecosystem and coevolution hypotheses?
- What are the strategic knowledge gaps?
  - What is critically missing right now to test our hypotheses?
- What are the next steps to fill these gaps?
  - Methods, instruments, technology, detection/identification thresholds, missions





Characterization of Habitability

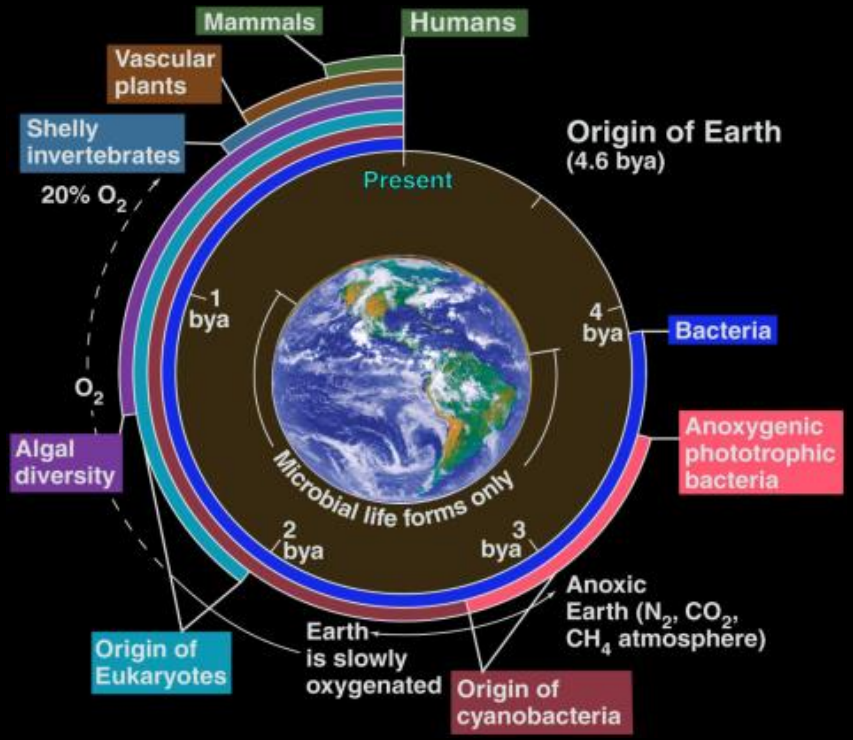
- Favorable planetary environmental conditions for:
  - The development of life.
  - The sustainability of life (as we know it).
- Life is a *passive* agent.



Searching for Biosignature

- Hypothesis: Life could have been present → Introducing life in an environmental system.
- → Biosphere, biozones, ecosystems.
- Life is *an active agent* of interaction and transformation:
- → *Coevolution* of life and environment
- Coevolution is dynamic:
  - Spatial & temporal evolution.

Biogeochemical Cycling & Energy Flow

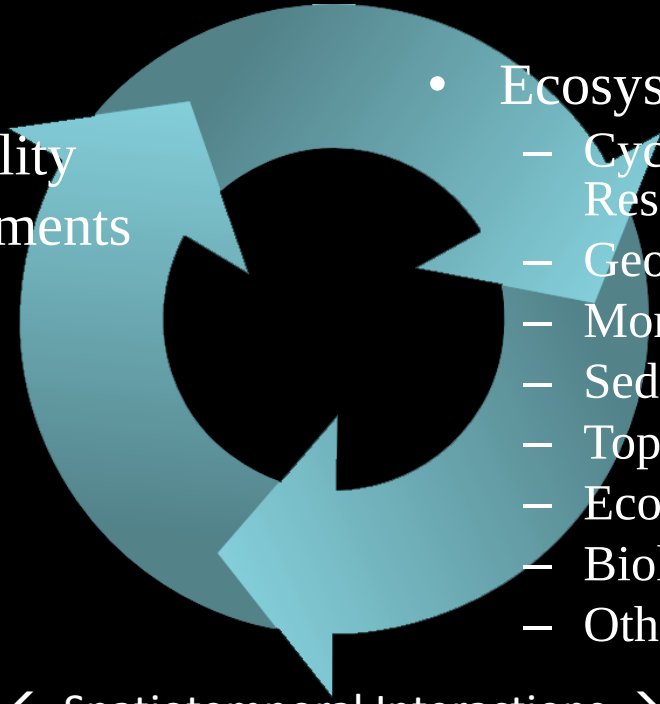


- Microbes profoundly shape the Earth's environment:
- Environmental changes affect microbial habitats, biogeochemical cycling, and energy flow.
- Interactions affect biogeochemical cycles (atm→ocean→crust) by altering the chemistry of C, N, S. P…
- Interactions are recorded in the atmosphere, C, S isotope patterns, crustal chemistry, organic reservoirs, biogeosignatures, other.

Habitability ≠ Habitats

ENVIRONMENTAL PARAMETERS

- Habitable Zone
- Planetary Habitability
- Habitable Environments
  - Lake
  - Delta
  - Hot Spring
  - Rock
  - Sediment
  - Ice
  - Other



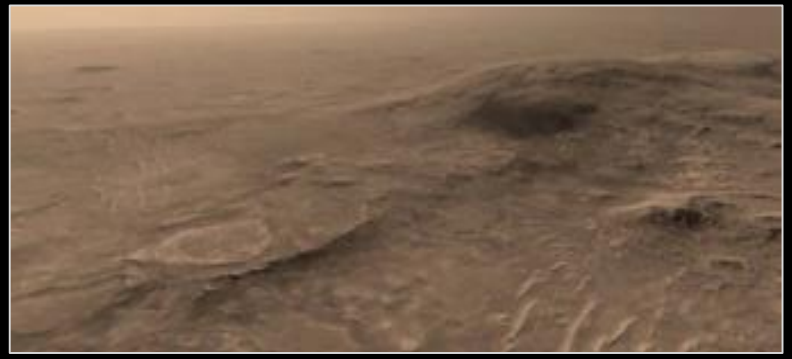
LIFE

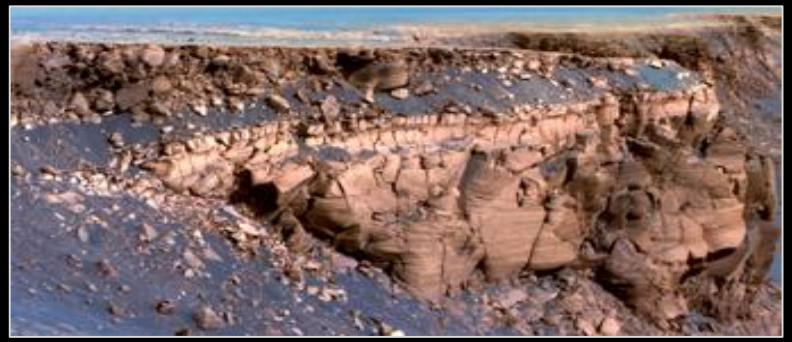
- Ecosystems
  - Cycling, Energy Flow & Resources
  - Geography/Geology/Tectonics
  - Morphology, Mineralogy
  - Sediment Texture
  - Topography/ Slope Exposure
  - Ecotones
  - Biological Dispersal Pathways
  - Other

← Spatiotemporal Interactions →

Exploration of Planetary Biospheres and Ecosystems

- How much RS megascale and mesoscale data about habitability inform us of the local habitat potential?
- How much (local) *in situ* data inform us of the broader habitat potential at global scale?
  - Hypotheses & Science Questions
  - Methods
  - Instrument Payload/Technology
  - Detection/Identification Thresholds
  - Missions

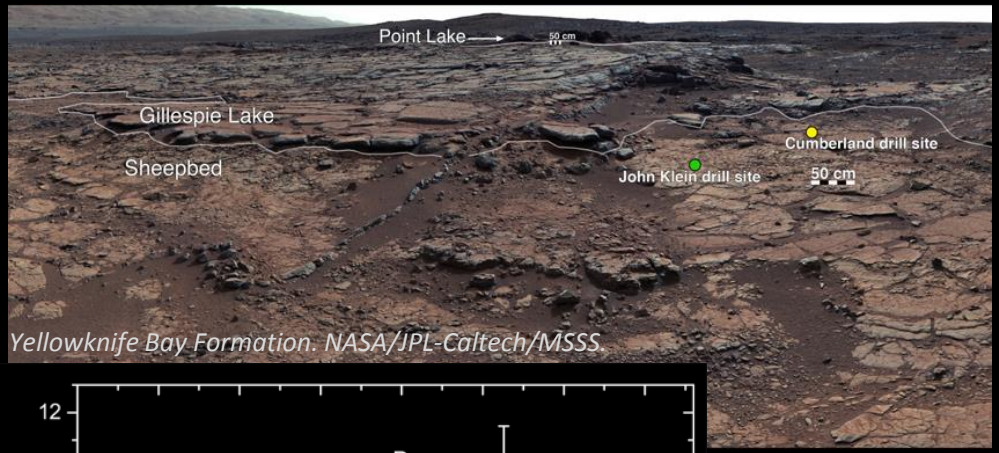




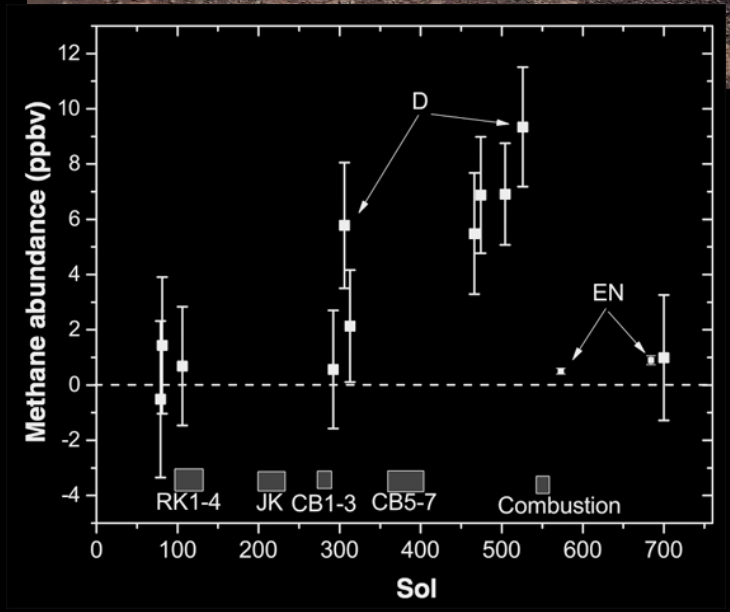
A Martian Coevolution?

Early Mars was Earth-like but never *exactly like* the Earth.
Does it matter?

- Basic elements for a biosphere.
- Evolving environmental envelop.
  - What is unique to Mars?
- Environmental polyextremes
  - Biomass production/preservation?
- Intellectual leaps and their significance for upcoming exploration



Yellowknife Bay Formation. NASA/JPL-Caltech/MSSS.



Webster et al. (2015), Science, DOI: 10.1126/science.1261713.

Elements of a Coevolution

- Environmental habitability.
  - Shelter(s)
  - Energy sources
  - Nutrients
  - Liquid water
  - Carbon source
  - Geologically active planet
- Building blocks of life.

ENERGY

WATER

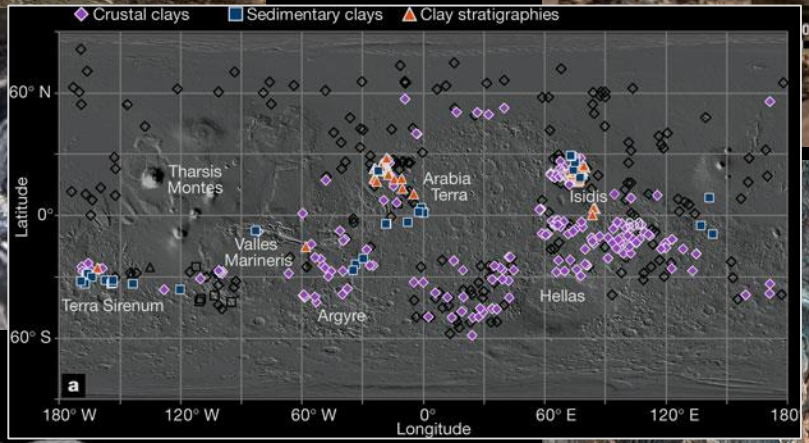
Terrestrial Analogy Principle: *Mars Habitability*

Volcanic activity

Deltas and lakes

Hydrothermal activity

Impact Cratering



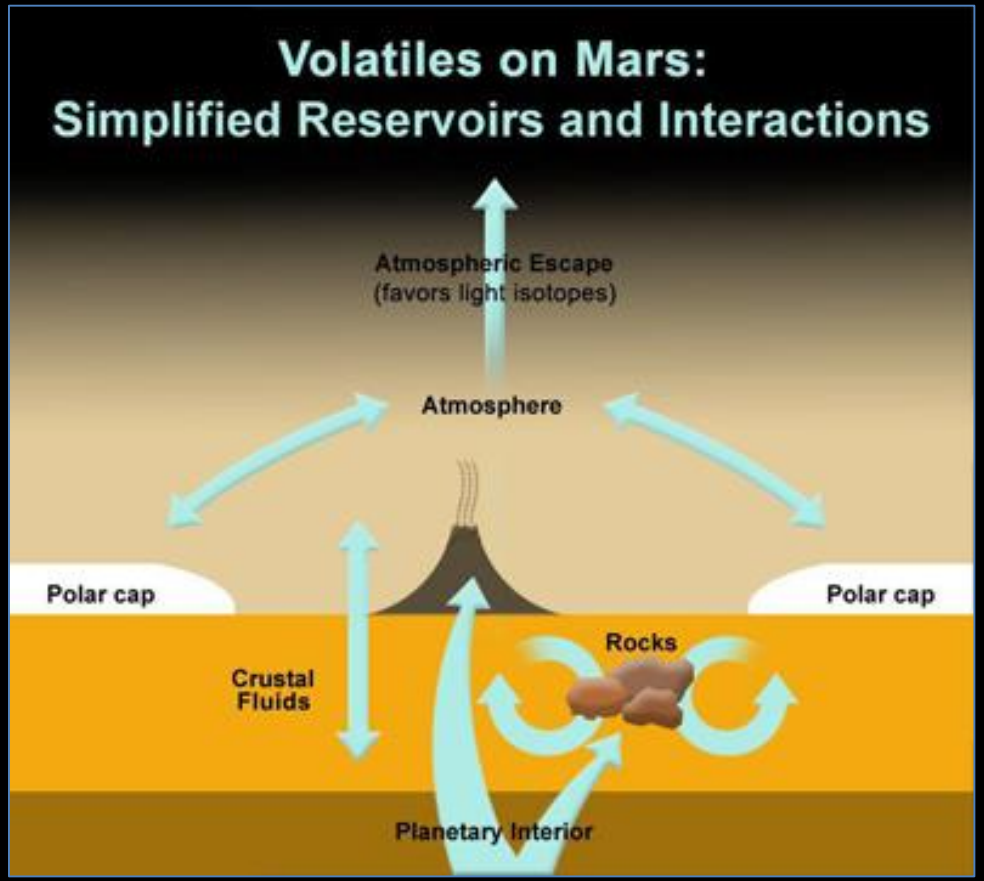
*BL Ehlmann et al. Nature **479**, 53-60 (2011)*

Migrating fluids and rock weathering

Rivers and Basins

Early Mars Biogeochemical Cycling

- Mantle/Crust Exchange
  - Volcanic activity
    - Atmosphere
    - Greenhouse
    - Free energy
    - Reducing power for life



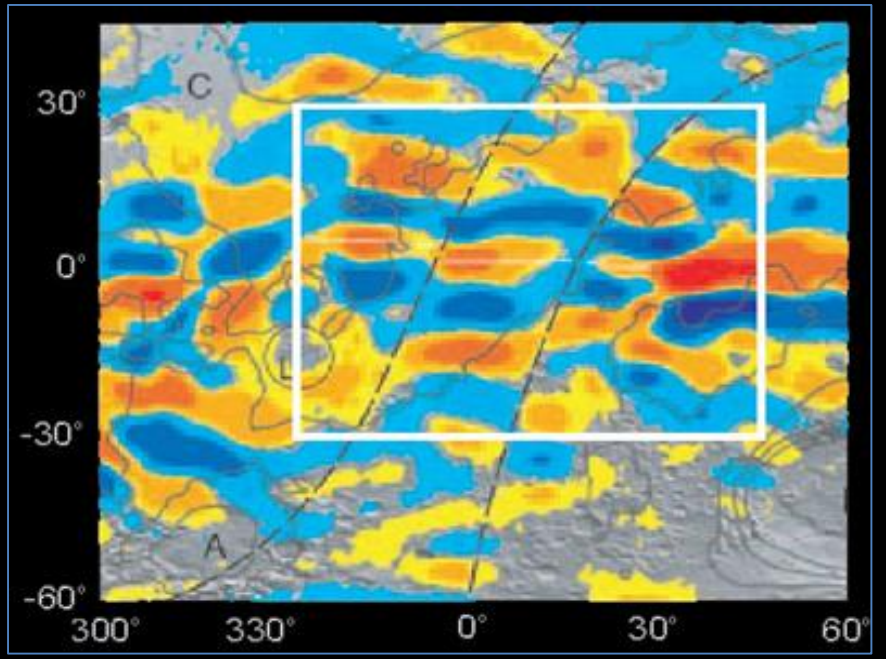
NASA/JPL-Caltech/PIA16463

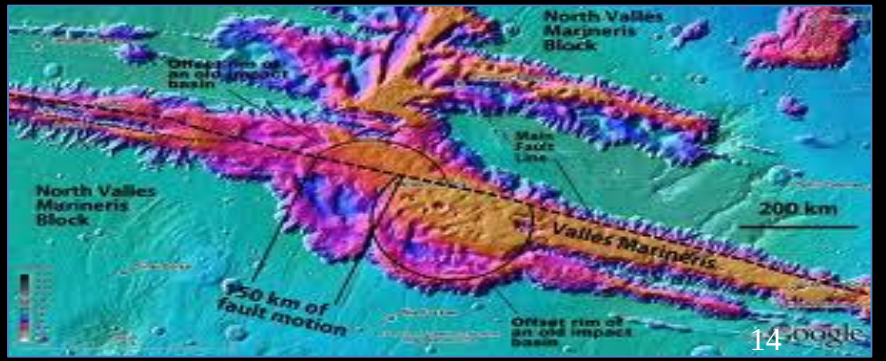
Early Mars Biogeochemical Cycling

- Crustal Dynamics/Tectonics
  - Contribute to maintain the flow of energy and production of nutrients.
  - Expose/Destroy ancient environmental (and biological) record.
- Key environmental habitability and to the preservation potential of biogeosignatures.

Early Mars Biogeochemical Cycling

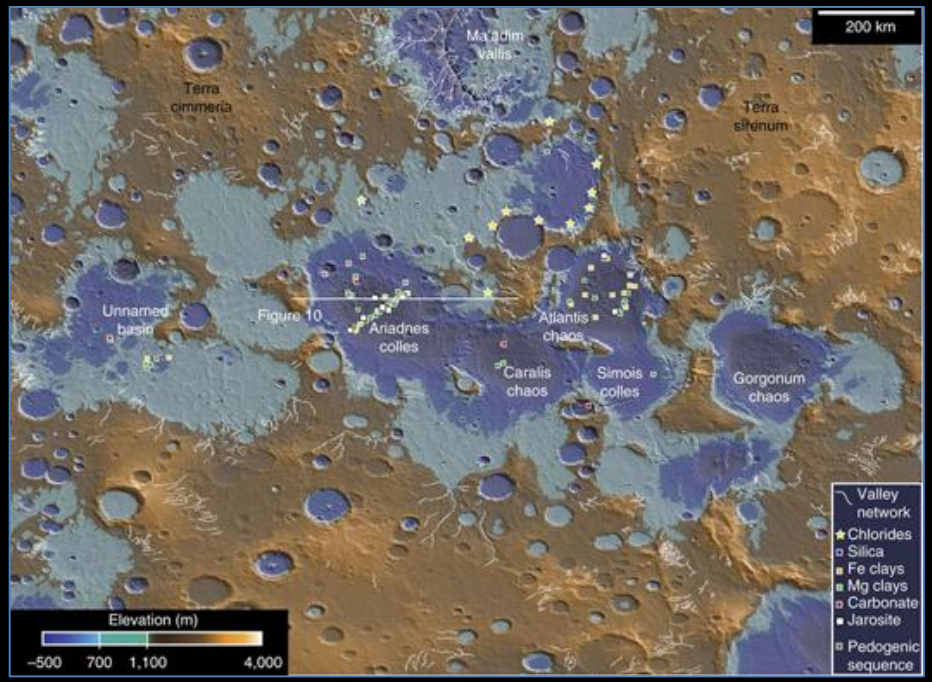
- Plate Tectonics?
  - Magnetic stripes. Magnetic field turns off (4.1 Gyr ago)
  - Valles Marineris, 2-plate system, primitive but ongoing.
  - Recent (10Myr) volcanic activity in VM.





Early Mars Biogeochemical Cycling

- Aqueous Activity
  - Multi-facetted, involved all scales, and all domains.
  - Earth-like Hydrological Cycle? "Sort of"
    - Formed Immature drainage systems.
    - Generated habitable environments → habitats?
    - Chemical evolution, life.

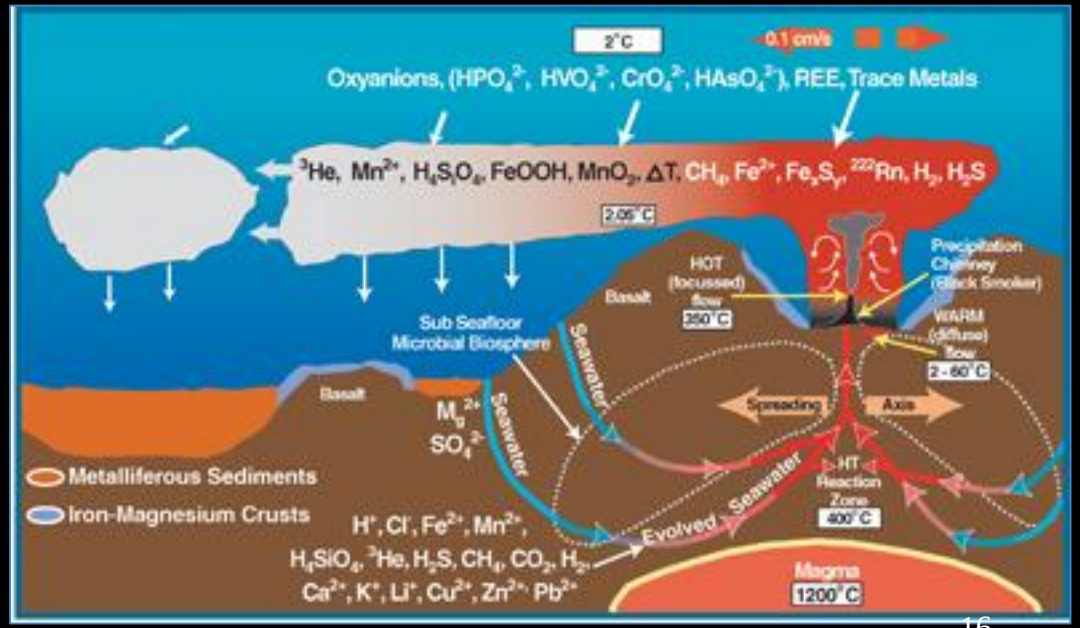


Michalski et al., Nature Com. 157978 (2017)
Eridania Region – Floor, 3.8 Ga

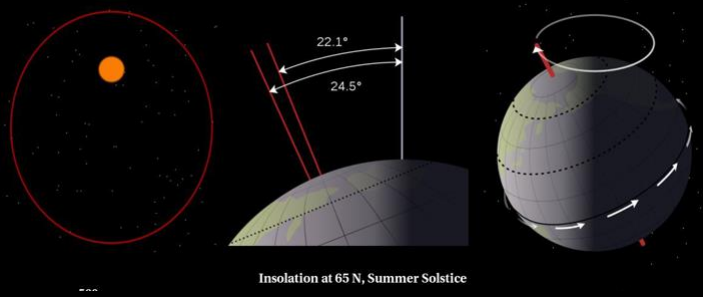
Early Mars Biogeochemical Cycling

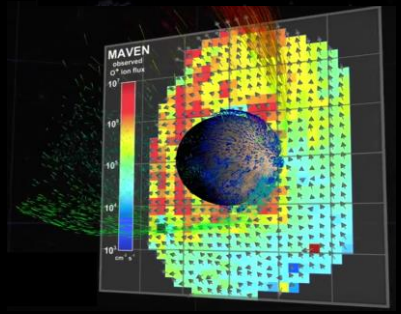
"**Earth's Dark Biosphere**" converting CO2 into biomass, acting as a carbon sink beneath the ocean floor. ~4% of ocean waters circulate in the crust

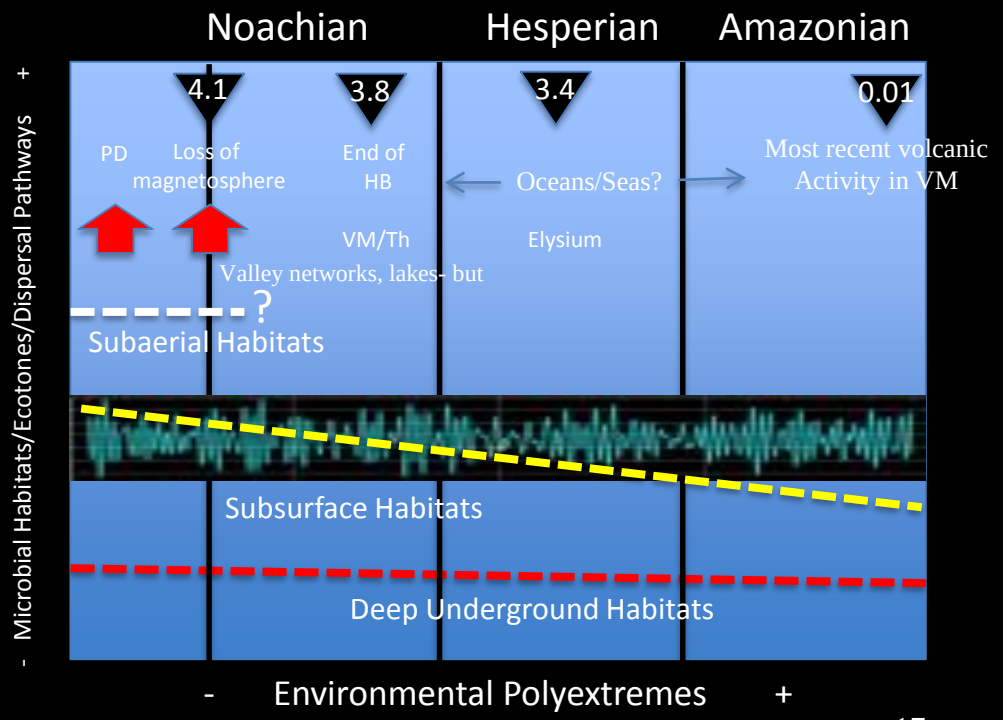
- Ocean/No Ocean?
  - Primary Pre-Noachian/Early Noachian Ocean?
  - Sea-size bodies of water mid-Noachian.
  - Evidence of catastrophic releases in the Northern plains in the Hesperian → Amazonian.



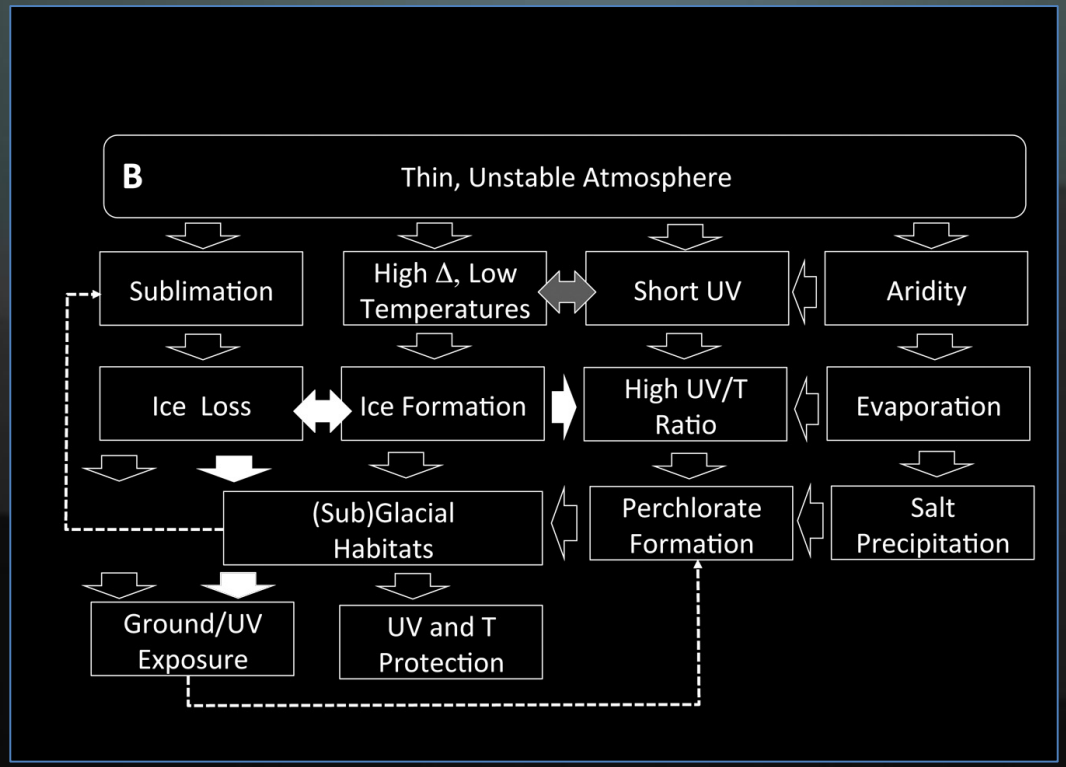
Environmental Envelop for a Biosphere & Ecosystems







A Polyextreme Planet Since Noachian



Cabrol, 2018 *Astrobiology 18(1)*

- Relative spatiotemporal influence of physicochemical parameters, and their ***interaction*** are critical to habitat evolution.
- Influence may vary on very short timescales.
- Climate change is the fundamental force driving changes in habitability globally.
- BUT…
- Extreme habitats are driven by processes at vastly different spatiotemporal scales (*e.g.*, micro- to "nanoclimate").

Impact on Subaerial Habitat Distribution & Abundance

Habitats dominated by LOCAL/REGIONAL FACTORS!

Global trends provide LITTLE INFORMATION on habitat location

Habitat distribution and abundance at the surface are **STOCHASTIC**

HABITABLE ENVIRONMENTS are measured in **m-µm**

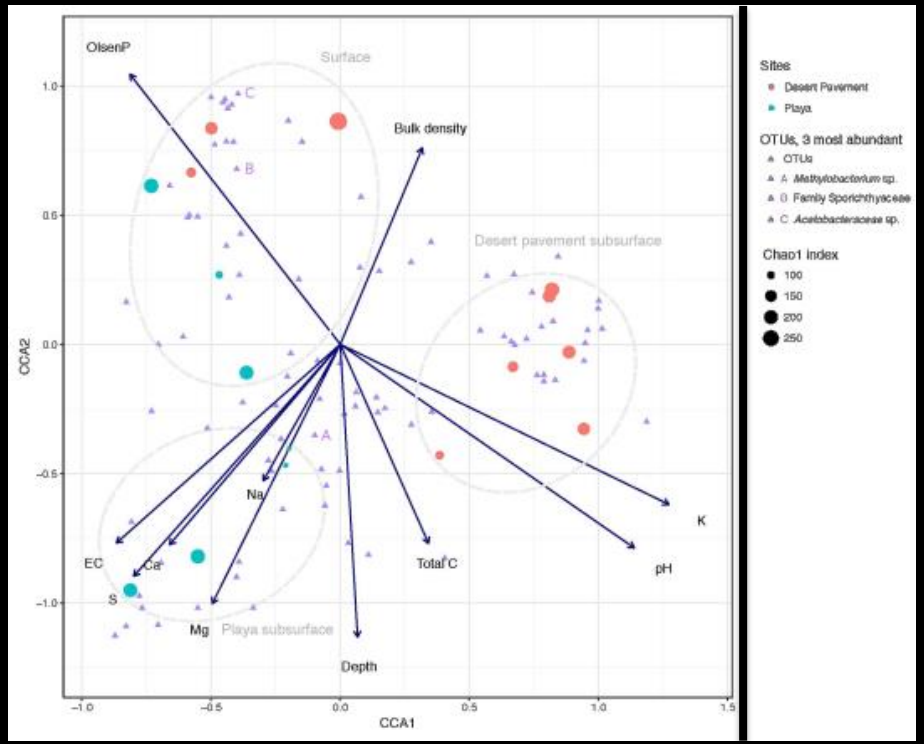
Slope Exposure
Water acquisition
Mineralogy
Geochemistry
Sediment Texture
Soil pH
Moisture
Temperature
Energy
Shelter
Other

Extreme Subaerial Habitats

NASA ASTEP LITA Project (2003-2007: Salar Grande A, B, D. E)

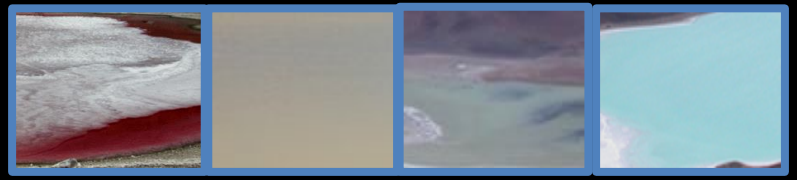
NAI SETI Institute Team Project (2015-2019: Salar Grande C. Salar de Pajonales, F)

Impact on Biodiversity (surface/subsurface)



Biosignature Clustering by Habitats & Depth Driven by Water and Salt
NASA ASTEP Subsurface Life in the Atacama (2011-2015 – Pointing et al., *Submitted)*

Impact on Biodiversity (subaerial/lacustrine)



Cabrol et al., (2009, 2010, 2015); Demergasso et al. (2010).

- Habitat fragmentation.
- Micro/"nano"climate.
- Increased role of sediment texture, mineralogy, geochemistry.
- Loss of local biodiversity and hyper-specialization.
- But…regional/global biodiversity through oasis effect?

The Noachian Paradox & Potential Intellectual Leaps

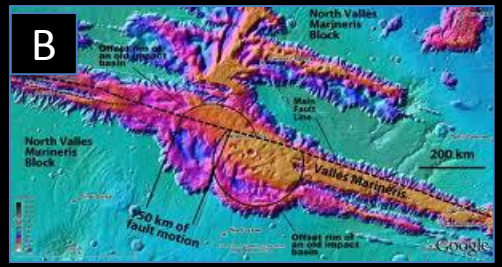
- Maximum hydrological activity
- Lakes, deltas, alluvial fans
- Clays
- Secondary atmosphere
- Hydrothermal systems

- Subaerial habitats were doomed (for most) **as soon** as the magnetosphere shut down. Mars was a polyextreme environment from that time on.
- Habitats in Earth's extreme environments may be the most favorable case scenario for early Noachian subaerial habitats.

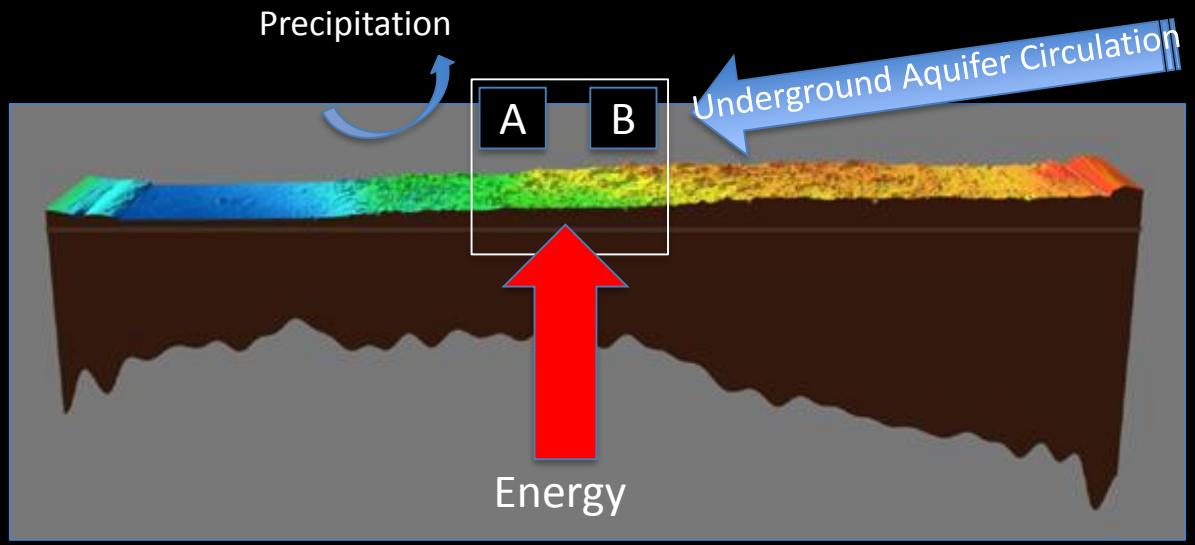
→ Biomass Production?

→ Biosignature Preservation?

→ Empty Noachian subaerial nests? Habitable *vs.* Inhabited…

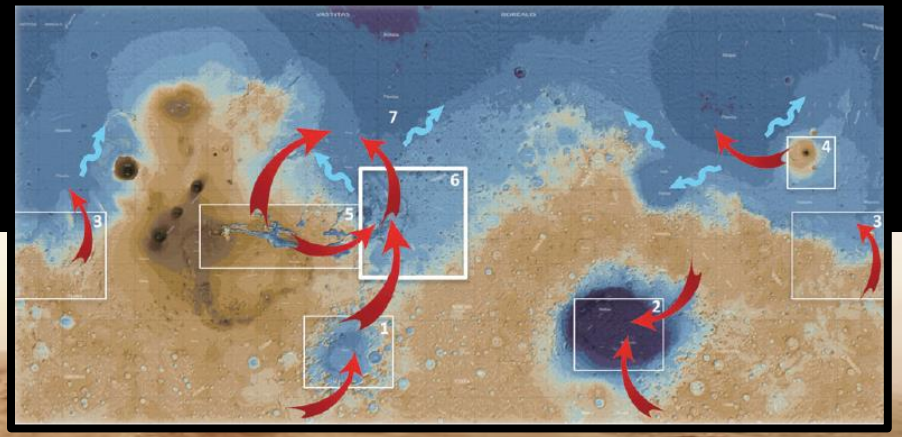


Martian Biosphere
A 4 Gyr Engine!

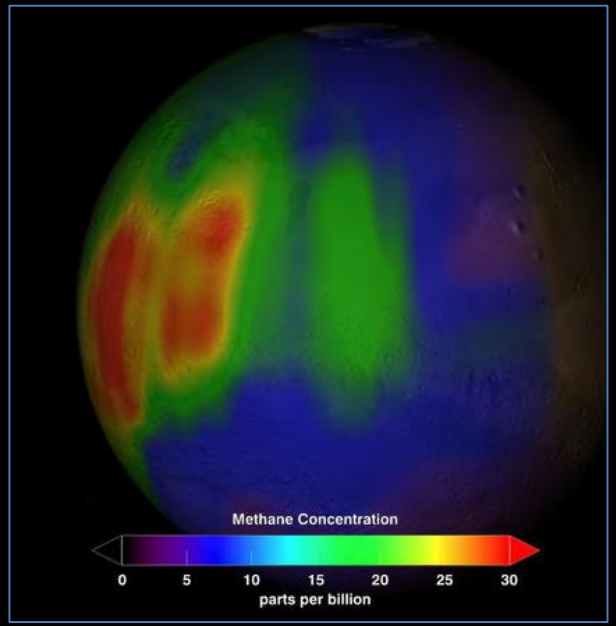


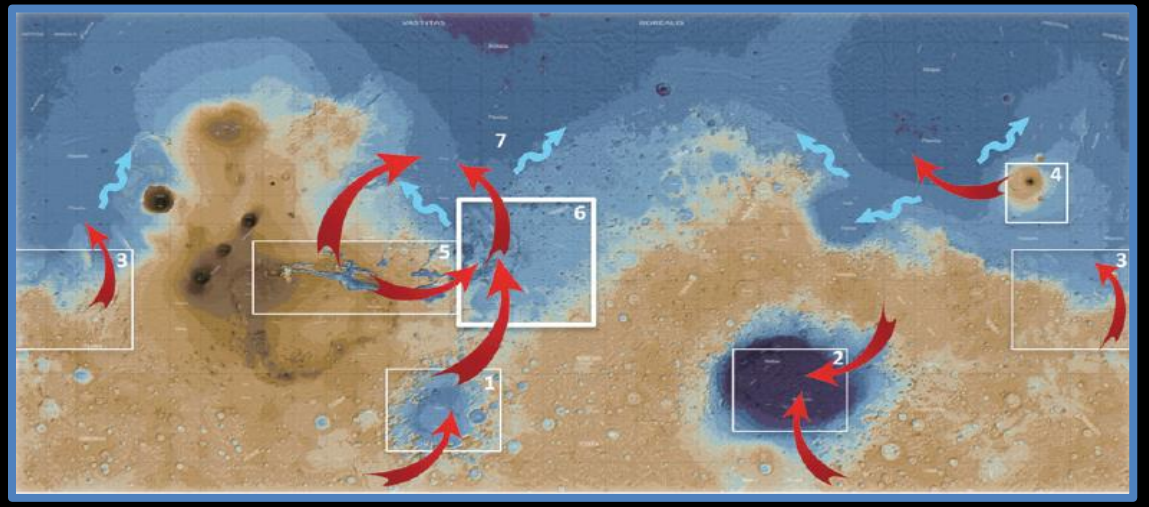
- Dichotomy forms 4.3-4.1 Ga
  - Energy centered at the equator
  - S/N Topographic gradient
  - Accumulation of volatiles at depth in the equatorial region.
  - Hydrothermal processes.
  - Ongoing engine? Latest volcanic activity in VM is 10 Myr old.
- Plate tectonic in VM?
- Cyclic orographic precipitation during favorable obliquity.

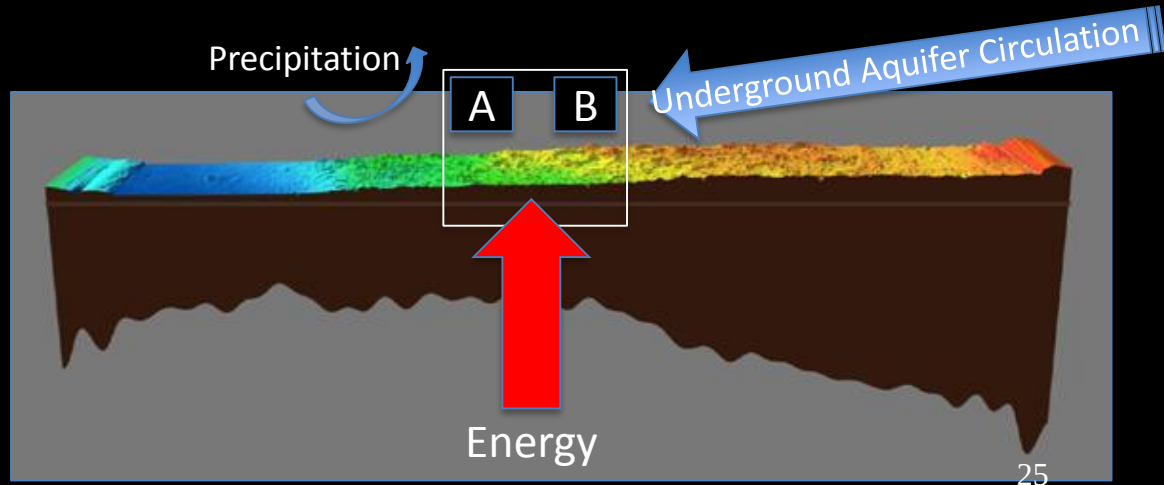
The Great Hesperian Dispersal



An Amazonian Biosphere?

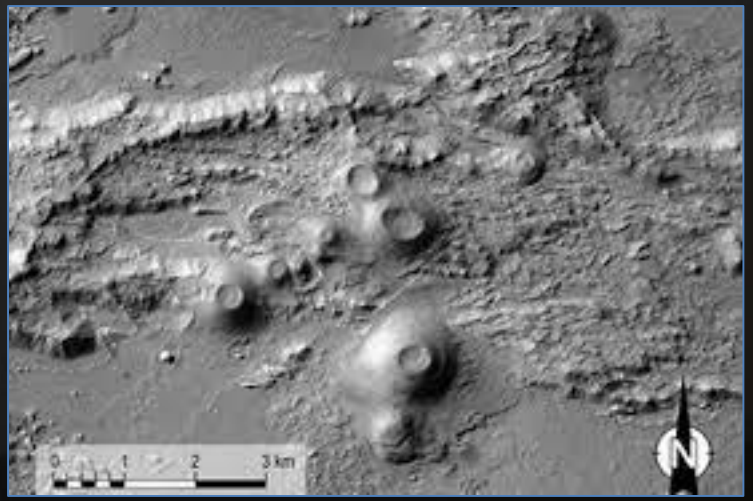






Summary of Some Key Points

- Early (Noachian) Mars was already a polyextreme environment.
- The loss of the magnetosphere:
  - dictates the **collapse of subaerial habitat** potential and habitat distribution.
    - As early as the during the Noachian?
  - **Limits the production of biomass** at/near the surface, and impacts its preservation.
- The Hesperian could have been a very dynamic period for catastrophic dispersal.
- **Underground** was always a better scenario for life on Mars.
- Large biomass repositories will be located underground.
- Mars has had a biosphere engine for the past 4 billions years. It is still active. **High potential for extant life**.

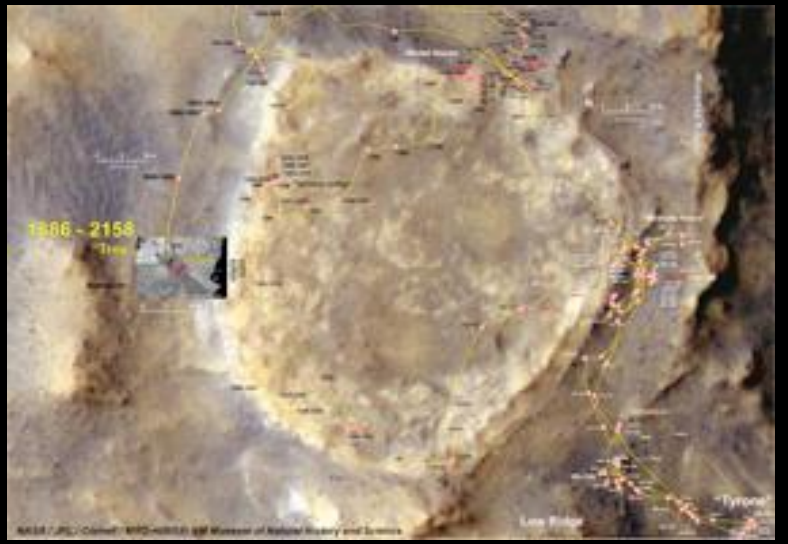


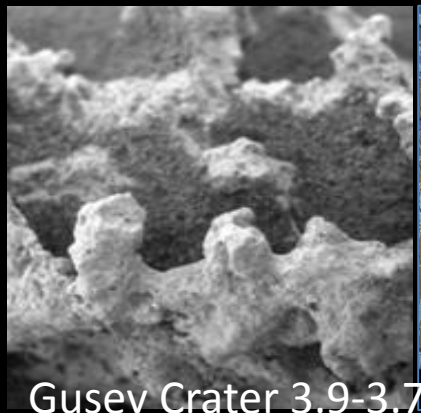
Broz et al., 2017

Exploring a Coevolution

NE Syrtis (4.0 Ga)

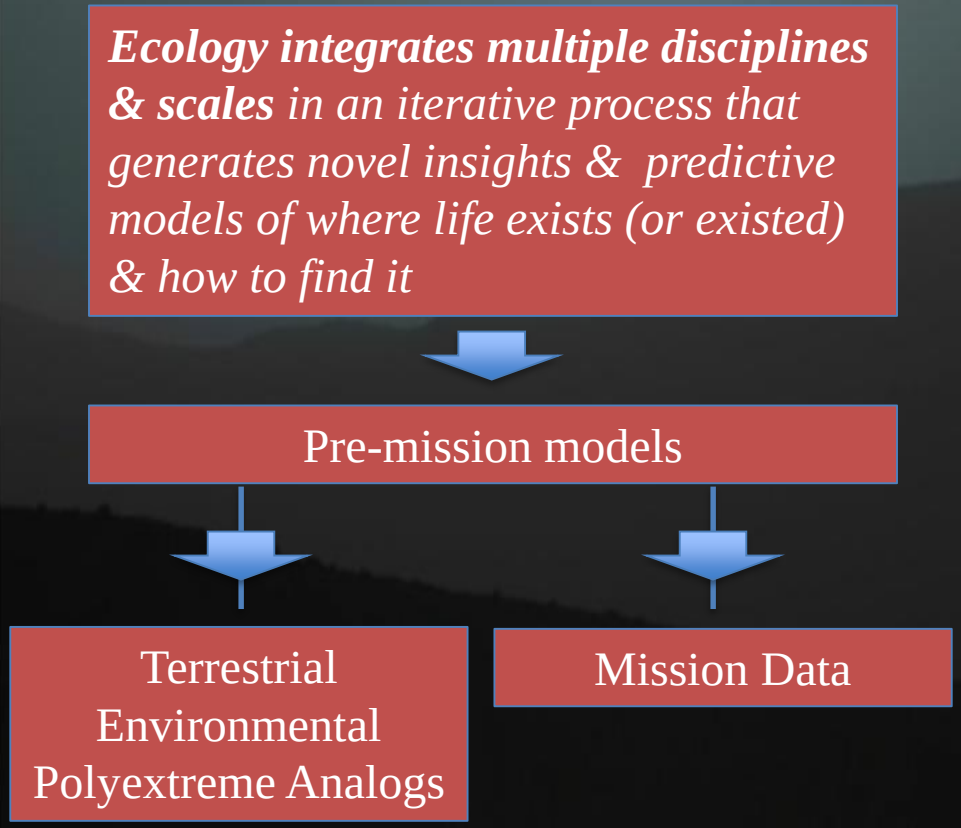
Jezero Crater (3.5 Ga)





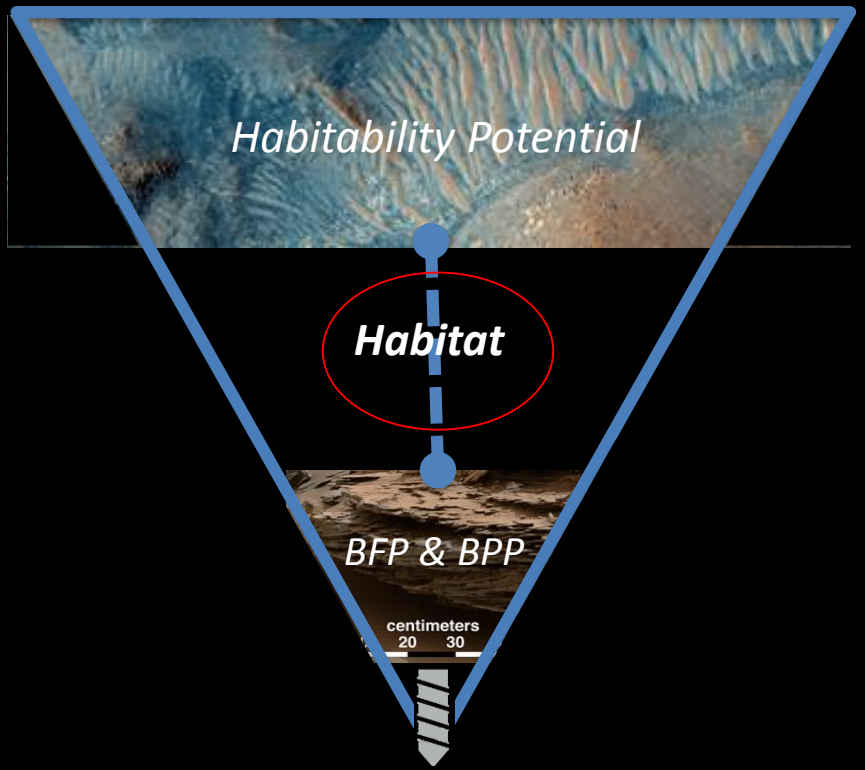
Gusev Crater 3.9-3.7 Ga

Ruff and Farmer, 2016



- Current biosignature missions still heavily influenced by MER and MSL strategies.
- Mars was *never* the Earth. It matters!
- **Bring ecology of extreme environments** and its methods (e.g., scales, resolution, instruments, detection levels) to explore subaerial habitats.
- What if? Exploring the underground…
- Adapt exploration to each mission. Not "one exploration fits all" – ***Habitability is to habitat what general medicine is to medical specialties. It goes so far.***

Missing Pieces: Bridging Orbit & Ground

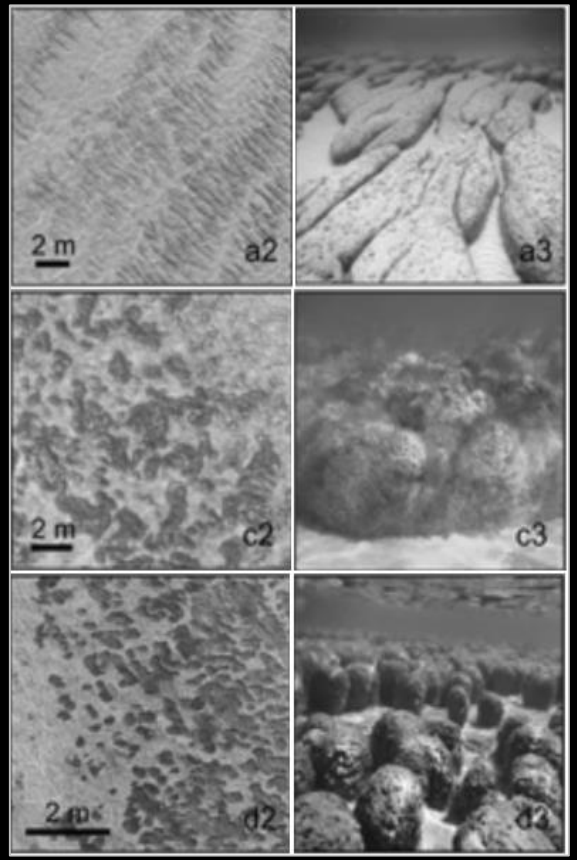


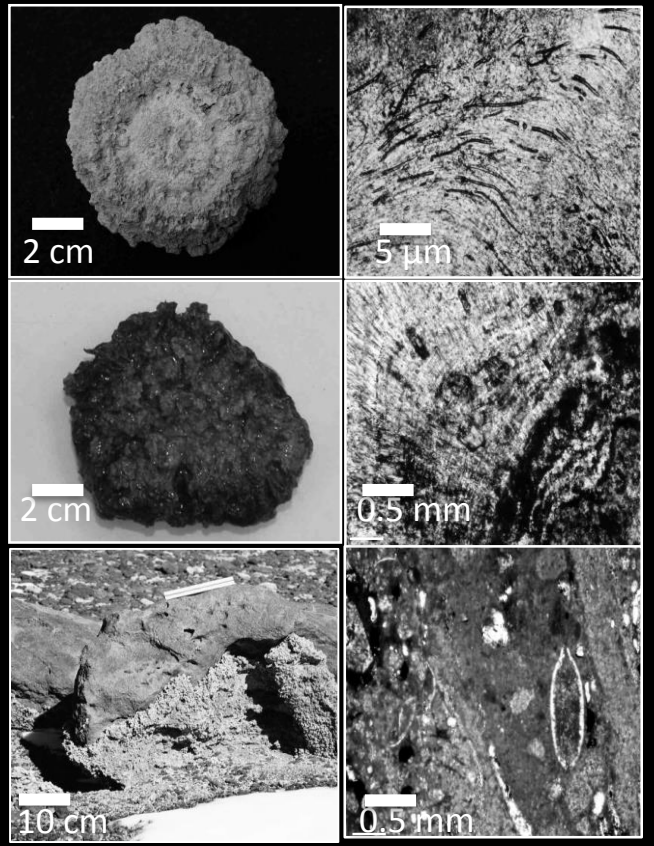
- Current orbital scales and resolution are adapted to broadly evaluate planetary and environmental habitability, ***not habitats***.
- A critical intermediate detection threshold (e.g., mineralogy/composition) is needed to:
  - Access geosignatures suites associated to potential habitats (and possibly ancient bio-mediated mineral deposits).
  - Understand climatic cycles and events that matter at the habitat level, and can change sediment origin, texture, mineralogy, and biosignature preservation potential.

BIOSIGNATURES

SPATIAL DISTRIBUTION

CONTEXT





*Susosaari et al. Nature, Sci. Rep. **6**, 20557 (2016)*

AUSTRALIA

ALTIPLANO

Cabrol et al., Geology of Mars, Chap. 10.,CUP, 2007

SETI INSTITUTE NAI-High Lakes Project (2003-2008)

Scales of Environmental Variability: The Lessons of Present-Day Mars

- Knowledge of early environment contains many uncertainties.
- Meanwhile, present-day Mars is a reflection of 3.7 Gyr of history.
- Understand the scale of environmental variability at high-resolution today will give a window into 75% of the environmental history of Mars.
  - Potentially reflects environmental patterns at the time of the last subaerial habitats (**end member**).
  - Current hot spots?
- **An HR Environmental array mission is a missing link** in the current strategic planning and it is key.

Coevolutions Beyond Mars

The nature of a biosphere? What dominant elements would shape ecosystems, i.e., what is the environmental and biological architecture?

- (1) The physical nature and structure of the (eco?) system.
  - Radiation environment provides the external envelop/boundary of a biosphere.
  - Geology, mineralogy, structure, physicochemistry, sediment/ice texture indicate available elements to generate habitats, and their plausible boundaries and connectivity networks.

  - Short/long term environmental variability and its impact on the physical nature/structure of habitats and their evolution, e.g., ***role of gravitational tides*** on the:
    - Location, state, and evolution of habitats?
    - Metabolic cycles
    - Loops and feedback mechanisms
- (2) Search for evidence of coevolution
  - Connectivity with the surface as an ecological requirement (e.g., nutrients)
  - No connectivity (possibly exposed accidentally)
  - Polyextreme Modeling approach