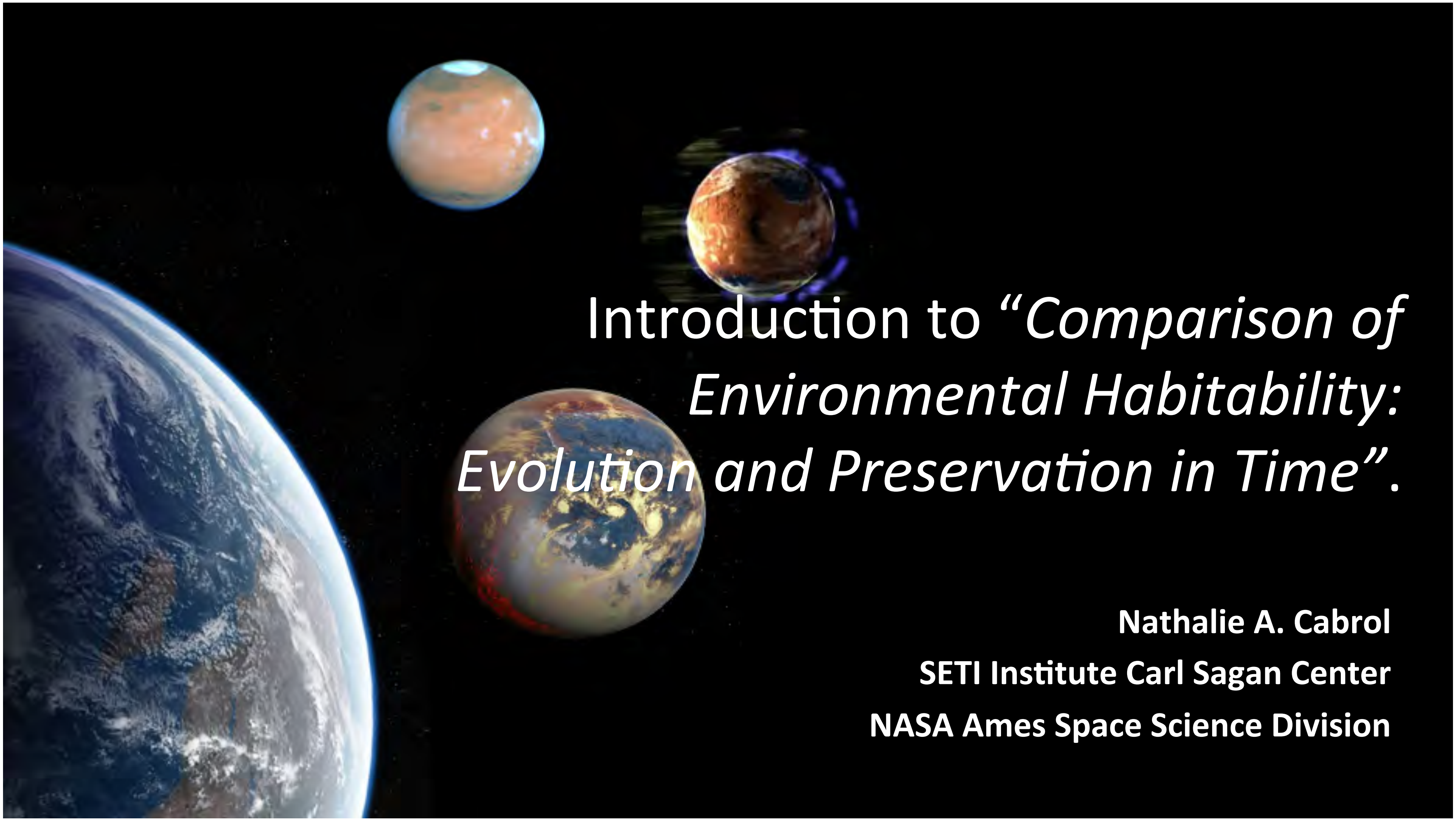
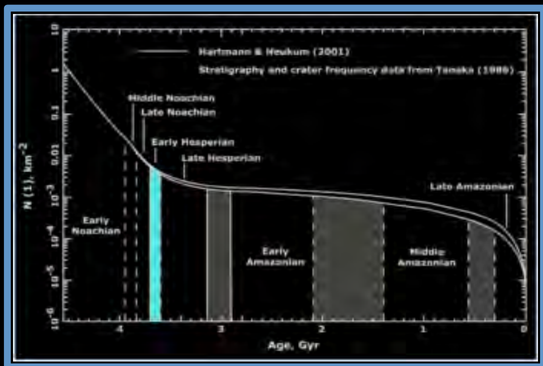
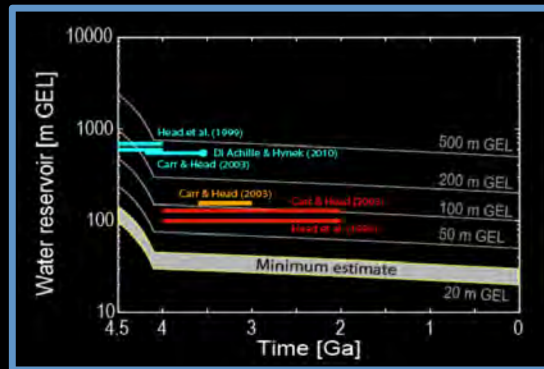

Introduction to "Comparison of Environmental Habitability: Evolution and Preservation in Time".
Nathalie A. Cabrol
SETI Institute Carl Sagan Center
NASA Ames Space Science Division

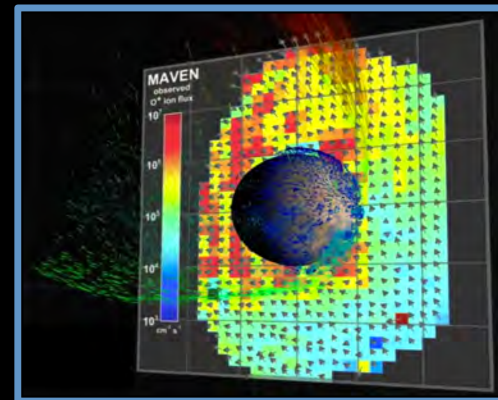
Overview

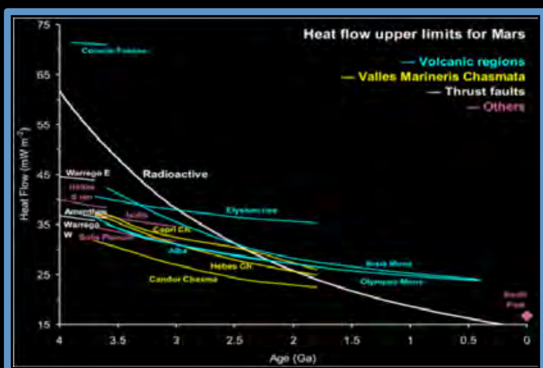
- Life and Biosignatures on Mars
  - ✓ Building Blocks (CHNOPS).
  - ? Transition from Prebiotic Chemistry to Life
  - ? Biomass on Early Mars? (Early Earth <<< Present Earth)
- ✓ Environmental Habitability
  - Liquid water + Energy Source + Carbon Source + Nutrients; Shelter -> + a Geologically Active Planet.
  - Spatiotemporal Evolution (4D)
- ✓ Preservation

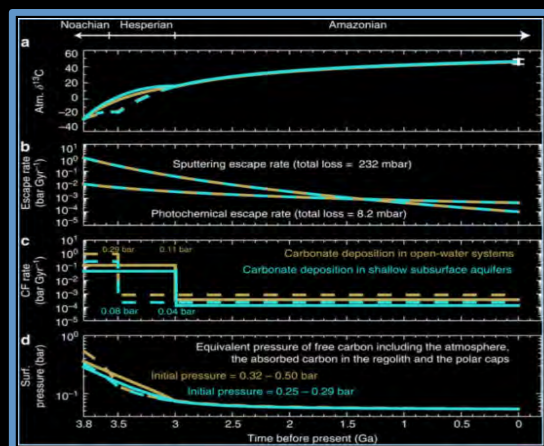
> Evolution of habitability and how it affects a biological record relevant to the Archean/Noachian

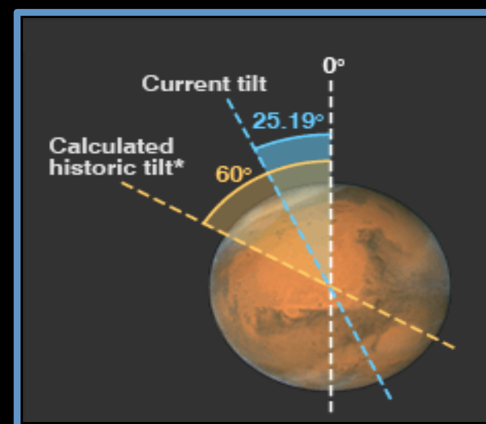

Hartmann & Neukum (2001)
Stratigraphy and crater frequency data from Tanaka (1986)
Middle Noachian
Late Noachian
Early Hesperian
Late Hesperian
Late Amazonian
Early Noachian
Early Amazonian
Middle Amazonian
Age, Gyr

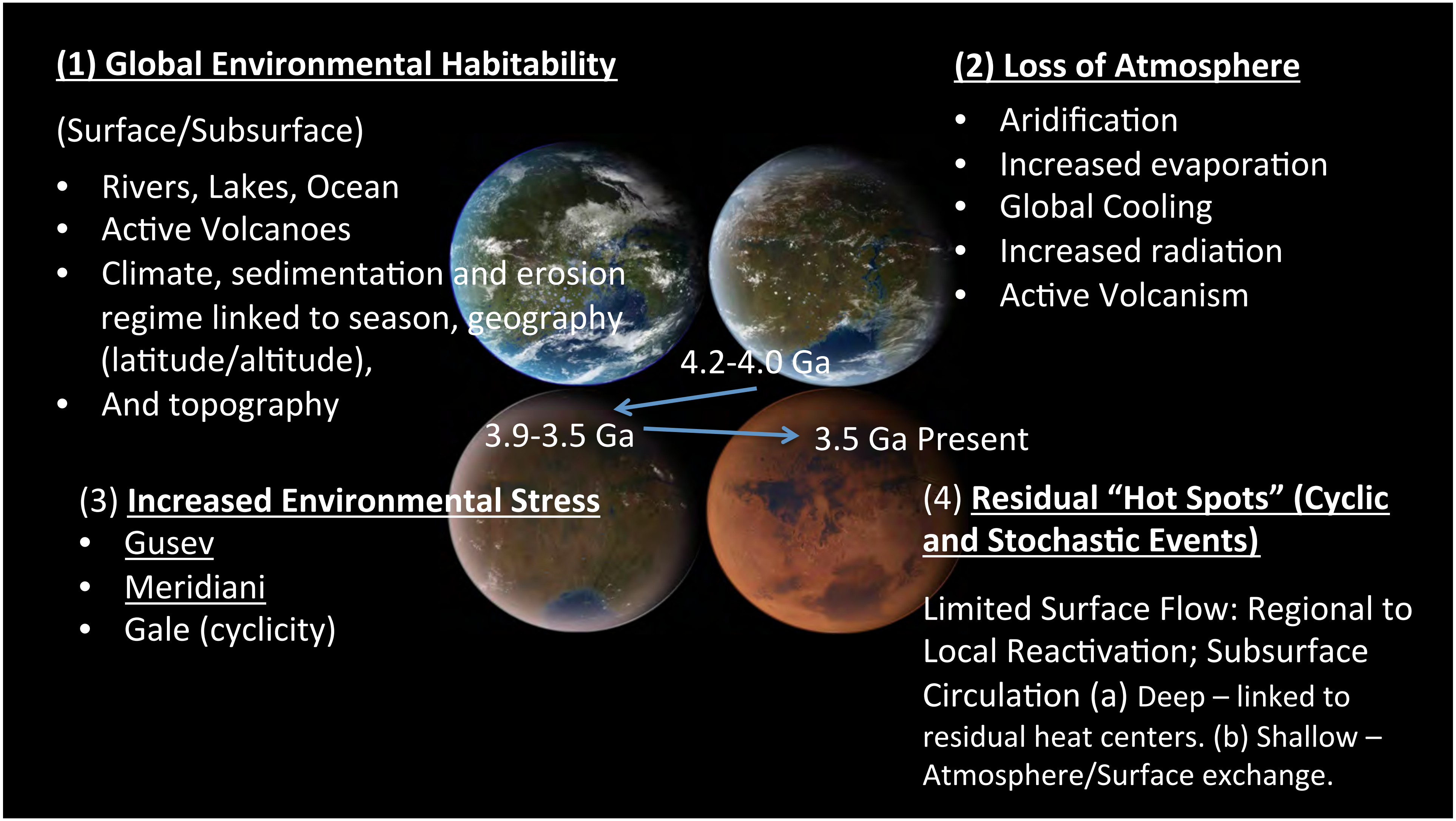

Water reservoir [m GEL]
Head et al. (1999)
Di Achille & Hynek (2010)
Carr & Head (2003)
500 m GEL
200 m GEL
100 m GEL
50 m GEL
Minimum estimate
20 m GEL
Time [Ga]


MAVEN


Heat flow upper limits for Mars
— Volcanic regions
— Valles Marineris Chasmata
— Thrust faults
— Others
Radioactive
Age (Ga)


Noachian
Hesperian
Amazonian
Sputtering escape rate (total loss = 232 mbar)
Photochemical escape rate (total loss = 8.2 mbar)
Carbonate deposition in open-water systems
Carbonate deposition in shallow subsurface aquifers
Equivalent pressure of free carbon including the atmosphere,
the absorbed carbon in the regolith and the polar caps
Initial pressure = 0.32 – 0.50 bar
Initial pressure = 0.25 – 0.29 bar
Time before present (Ga)


Current tilt
0°
25.19°
Calculated
historic tilt*
60°


(1) Global Environmental Habitability
(Surface/Subsurface)
• Rivers, Lakes, Ocean
• Active Volcanoes
• Climate, sedimentation and erosion regime linked to season, geography (latitude/altitude),
• And topography
(2) Loss of Atmosphere
• Aridification
• Increased evaporation
• Global Cooling
• Increased radiation
• Active Volcanism
4.2-4.0 Ga
3.9-3.5 Ga
3.5 Ga Present
(3) Increased Environmental Stress
• Gusev
• Meridiani
• Gale (cyclicity)
(4) Residual "Hot Spots" (Cyclic and Stochastic Events)
Limited Surface Flow: Regional to Local Reactivation; Subsurface Circulation (a) Deep – linked to residual heat centers. (b) Shallow – Atmosphere/Surface exchange.

Outstanding Questions

- Conditions were analogous but not identical on Mars. What was the impact of a greater climatic variability on top of the global decline?

CO-EVOLUTION OF LIFE AND ENVIRONMENT

- How did this affected environmental habitability?
  - At the Surface
  - In the Subsurface
  - Deep Underground

Taphonomic Windows

"Sedimentary and diagenetic conditions conducive to preservation".

Environment

Preservation ←→ Degradation

- Conditions:
  - Environments enriched in organics
  - Survival of the organic record through diagenesis (OM degradation/rate of mineralization);
  - Survival to exposure (e.g., radiation, and other chemical and physical destruction).
    - No plate tectonics – Less Erosion but
    - >> Continued Impact Cratering

What are we Looking For?
Variations on the “F_{ossil}” Word on Mars and Context

Biosignatures Taphonomic Window	Confidence in the Geological Context	How this Informs about BPP
Atmospheric Gases	Very High	• Predictable via chemical modeling
Crystalline sedimentary mineral entrainment of organics	Very High	• Formation mechanism and history retained in texture, minerals, composition
Biofabric lithification	Very High	• From lithology and stratigraphy
Body fossil preservation	Very High	• From lithology and stratigraphy
Mineral replacement of body fossil	High	• From mineralogy

From Summons et al. (2011) – *Preservation of Martian Organic and Environmental Records: Final Report of the Mars Biosignature Working Group.*

Where to Search?

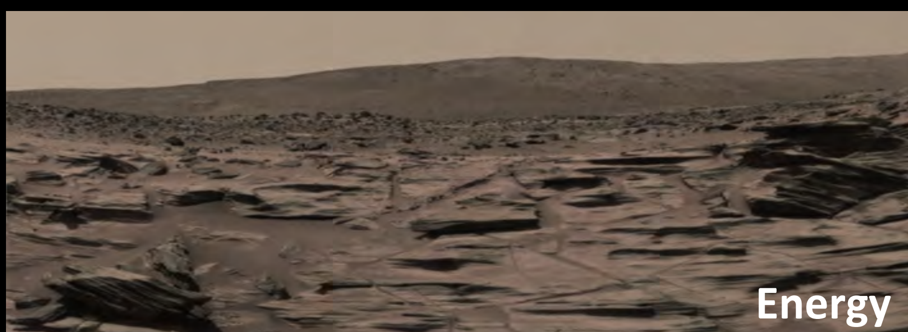
Landforms/Features

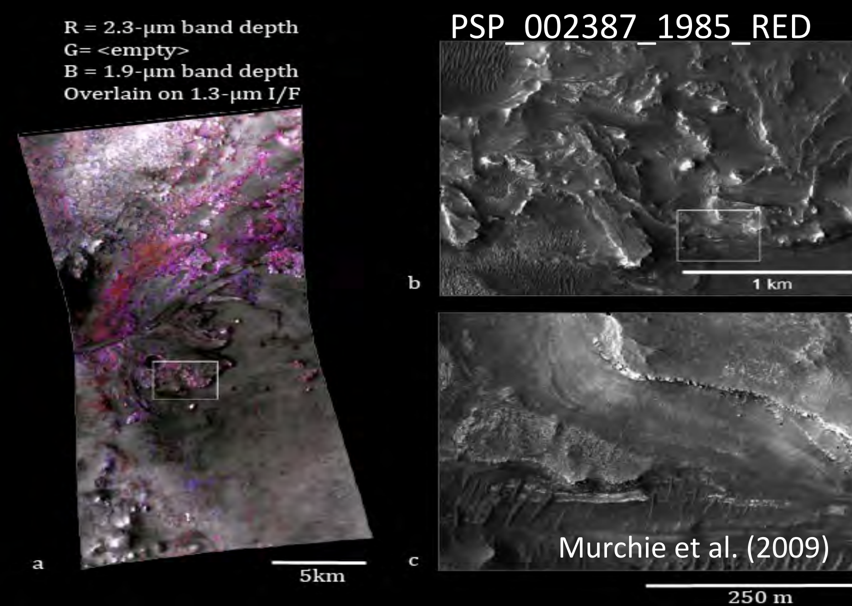
- Aqueous Environments: Lacustrine and Deltaic sediments.
- Near-Surface Chemical Sediments (including hydrothermal and pedogenic).
- Deep crustal rocks (including hydrothermally altered).
- Wild cards --- non-sedimentary and sedimentary, freshly exposed records (e.g., collapsed lava tubes; accessible caves remnants - biomineralization).

Materials/Deposits

- Marine and Lacustrine Deposits
- Sedimentary rocks
- Carbonates
- Evaporites (Sulfates)
- Clastic, Fined-Grained Sediments
- Reducing Environments
- Thermally and tectonically stable Environments

Lake Environments





Habitability Potential

Wet Early Mars

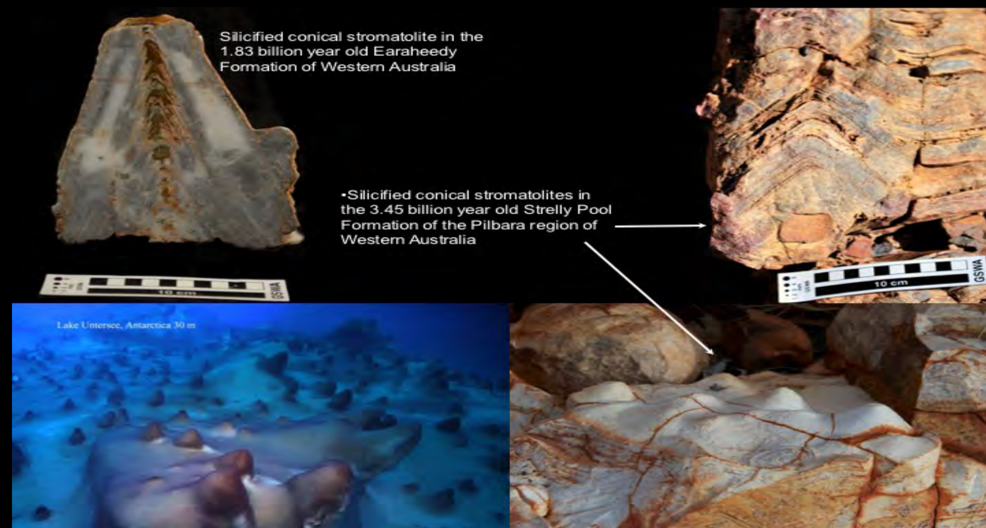
- Early Noachian: Polar and high altitude glacial lakes.
- Lake Untersee, East Antartica.
  - Physically-driven system → Local conditions drive physics, chemistry, and biology.
  - Formation of modern, large, (up to 70 cm high), conical stromatolites.
    - Filamentous cyanophytes
    - Lamination: clay + organic material

- Lake Dimensions: (6 x 2 km)
- Depth: 160 m
- Mixed
- Ice-cover: 100,000 years?
- DO: 150% - pH: 10.4
- Air Temp: 0/-35C; Water: 0.5/5C
- 0.1 % of surface life allows photosynthetic activity at 130 m depth.

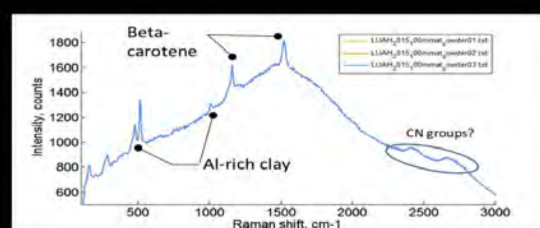
Andersen et al., 2015

Early Mars Aqueous Environment BPP

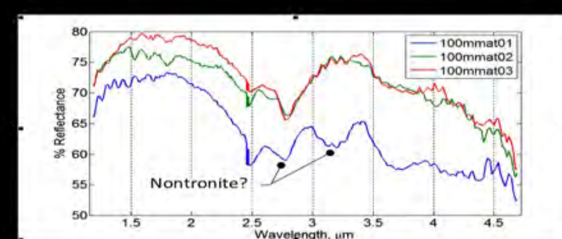
- Window into a primarily prokaryotic world absent "higher" life in a setting of thick, continuous permafrost.
- 10,000s years with sediment buildup of clays, sulfates and biomarkers
- Laminated, non-lithifying large, conical stromatolites still forming in the lake today.
- Biomarkers deposited in sediments include lipids and hydrocarbons, and variations in carbon isotopes



Lakefloor: Anaerobic Basin



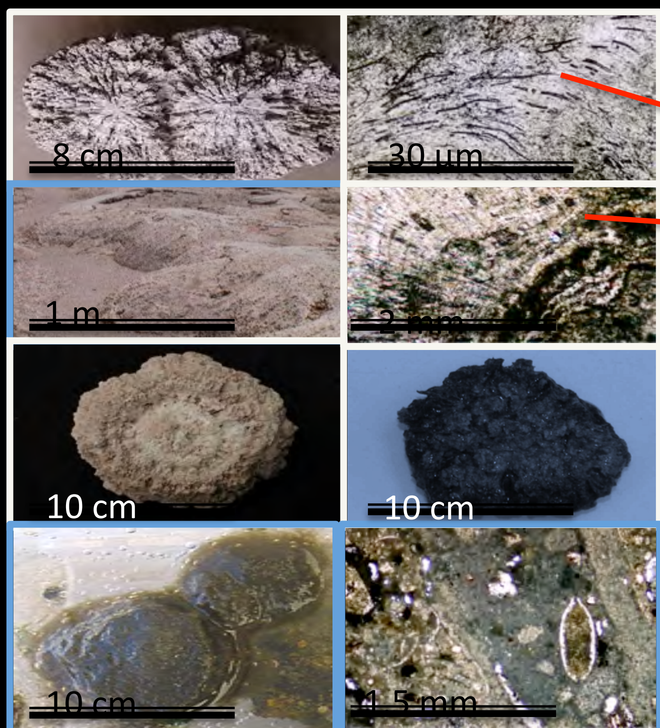
Lakefloor: Anaerobic Basin

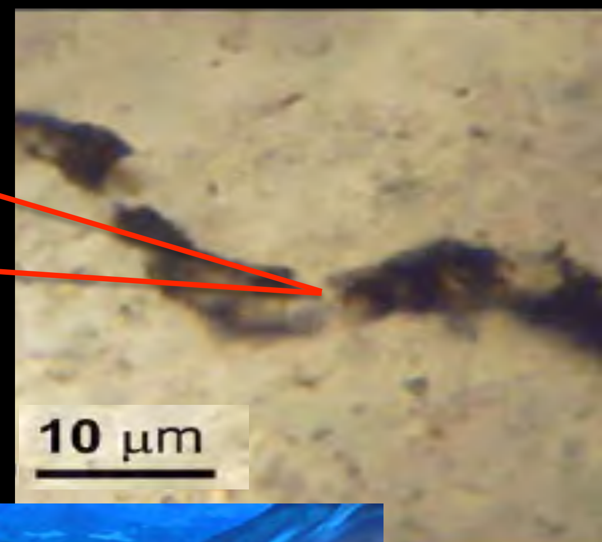


Andersen et al., 2015; Sobron et al., 2015.

Adaptation to a Changing Environment

Schopf et al., 2007

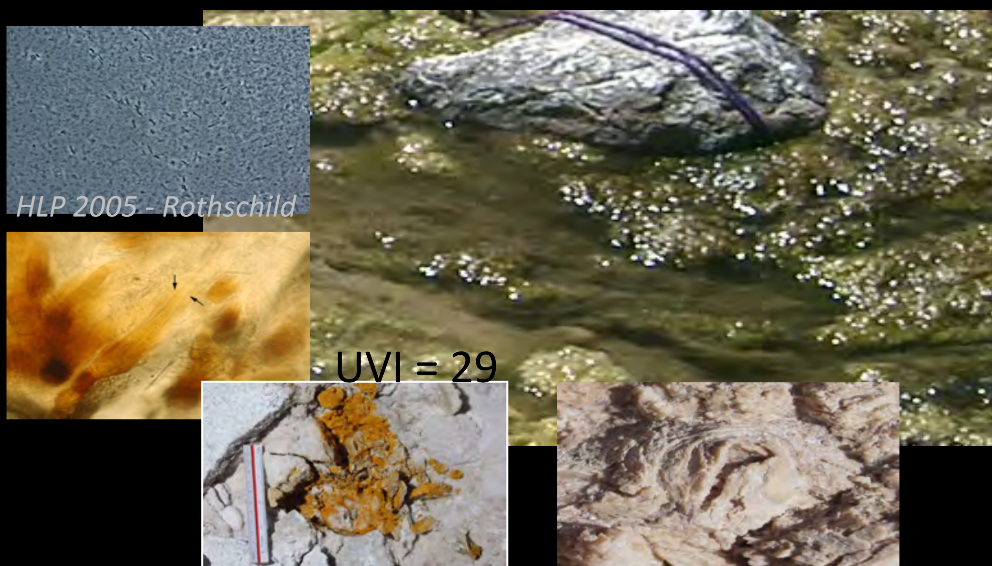




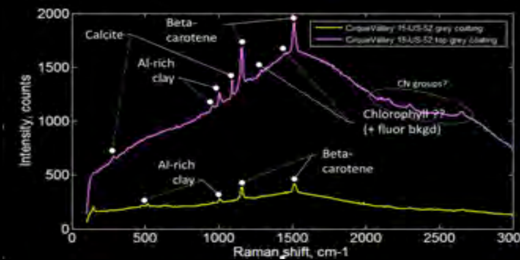
NAI HLP Project – Cabrol et al. (2007; 2009)

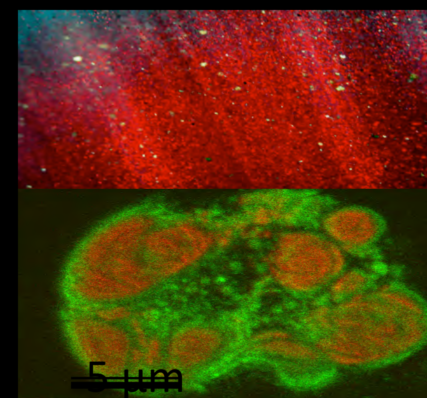
Andersen et al., 2015 – Am. Met. Soc..

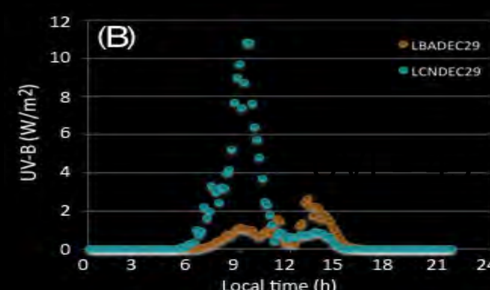
Declining Aqueous Habitats:
HP and BPP --- *Aridity + Radiation*



- UV-protecting pigments are detectable with Raman (SHERLOC/SUPERCAM).
- They are concentrated in extreme environments.





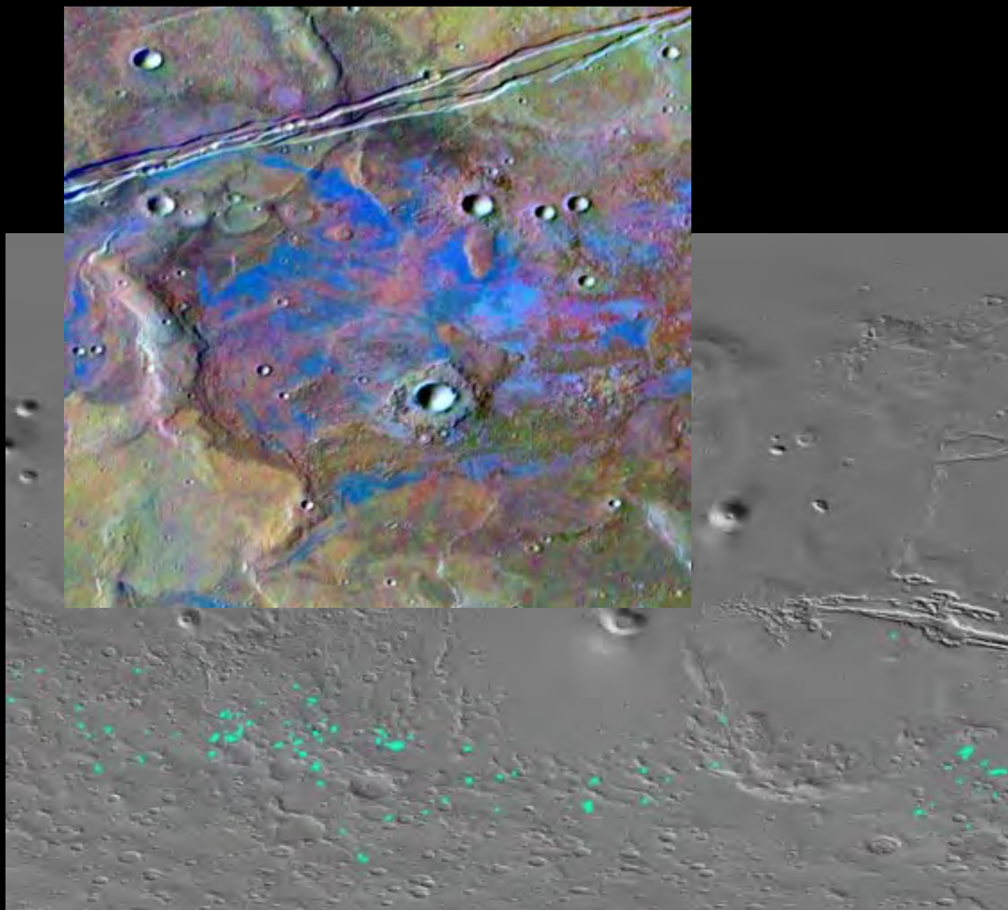


HLP Project: Cabrol et al., 2010, 2011, 2014

Evaporitic Salt Crusts

Ancient salt-flats in the hyperarid Atacama Desert
Davila et al.

- **Massive NaCl evaporites (+ gypsum & clays) formed c.a. 5 My ago.**
- **Surface morphology: polygons and salt nodules shaped by wind and dissolution/precipitation cycles.**
- **Habitat to a deliquescence-based community. Signals the dry-limit of habitability in the Atacama.**
- **Cyanobacteria, archaea, and heterotrophic bacteria; viruses.**



Evaporitic Environments

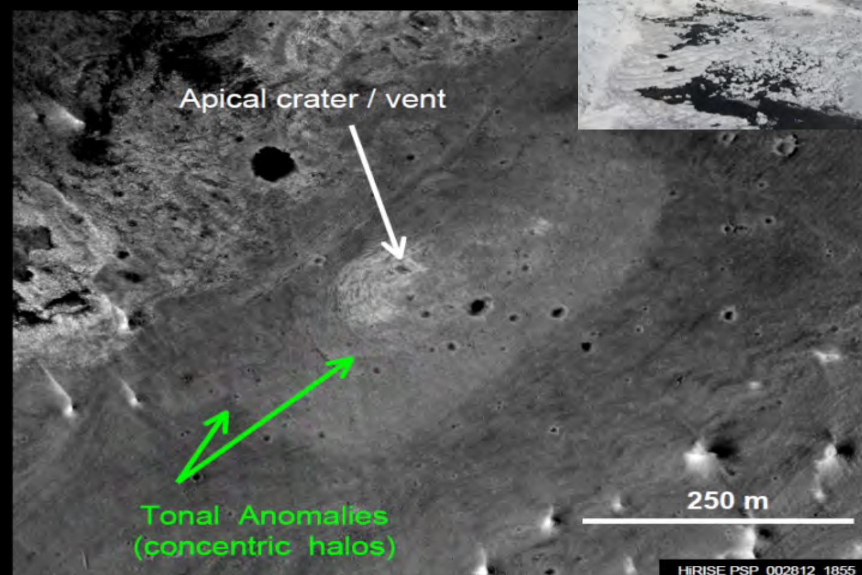
- Evaporative concentration of salts.
- Possibly >100 occurrences in the southern highlands (Noachian and Hesperian)
- Identified as Cl-bearing deposits.
  - Topographic lows
  - Locally associated to phyllosilicates and sulfates

After Osterloo et al. (2008, 2010)

Mineralization – Cold Springs

- Modern perennial springs and residual icings (Ellesmere Island). Melting by seasonal and geothermal warming.
- Permafrost depths 600m
- Depositional environment includes formation of travertine barrage pools and terraces.
- Robust prokaryotic community associated with saline spring outflows in a range of pH and Eh environments.


NAI SI Team: Arctic Springs Andersen and Sobron (2015)



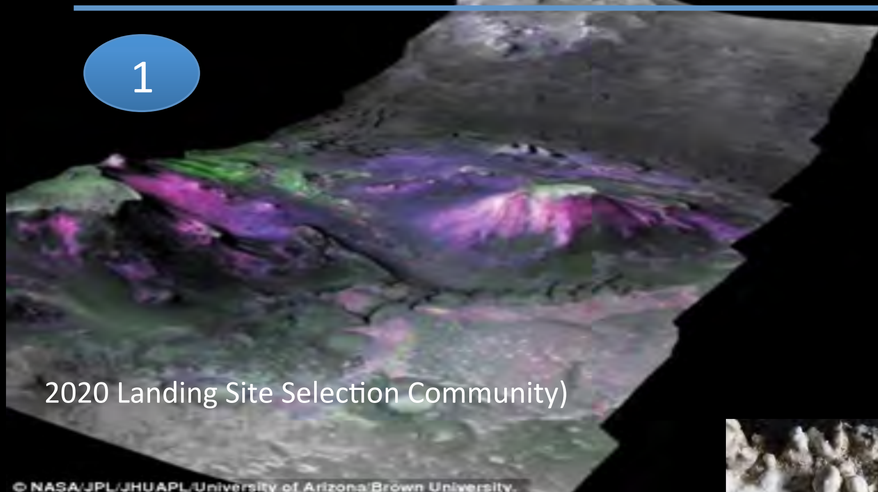
Springs at Vernal Crater (Arabia Terra Allen, C. C., and D. Z. Oehler (2008)

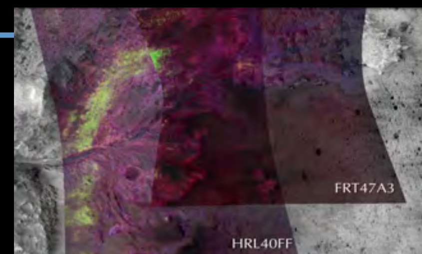
Habitability and BPP

Type	Feature	Vernal Crater	Axel Heiberg Springs
Evidence for habitable environments	• Springs terraces • Subsurface water	Mineralogy not detectable form orbit (dust layer) **…but…** Strong indications for fluid flow provided by the aligned outcrops associated. **and** High concentrations of shallow ice or hydrated minerals from gamma-ray spectrometry data.	General mineralogy dominated by halite, hydrohalite, calcite, gypsum, elemental sulfur, thenardite, and mirabilite. **Fossil springs**: chaotic limestone breccia with calcite infillings in pores, and calcite veins with pyrite. **Wolf Diapir site**: large mound of salt 3m in height and 3m in diameter; a saltpan extends about 0.5 km to the west. Water at -3.5°C, pH of 6.4. **Gypsum Hill**: gypsum, halite, elemental sulfur, and organic compounds; evidence of end- and intermediate-products of a (biomediated) sulfide-to-sulfate oxidation, kerogens.
Preservation of Bio-Signatures • Organic Material • (Pre) Biotic Material • Biotextures • Mineral Biosignatures	• Spring sinters • Tonal anomalies (concentric halos) near springs		

High- Temperature Mineralization Environments – Warm Springs

1

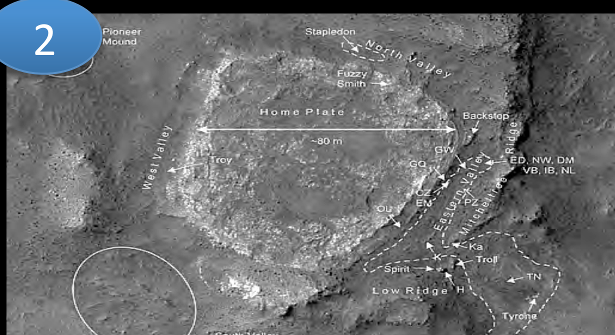


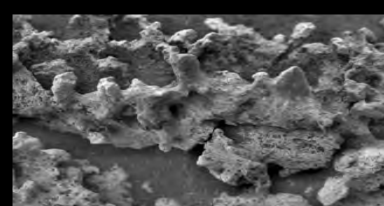


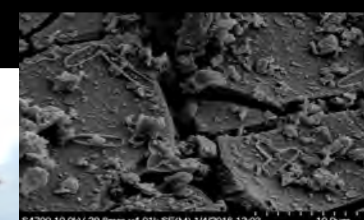
Clay-Carbonate Alteration Assemblages *Nili Fossae*

Silica sinter deposits *Gusev crater – El Tatio: entombed fossil microorganisms.*

2



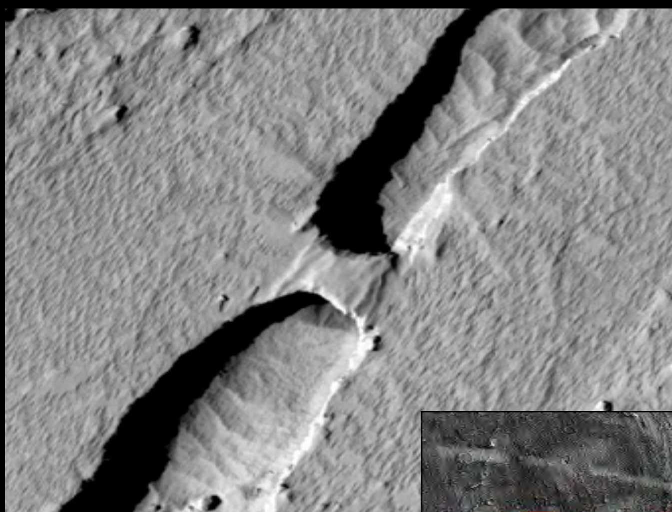


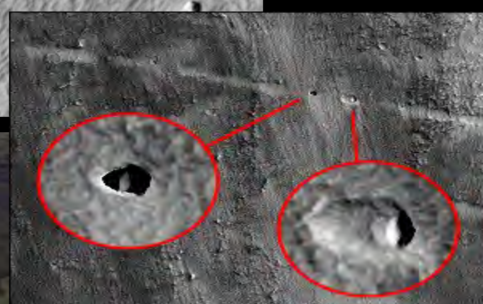


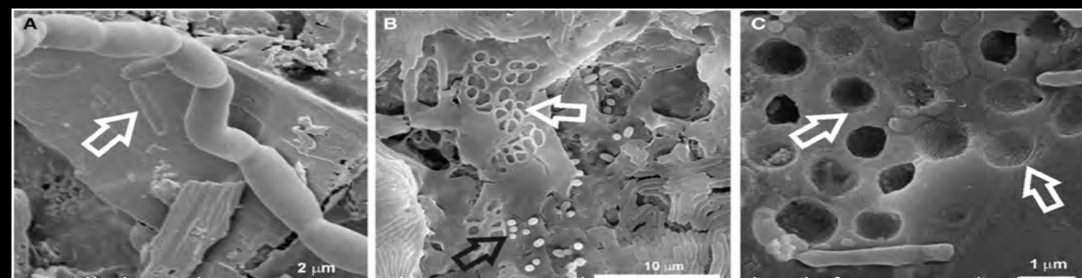
Ruff et al. (2015, 2016)

Cabrol et al. NAI HLP Project

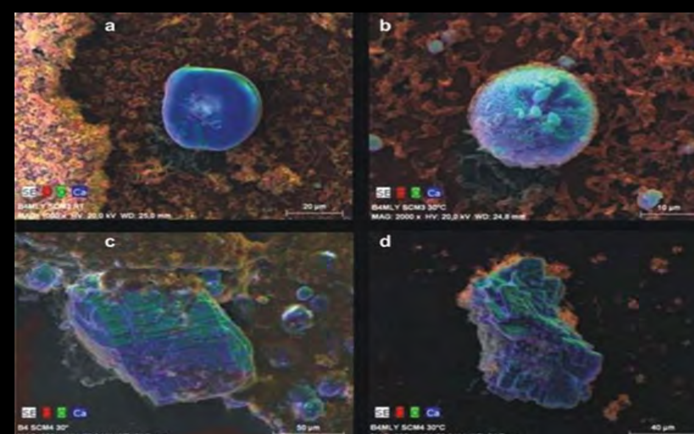
Hidden Gems Brought to Light…
Collapsed Lava Tubes and Exposed Cave Walls







A. Cell-shaped pits on minerals grain; B. Cell imprints and rods from microbial mat; c. Microborings produced by euendolithic cell on silicified mineral grains. Riquelme et al. 2015.



Biominerals – Bacterial calcite minerals, Rusznyák et al. 2012

Conclusions and Main Points

- The martian biological record, if any, might be rare and difficult to find. Deciding what samples to select will rely on:
  - Converging evidence → **CONTEXT** will be paramount (stratigraphy, mineralogy,…).
- Landing site selection for life seeking missions should focus on sites where BOTH environmental habitability and conditions for preservation can be demonstrated over extended periods of time:
  - **Lacustrine environments** meet many of the environmental and preservation criteria.
  - **Deltaic environments** are excellent to provide environmental context and stratigraphic continuum. They are not so good for preservation (dynamic environments).
  - **Ideally both** (e.g., Gale, Jezero, …)

Conclusions and Main Points

- **Volcanic/Hydrothermal centers**: Plumes reactivated over eons. Subsurface and deep habitats could have been maintained and record preserved and accessible in exposures.
- **Cold Springs**: Underground circulation and seepage through permafrost reactivated over eons (e.g., gullies). Mineralization may have preserved the record of subsurface microorganisms.
- **Evaporitic basins**: Long habitability window through the Noachian into the Hesperian, and possibly the last near surface habitats for life. Terrestrial analogs show the preservation of biogenic organic molecules, body fossils, isotopic composition of organic C.
- **Exposed Deep Habitats**: Caves (lava tubes, other) might have been the safest shelters for life over eons at depth, especially in contact with sources of water and energy (groundwater circulation and thermal centers).

Recommendations

- We need to understand better how climate change (global decline and obliquity change) affected the record:
  - Surface (>> radiation + Loss of water + >> impact cratering).
  - Subsurface (water circulation? Penetration depth of radiation).
  - Deep habitats (at what depth does it not matter anymore?).

- A sustain effort should be put in fieldwork, lab experiments, and modeling that can address these questions in support of the upcoming missions.

Acknowledgments

- Thank you to:
  - Dale Andersen, Adrian Brown, Alfonso Davila, Nancy Hinman, and Pablo Sobron; The NAI Biosignature Detection Working Group and the Serpentinization Systems Working Group for contributing material to this presentation.
  - The NASA Astrobiology Institute, ASTEP/PSTAR program, and MDAP for supporting the research presented here.