How Mars 2020 Could Look for Life in the Noachian Stratigraphy at NE Syrtis or Midway

A Guide to Finding Rock-Hosted Life on Mars

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Outline

- History – Workshop to Publication
- Case for targeting subsurface based upon martian history
- Diversity and Biomass of Terrestrial (continental and marine) subsurface biosphere
- fossil record of subsurface – types and characterization
- metabolic footprint of life – modern and ancient
- exploration strategy for Mars
- example at NE Syrtis or Midway

Mars-2020 Landing Site Workshop

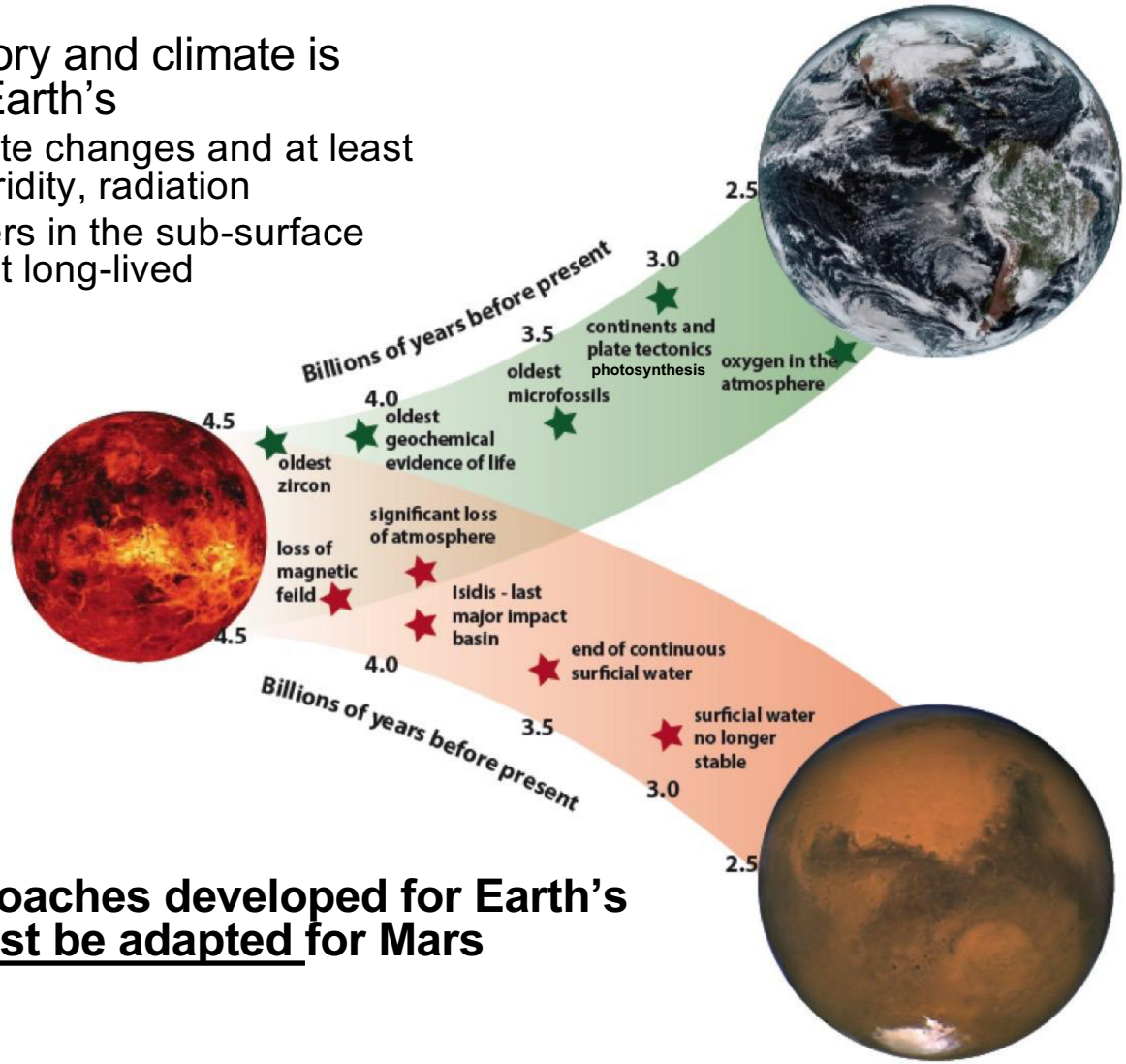
Summary of Finding Signs of Past Rock-Hosted Life

on Behalf of the Rock-Hosted Life Working Group
archived at http://web.gps.caltech.edu/~rocklife2017/
Bethany Ehlmann (Caltech) and TC Onstott (Princeton) February 8, 2017

publication under review at *Astrobiology* | available at https://arxiv.org/abs/1809.08266

Why emphasize searching for rock-hosted life on Mars?

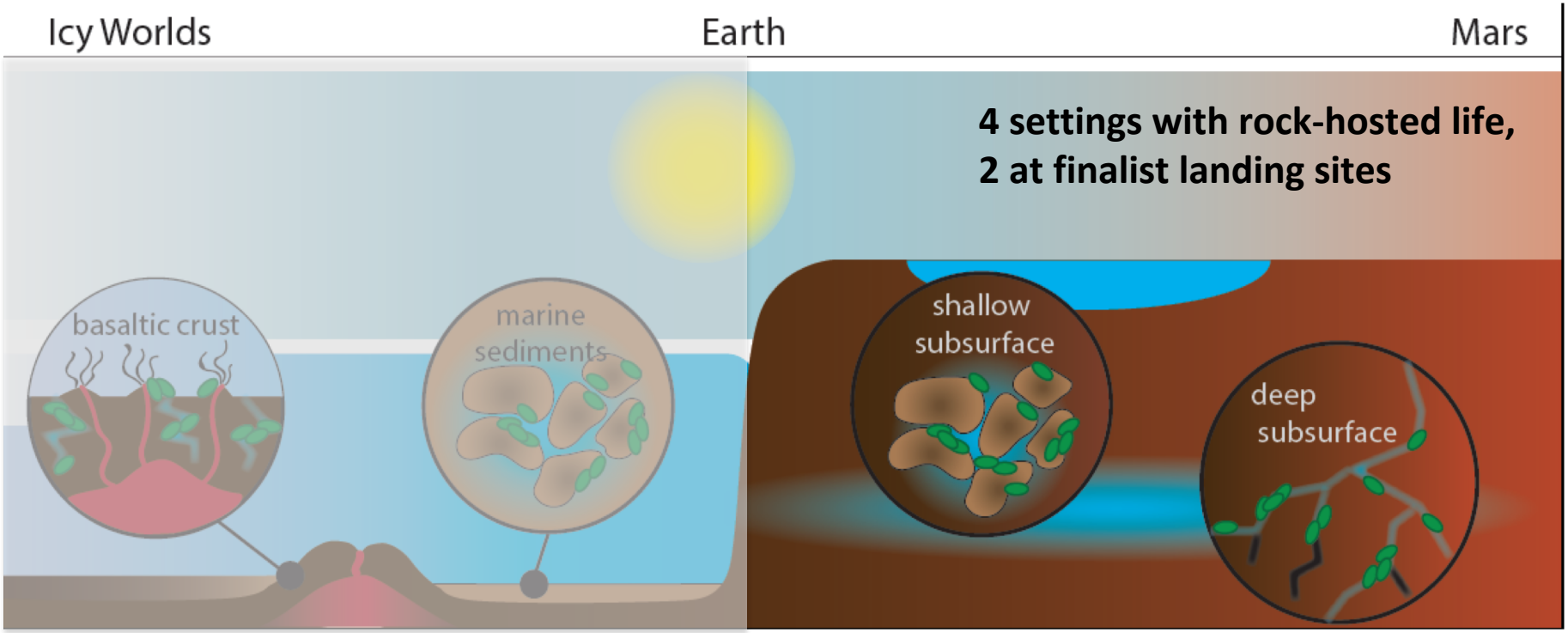
- The trajectory of Martian history and climate is starkly different from that of Earth's
  - Obliquity drives radical climate changes and at least episodic extreme cold and aridity, radiation
  - No long-lived oceans. Aquifers in the sub-surface instead represented the most long-lived environments with water
  - If life emerged on Mars its evolution would have been quite different than the early Earth's



- **Biosignature search approaches developed for Earth's subsurface biosphere <u>must be adapted</u> for Mars**

Where do we look for rock-hosted life?

Onstott et al., in review, Astrobio



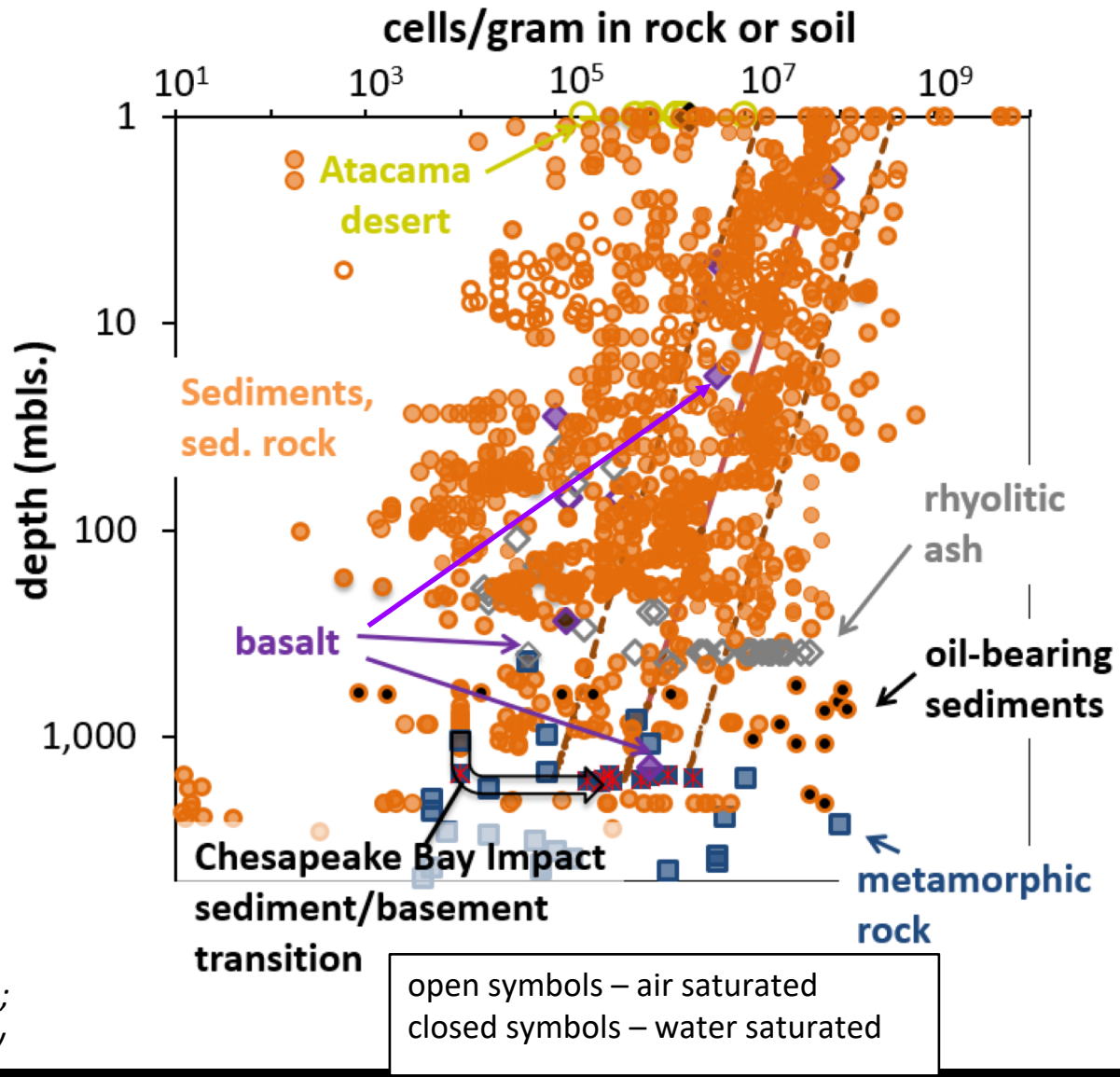
not at current finalist landing sites

recorded in the rocks of Midway and NE Syrtis

Subsurface life is abundant when you know where to look

General cells/gram decrease with increasing depth and temperature, and decreasing porosity BUT are highly variable. They do not correlate with rock type or water saturation or organic carbon content.

Energy flux across chemical redox interfaces and physical interfaces play a significant part in explaining high biomass occurrences.

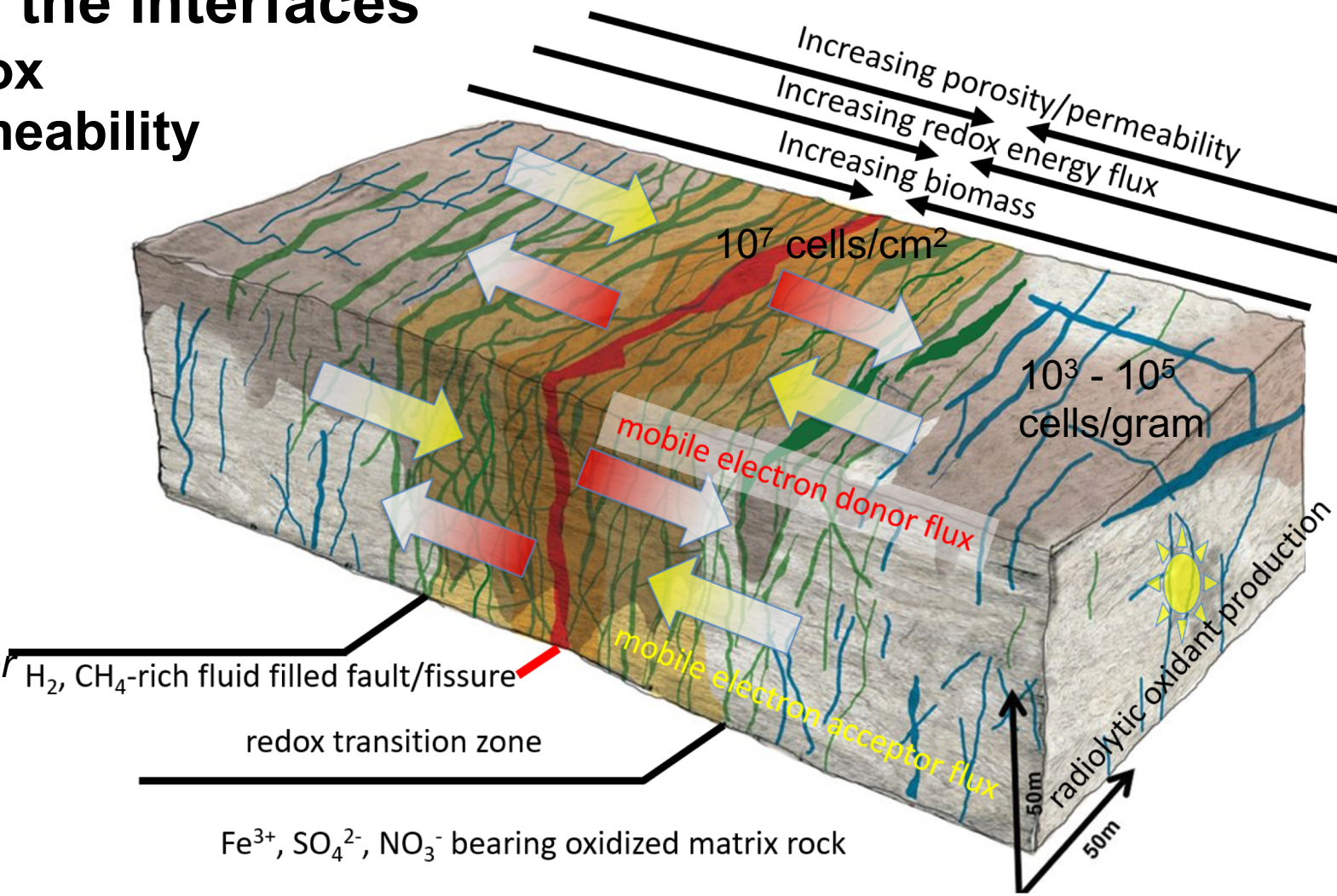


Magnabosco et al., 2018, Nat. Geosci.; Onstott et al., submitted, Astrobiology

Where is rock-hosted life thriving?

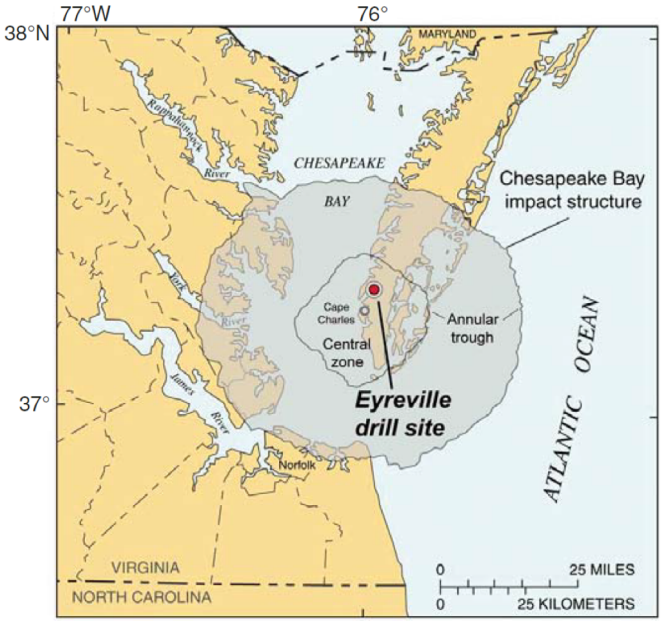
- **Follow the interfaces**
  - **Redox**
  - **Permeability**

*Rock hosted life thrives off of **chemical and physical gradients focused by fractures** where reactants and products can exchange over long time scales*

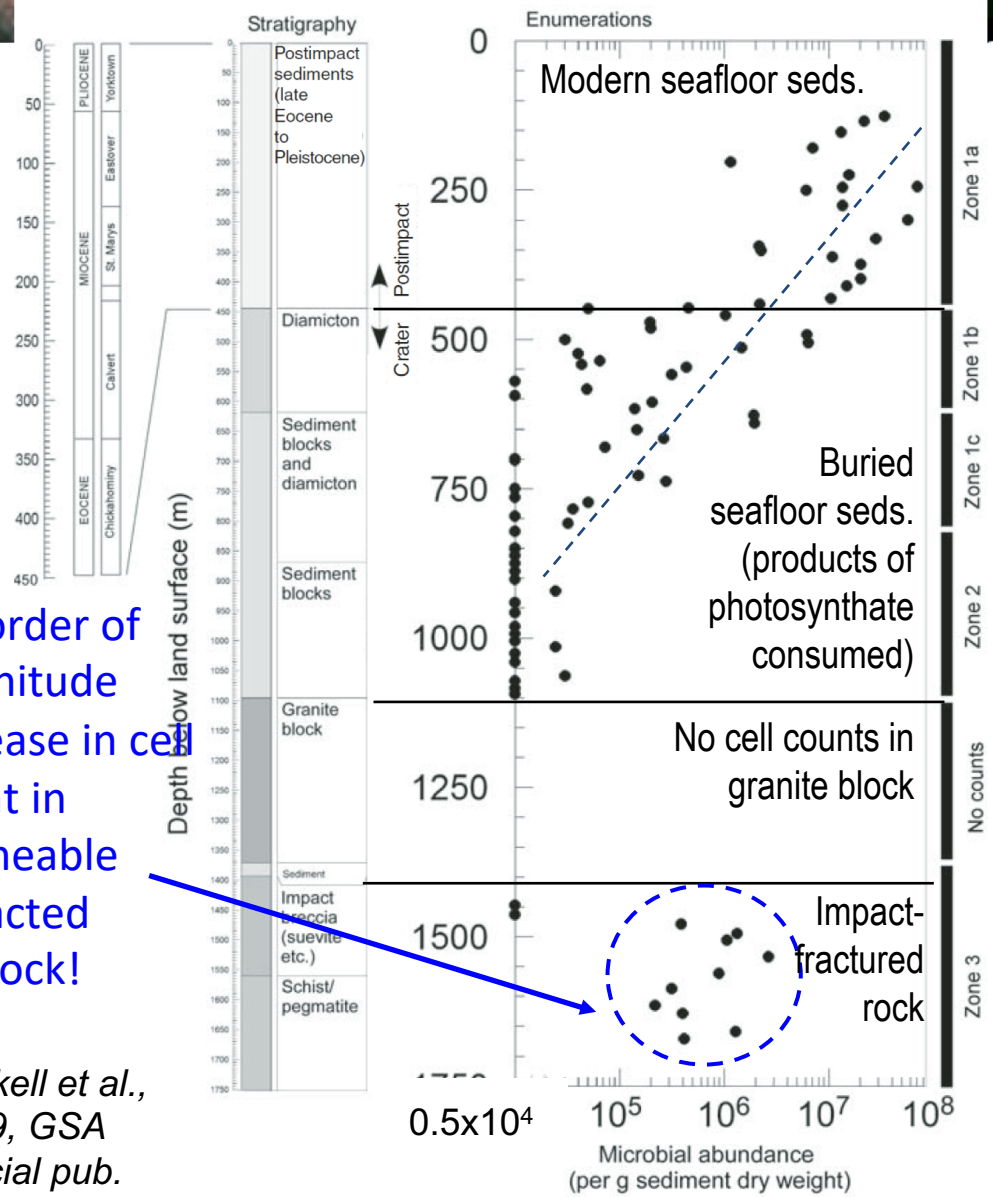


Ex. #1: Buried Chesapeake Impact Structure

- Typical decline in biomass with depth in seafloor sediments reverses in permeable impact-fractured rocks
- **Strategy: Follow the permeability!**



2-3 order of magnitude increase in cell count in permeable impacted bedrock!



Cockell et al., 2009, GSA special pub.

Ex. #2: Oman Olivine-Carbonate

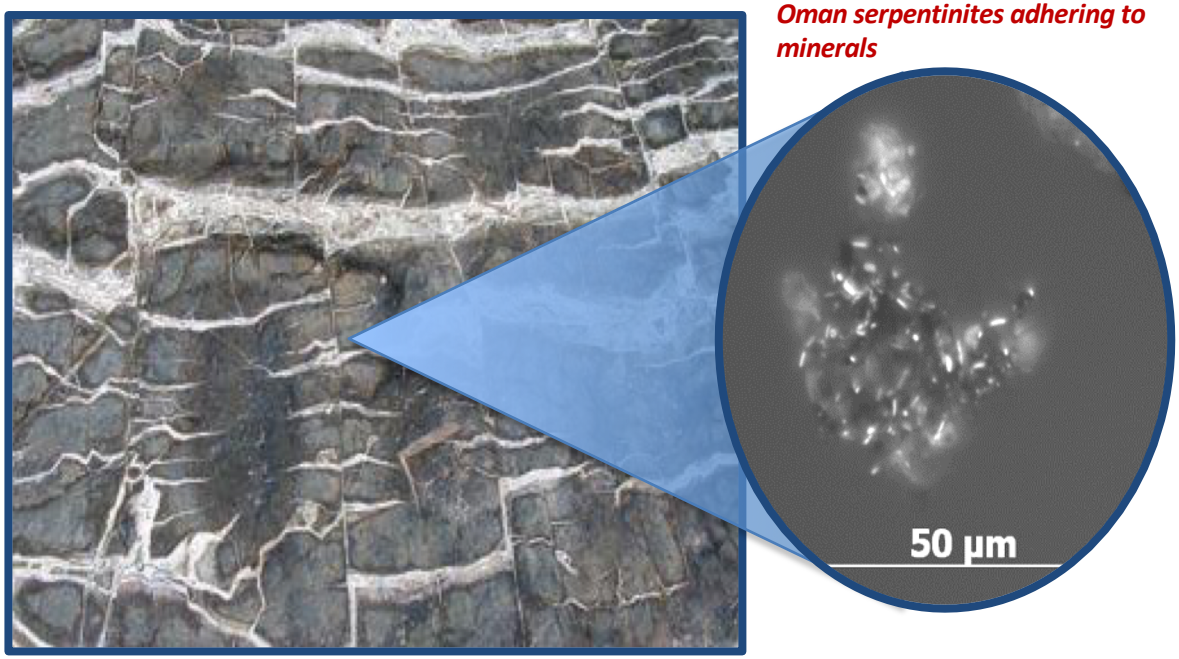
Is there evidence for microbial life & life activity in Olivine/Carbonate rocks?

Yes. Abundant

- Driven by **hydration of olivine, oxidation of iron**
- Hyperalkaline biological CH_4 production, and **unique isotope signals from methanogens** using H_2 **& carbonate**: *Miller et al. 2018; Nothaft et al. (in prep)*

- Biological activity assays showing C and S reduction from rock-derived organisms: *Fones et al. (in prep); Glombitza et al. (in prep).*
- Characterization of habitable conditions, and analysis of biomass and genomic data for organisms inhabiting fracture fluids: *Miller et al. 2016; Remfert et al. 2017; Coleman et al. (in prep); Kraus et al. (in prep); Rempfert et al. (in*

Methanobacterium sp. from Oman serpentinites adhering to minerals



Two rock-hosted microbial metabolisms confirmed by the RPL team:

Methanogenesis: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

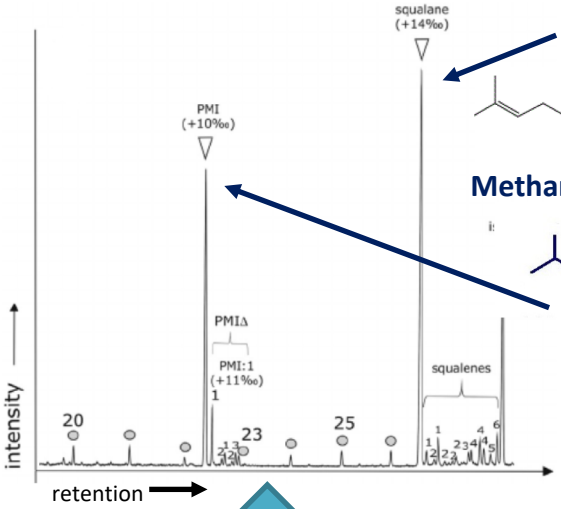
Sulfate reduction: $4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O$

slide provided by A. Templeton, K. Rempfert

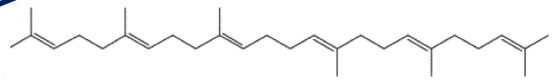
Ex. #2: Oman Olivine-Carbonate Preserved Biomass

Isotopic and organic biosignatures (lipids) preserved in carbonates

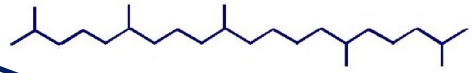
Diagnostically heavy in $\delta^{13}C$- from carbon limitation



Squalene $\delta^{13}C$ ~ 14‰

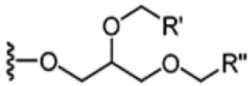


Methanogen lipid-derived hydrocarbons

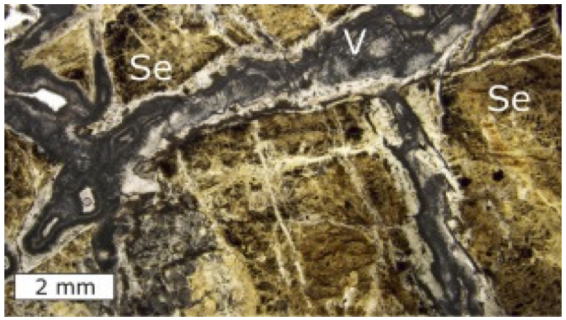


PMI $\delta^{13}C$ ~ 10‰

Extracted hydrocarbons



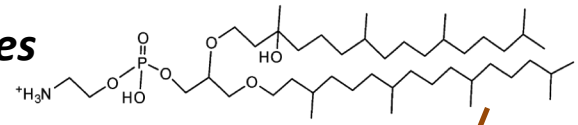
Dietherglycerol
(DEG)



Zwicker et al. (2018)

Terrestrial carbonated serpentinites, Chimaera seeps, Turkey

SE serpentine
V carbonate vein



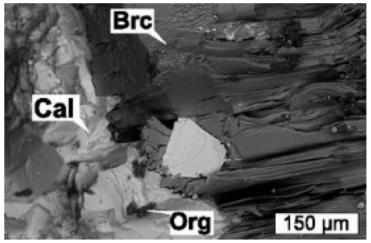
Hydroxyarchaeol with PE headgroup

Archaeal intact lipids

Rempfert et al. (in prep)

Intact polar lipids captured in precipitating carbonate, Samail Ophiolite, Oman

Biomarker: Bacterial (sulfate-reducer?) core lipids



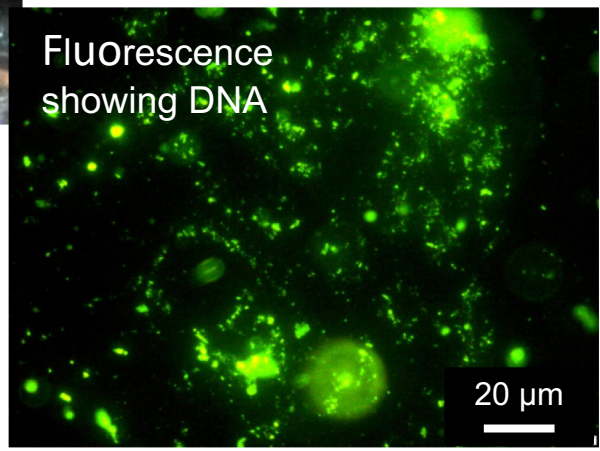
Klein et al. (2015)

~100 Ma, Preservation of lipid degradation products in carbonate veins from a fossilized serpentinizing system, Iberian Margin (for more detail, see Extras)

slide provided by A. Templeton, K. Rempfert

Ex #3, Clay/Fe-ox. Mineralization in Basalt

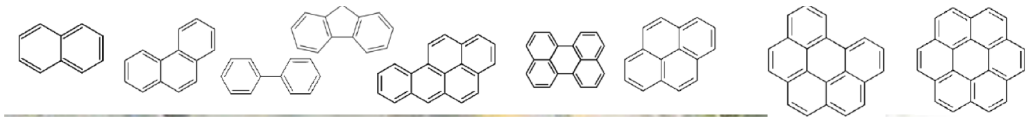
Trias et al, 2017, Nat Comm. (Suppl)



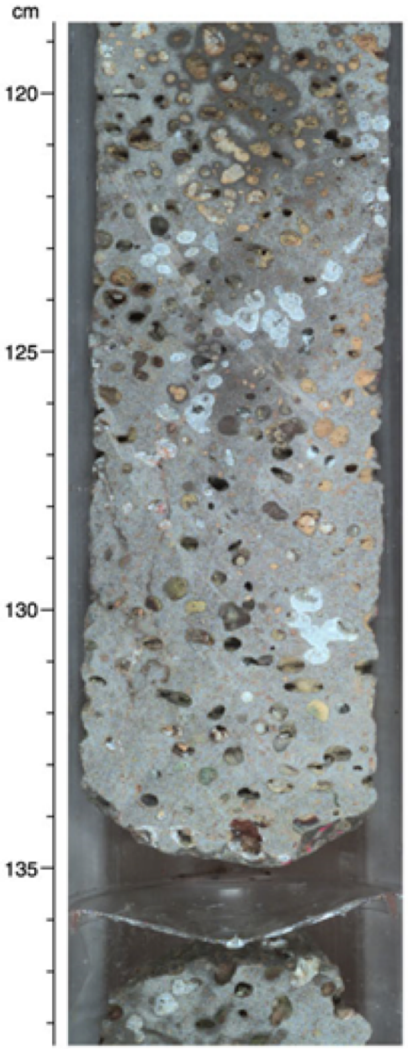
In the Holocene Hellisheidi cores through Icelandic basalt, microbial cells are associated with clay minerals and Fe oxides in vesicles

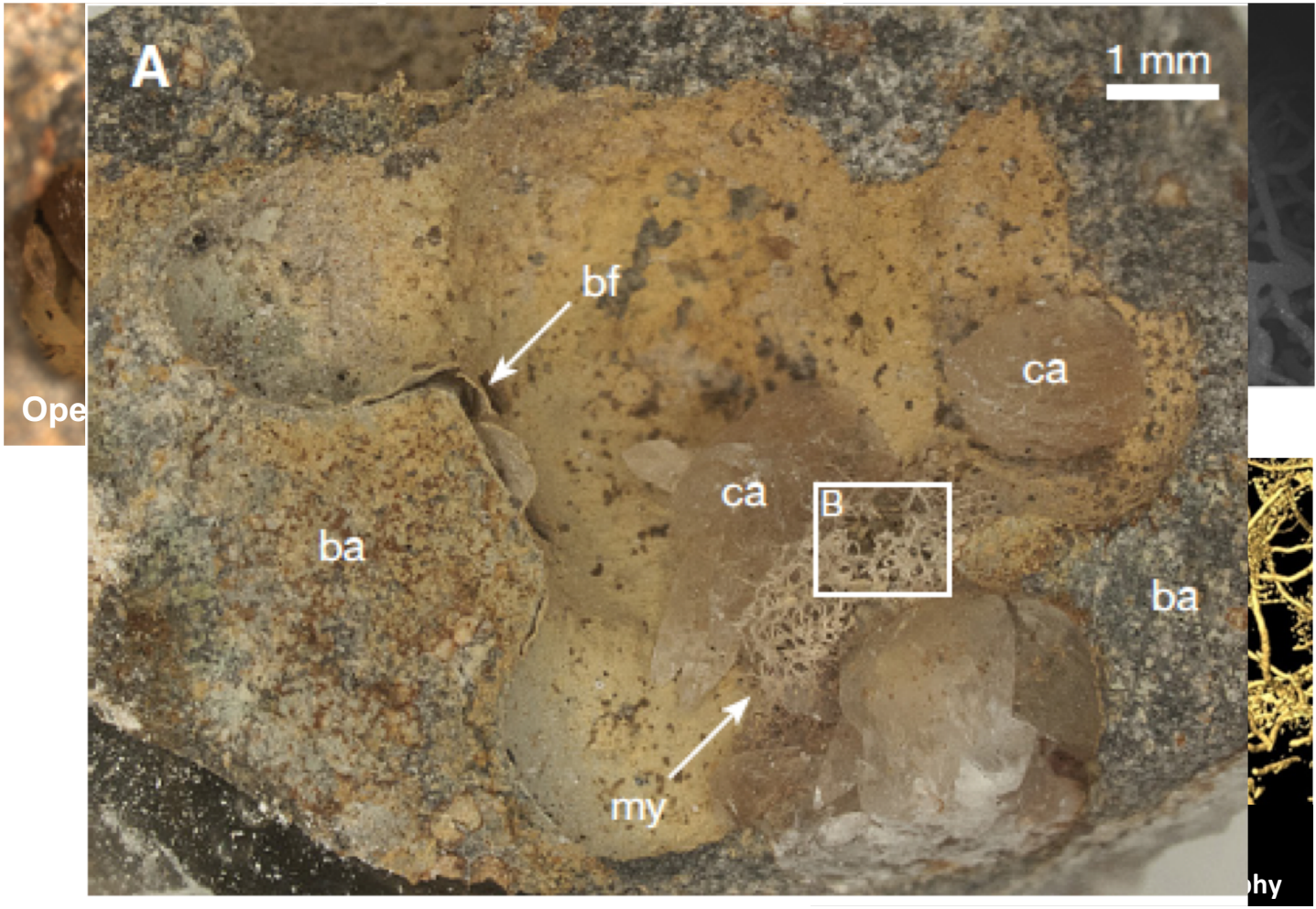
Microbial activity facilitates the creation of permeability by dissolution of primary materials (contrast with the “self-sealing” idea of mineralization in hydrothermal systems)

Feed-zones (made of fracture and rubbles) provided flow pathway for CO_2 charged ground waters
Dissolving the rock and feeding microbes (including iron-oxidizers) with aromatic compounds and metals
Cells found in Fe oxides, clay minerals



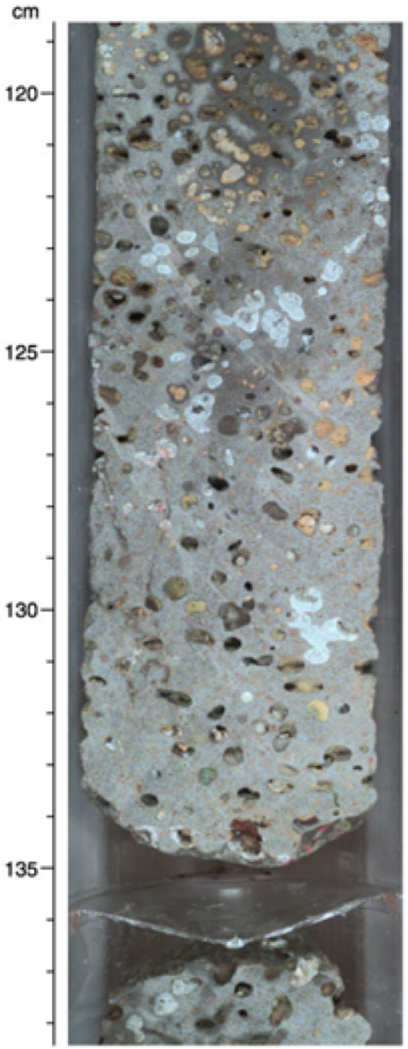
Ex #4, Clay/Fe-ox. Mineralization in Basalt: Ancient Biosignatures

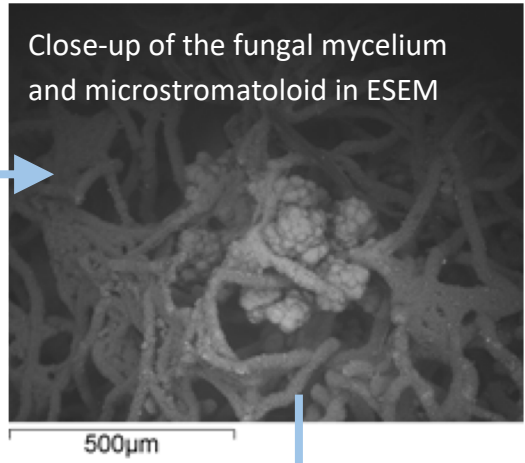


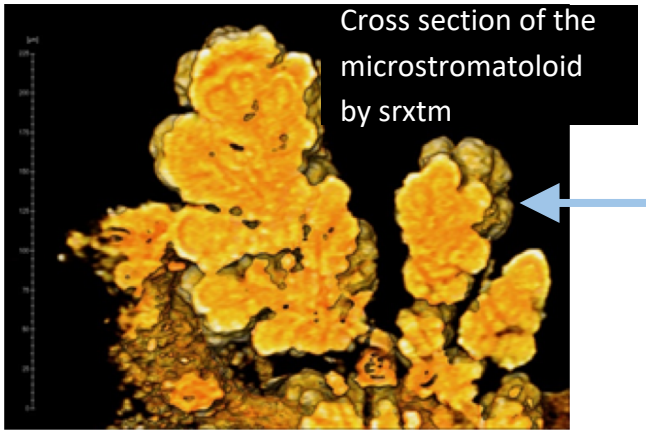


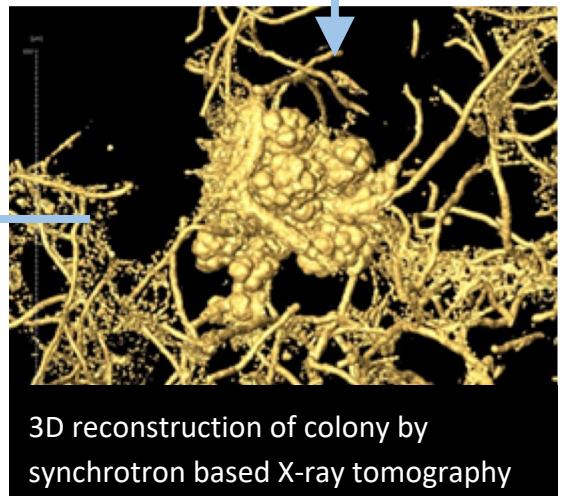
Fossilized prokaryotes and heterotrophic fungal colonies in basaltic subsurface basalt (8-43 Myr old) *Bengtson et al., Geobiology, 2014; Ivarsson et al., PLoS One, 2015*

Ex #4, Clay/Fe-ox. Mineralization in Basalt: Ancient Biosignatures









Fossilized prokaryotes and heterotrophic fungal colonies in basaltic subsurface basalt (80-43 Myr old) *Bengtson et al., Geobiology, 2014; Ivarsson et al., PLoS One, 2015*

Metabolisms: Life in the Rocks at NE Syrtis and Midway

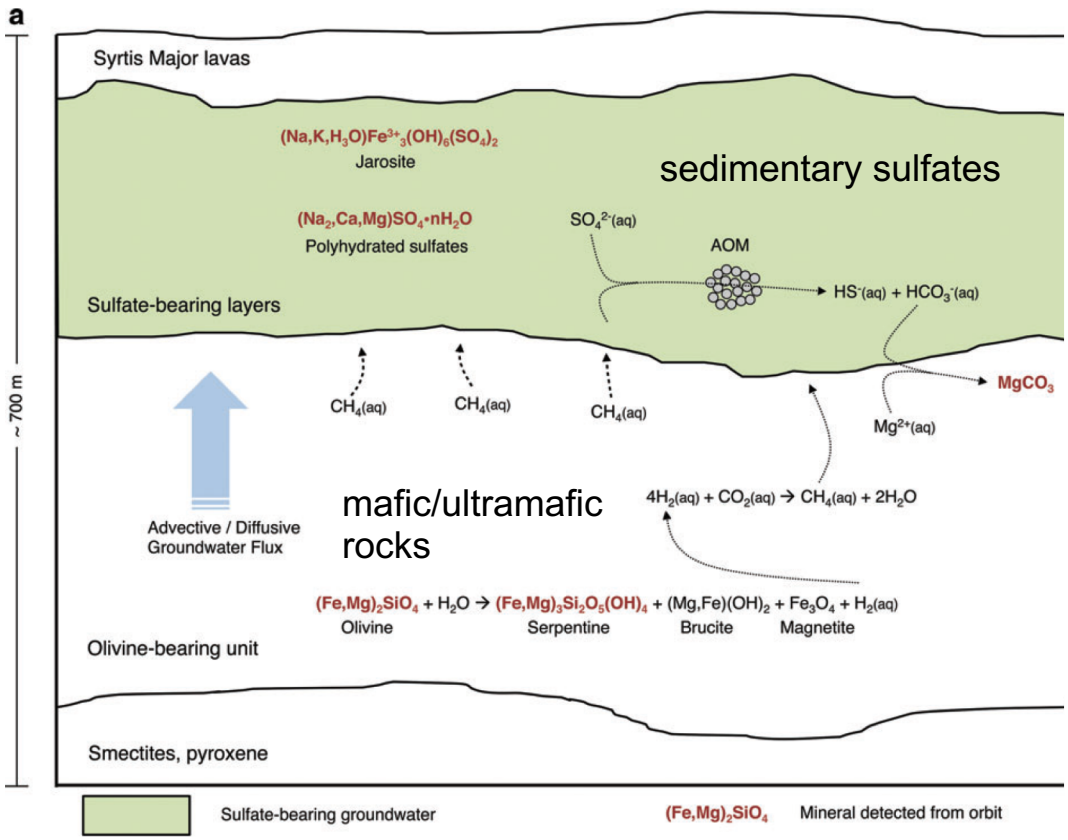
Multiple metabolisms are energetically favorable, as in Oman: As in Oman:

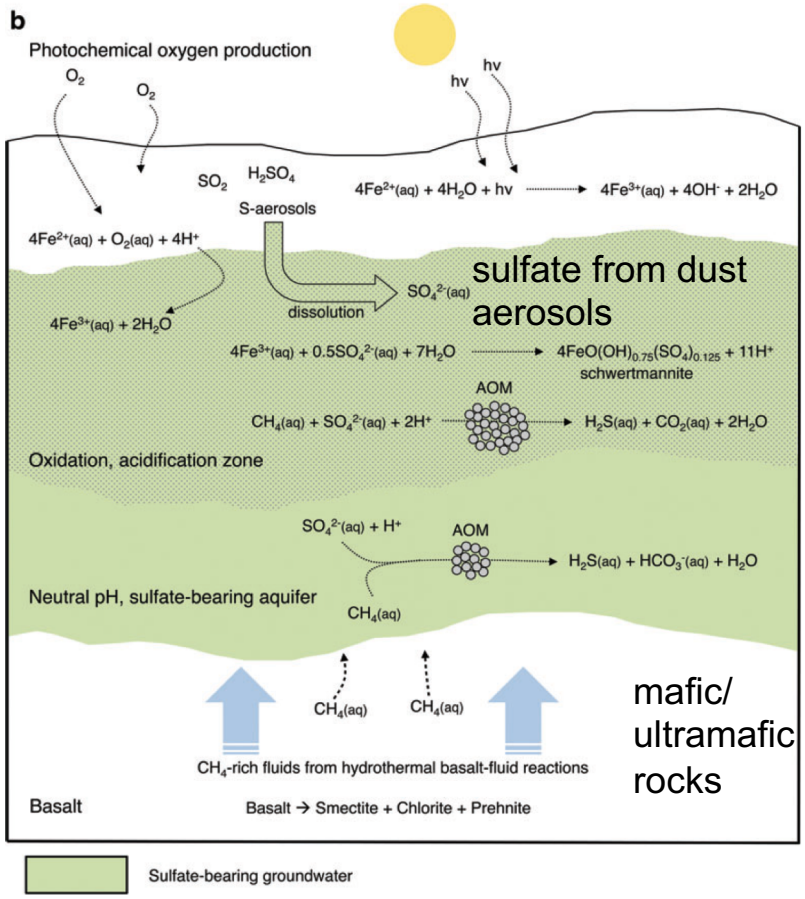
Methanogenesis: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

Sulfate reduction: $4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O$

Also energy to support for Anaerobic Methane Oxidation (Marlow et al., 2014, Astrobio):

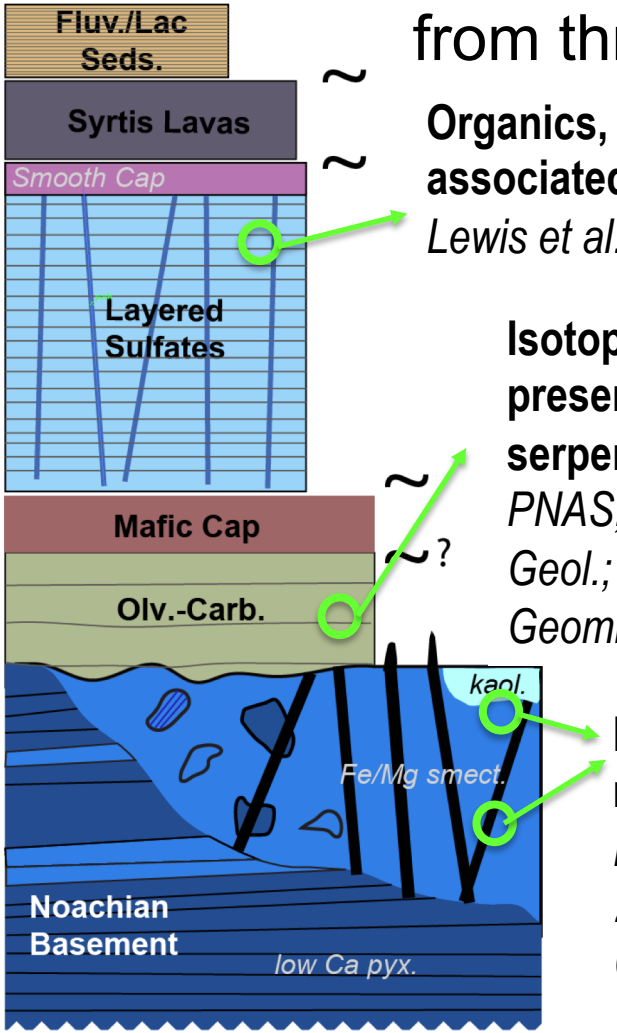
$$CH_4 + SO_4^{2-}(aq) + H^+ \rightarrow HCO_3^-(aq) + H_2S + H_2O$$



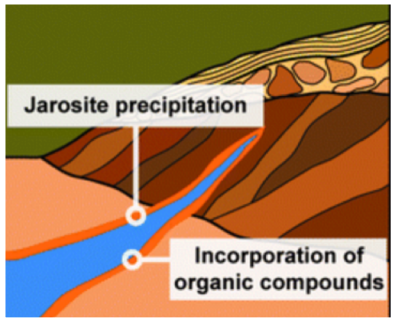


Could rock-hosted life be preserved at Midway/NE Syrtis? Yes! With multiple opportunities!

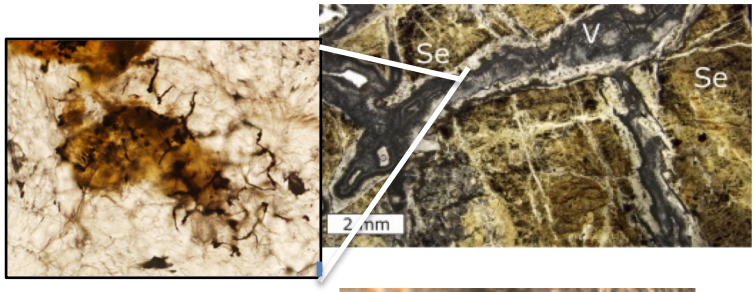
- Yes!!! ≥3 opportunities in 3 different rock units from three different time periods



Organics, fatty-acids preserved in jarosite-associated Fe oxides. *Tan et al., 2018, Sci. Rpts; Lewis et al., 2018, Astrobio. (Sephton lab)*

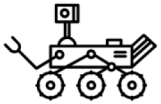
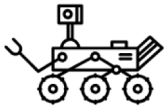
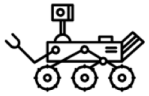


Isotope ratios, organics, lipids preserved in carbonates and serpentines. *Klein et al., 2015, PNAS; Zwicker et al., 2018, Chem. Geol.; Ivarsson et al., 2018, Geomicrobio*

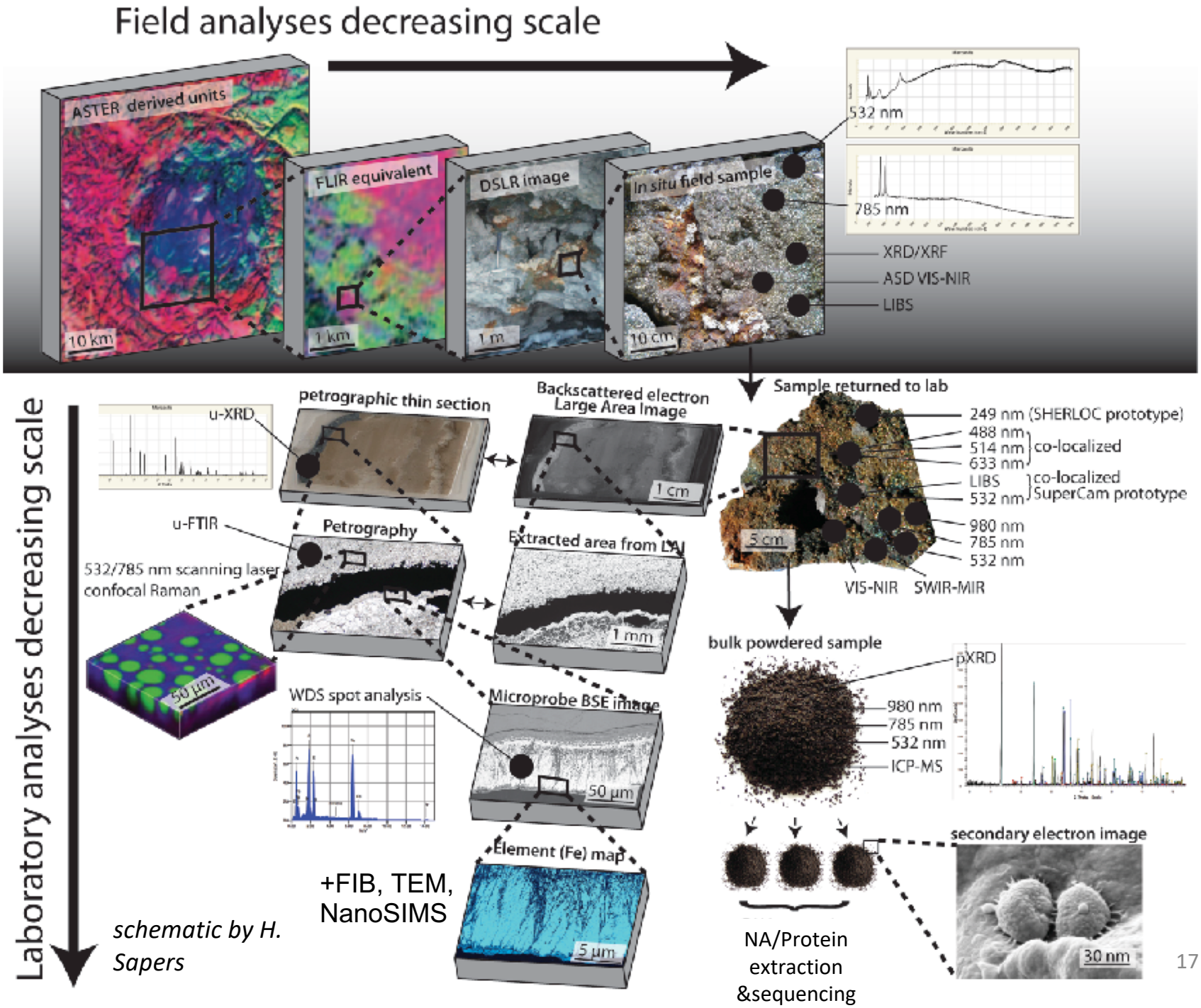


Microfossils, organics, lipids, isotope ratios, preserved in clays, Fe-Mn oxides *Klein et al., 2015, PNAS; Zwicker et al., 2018, Chem. Geol.; Ivarsson et al., 2018, Geomicrobio*

The Strategy for Biosignatures: How to Find Rock Hosted Life on Mars

Step	Spatial Scale	Key Measurement Requirements	
1. **Identify** rocks with **ancient subsurface habitats**	<100 m sampling	Ability to identify water-related mineral deposits from orbit, determine stratigraphic context	✓ Done! NE Syrtis, Midway (thanks orbiters!+more to come with CaSSIS)
2. **Locate interfaces** that represent favorable locations for rock life	Meter- to cm-scale	Ability to identify redox and permeability interfaces by identification of distinct lithologic units	 Mastcam-Z, Supercam (+RIMFAX)
3. **Search for mineralization from fluid flow** at interfaces	Centimeter- and millimeter-scale	Ability to identify silica, carbonate, sulfate, phyllosilicate, and oxides that may mineralize microbial life	 Mastcam-Z, Supercam, PIXL, SHERLOC
4. **Search for organics, mineralization,** and isotopic anomalies at the interface	<100 µm sampling	Ability to detect organics, chemical, mineralogic, and/or isotopic differences between interface rocks and surrounding rocks indicative of biosignatures	 PIXL, SHERLOC
5. **Map putative biosignatures in 3-dimensions**, tracking chemical and organic variations with texture	<1 µm sampling in 3-D	Ability to identify microbial textures and distinguish biotic and abiotic processes to definitively confirm fossil rock-hosted life	Sample Return

rover icon made by Freepik from www.flaticon.com - thanks!


Field analyses decreasing scale
ASTER derived units
10 km
FLIR equivalent
1 km
DSLR image
1 m
In situ field sample
10 cm
532 nm
785 nm
XRD/XRF
ASD VIS-NIR
LIBS
Laboratory analyses decreasing scale
u-XRD
petrographic thin section
Backscattered electron Large Area Image
1 cm
Sample returned to lab
249 nm (SHERLOC prototype)
488 nm
514 nm
633 nm
co-localized
LIBS
532 nm
co-localized SuperCam prototype
980 nm
785 nm
532 nm
5 cm
VIS-NIR
SWIR-MIR
u-FTIR
Petrography
Extracted area from LA
1 mm
532/785 nm scanning laser confocal Raman
50 µm
WDS spot analysis
Microprobe BSE image
50 µm
Element (Fe) map
5 µm
+FIB, TEM, NanoSIMS
bulk powdered sample
pXRD
980 nm
785 nm
532 nm
ICP-MS
secondary electron image
30 nm
NA/Protein extraction &sequencing
schematic by H. Sapers

The National Academies Has Also Recommended the Search for Subsurface Life

Report Release Event/Webcast on October 10, 2018 at 11am ET

Academies Report pdf at http://nap.edu/25252

Explore with the latest science: The last 30 years of Earth Astrobiology work on the subsurface biosphere must drive how we look for life on Mars

Key Take Home Messages

Go Broad: Successful search strategies for life must integrate the idea that no one biomarker is infallible, no single geochemical scenario is the key, life need not be "as we know it." The central theme to the report is the recommendation for "outside the box" thinking in all things pertaining to the search for life.

Go Deep: Flowing from this, and in light of recent exciting discoveries on Earth, Mars, Ocean Worlds and exoplanets, the report recommends a broader perspective that includes subsurface environments as targets for the search for life.

Go High-Contrast: Spectroscopic measurements and high-contrast, near-term space- and ground-based direct imaging missions will, over the next two decades, enable remote characterization of exoplanet atmospheres and the search for potential biosignatures for terrestrial exoplanets orbiting M-dwarf stars—a major theme identified as well in the Exoplanet Science Strategy (2018).

The National Academies of SCIENCES ENGINEERING MEDICINE

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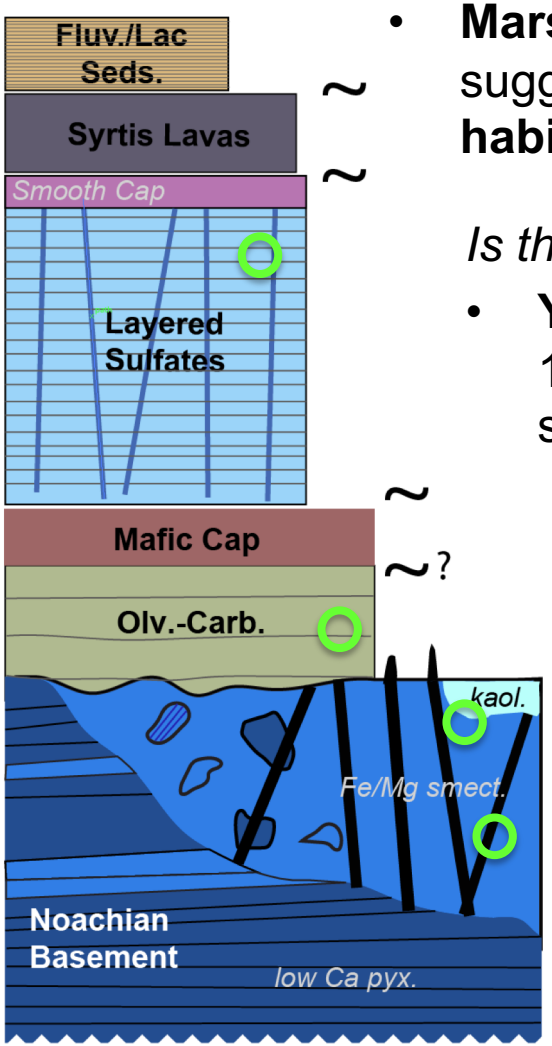
Conclusions: Go deep! Go Noachian to search for evidence of life on Mars



*Why focus the search on **rock-hosted life** on Mars?*

- **Mars is different from Earth** and its specific geologic history suggests the best places for life are the **longest-lived stable habitats: groundwater aquifers**

*Is there **enough subsurface life** that Mars-2020 **could find?***

- **Yes!** Found on Earth at **>10^6 cells/cm^3** (SHERLOC threshold: 10^3); also **lipid, isotopic, morphologic evidence** in returned samples

*Is there a **search strategy** to direct the rovers? **Yes!***

- **Follow the interfaces (redox, permeability)** to find the highest concentrations of organic matter

- Is **Noachian stratigraphy** at NE Syrtis or Midway **a good place** to do this? **The ideal place.** ≥3 opportunities in 3 different rock units from three different time periods

EXTRAS

Fossil record of subsurface life

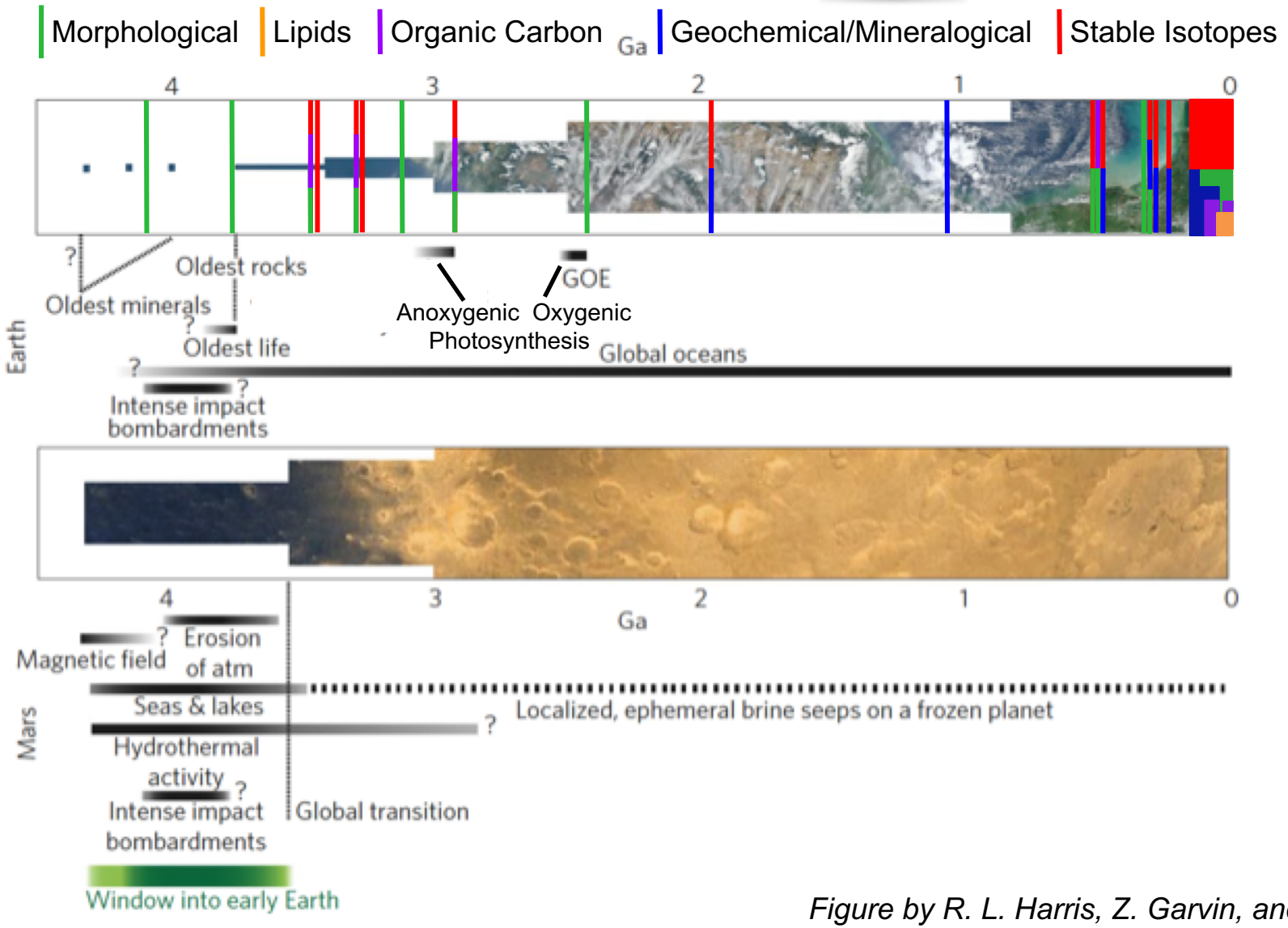
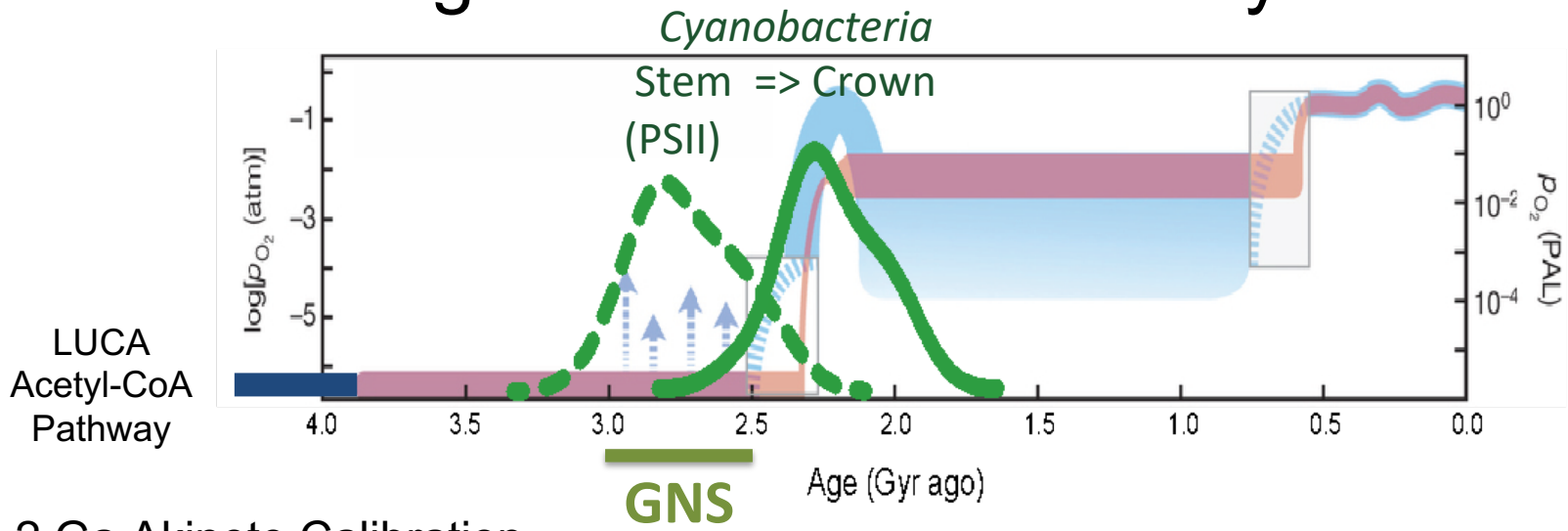


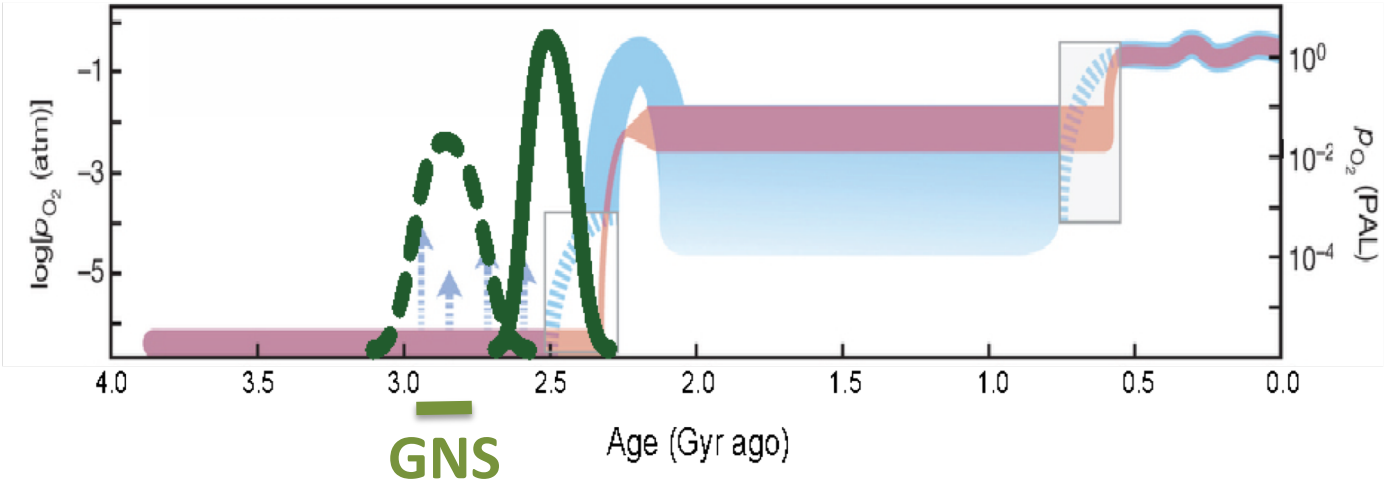
Figure by R. L. Harris, Z. Garvin, and D. Nisson

Michalski et al.. 2018 – Nature Geoscience – https://www.nature.com/articles/s41561-017-0015-2;
Onstott et al. 2018 – arXiv – https://arxiv.org/abs/1809.08266; Astrobiology – in review

Pathways Utilized by Subsurface Chemotrophs Evolved Long Before Those Used By Phototrophs

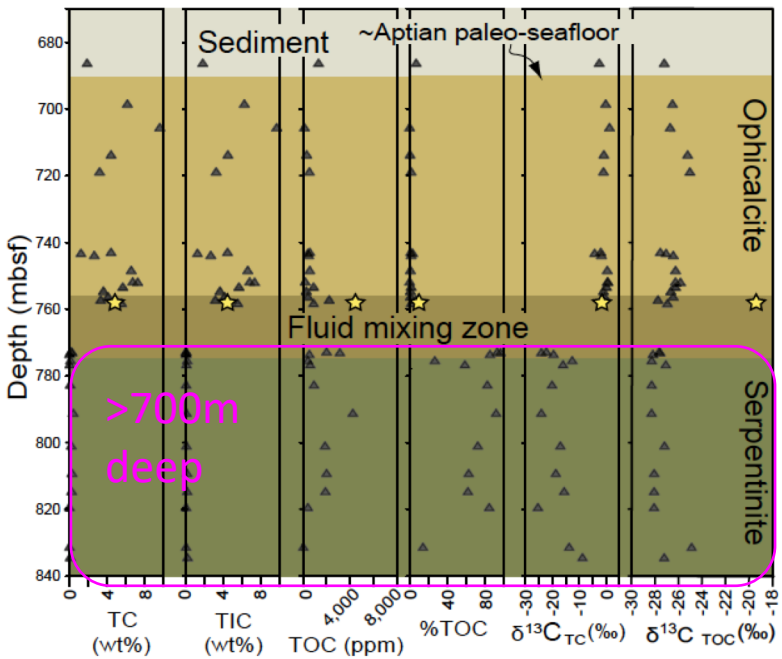


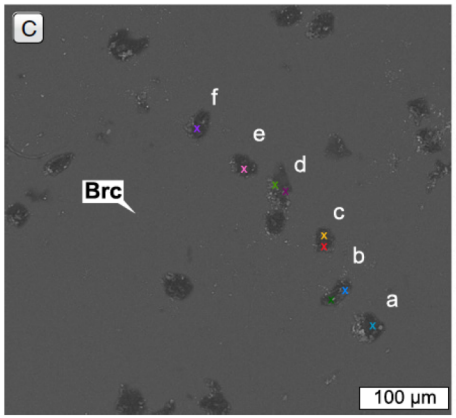
1.2 Ga Akinete Calibration

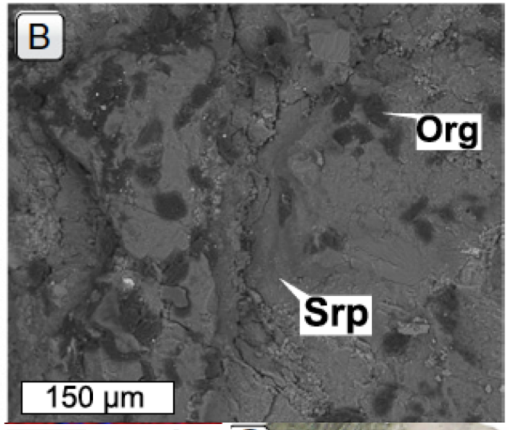


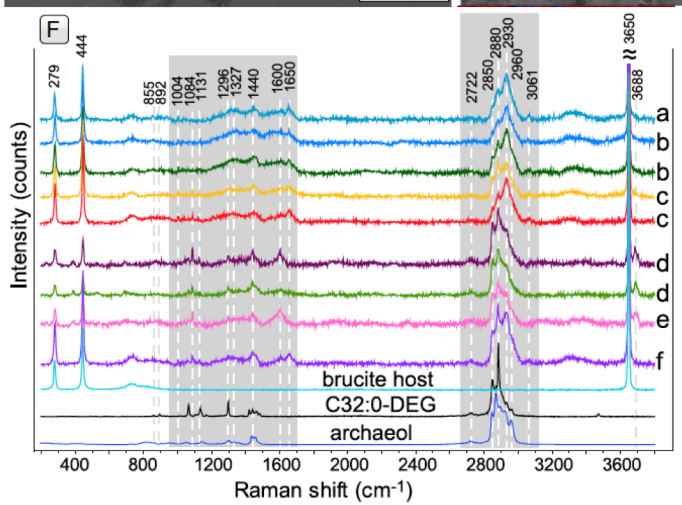
1.6 Ga Akinete Calibration

Preserved Biosignatures of Rock-Hosted Life: 100Ma Carbonate/Serpentine-Hosted

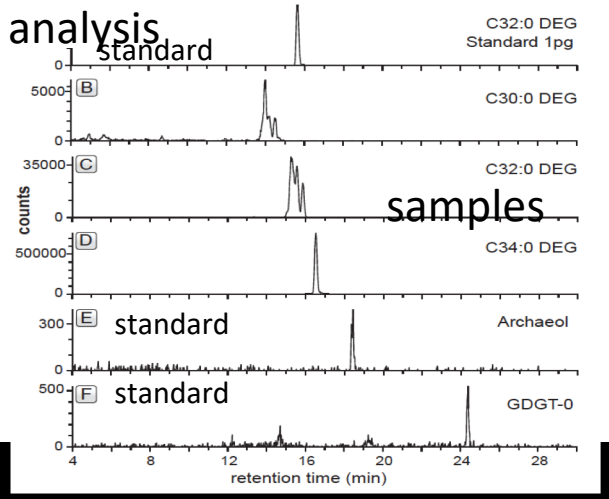








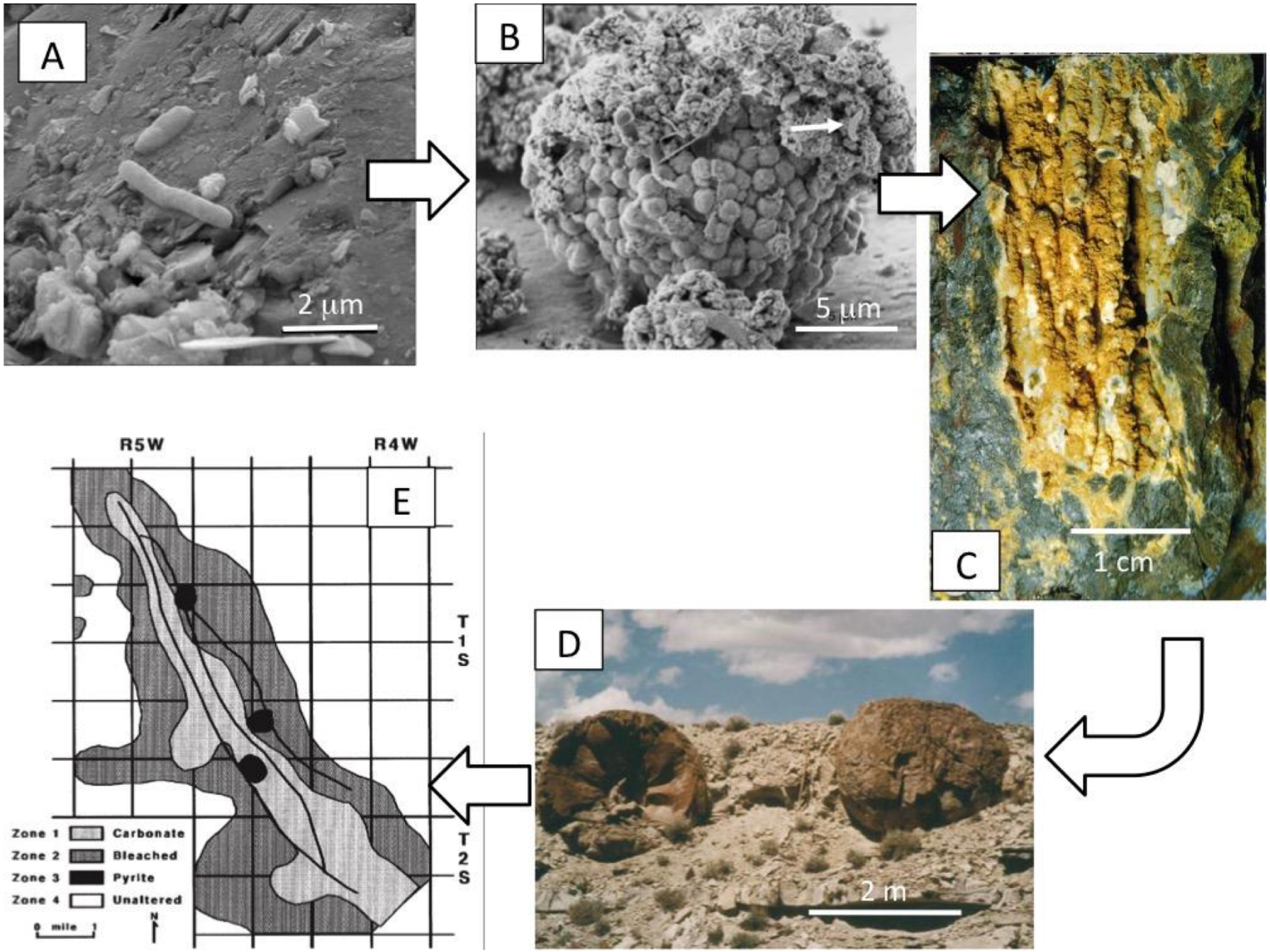
Lipid analysis



Klein et al. 2015, PNAS

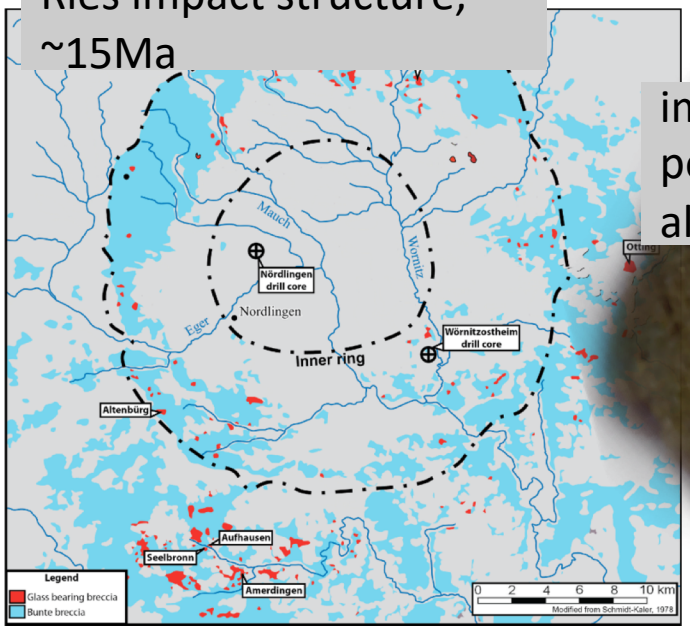
Fossil Lost City Hydrothermal System, deep rocks. 125 - 113Ma)

Metabolic Footprint

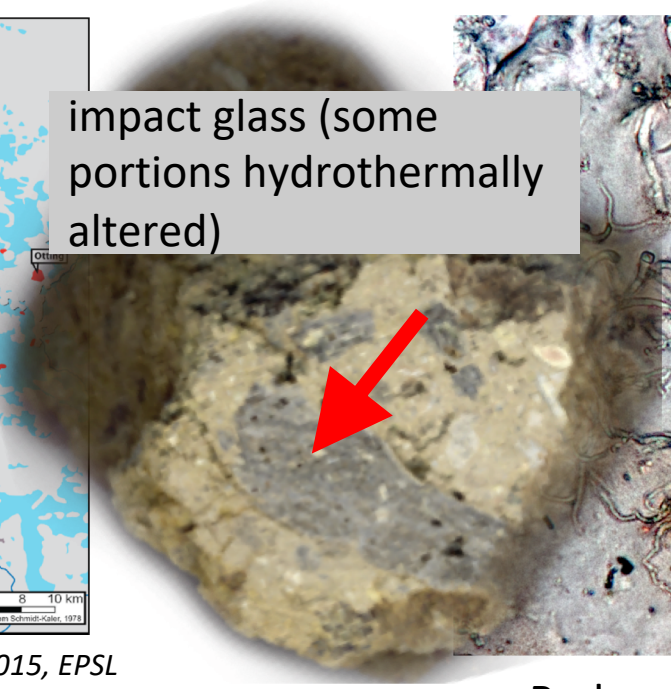


Preserved Biosignatures of Rock-Hosted Life: Example, Organics from Trace Fossils in Impact Glasses

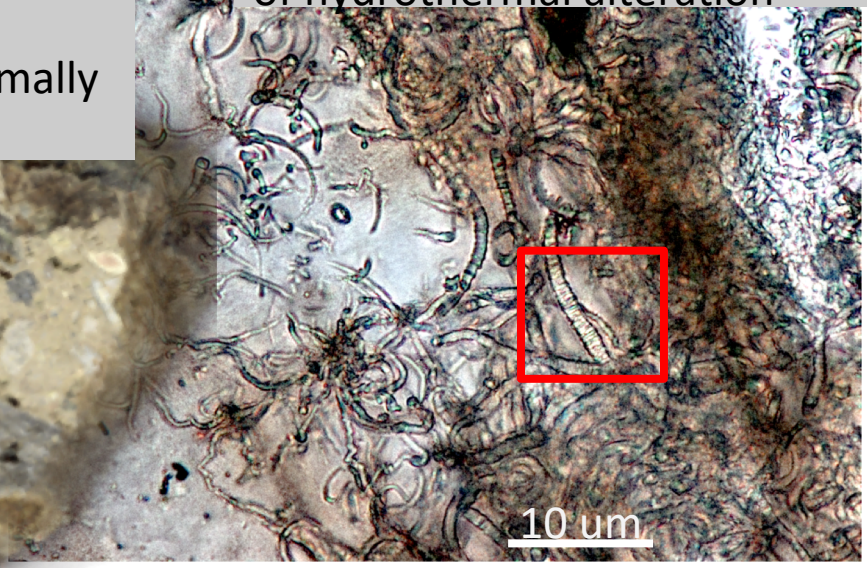
Ries impact structure, ~15Ma



impact glass (some portions hydrothermally altered)

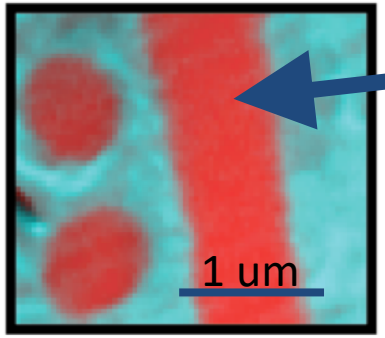


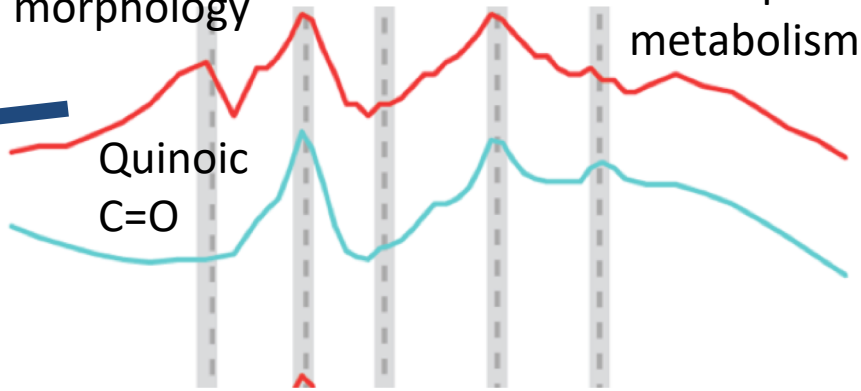
Pervasive microtubles in zones of hydrothermal alteration



Sapers et al., 2015, Geology; Sapers et al., 2015, EPSL

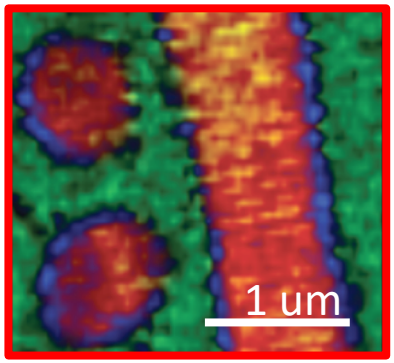
Organics co-located with morphology





C K-edge

Redox patterns consistent with metabolism

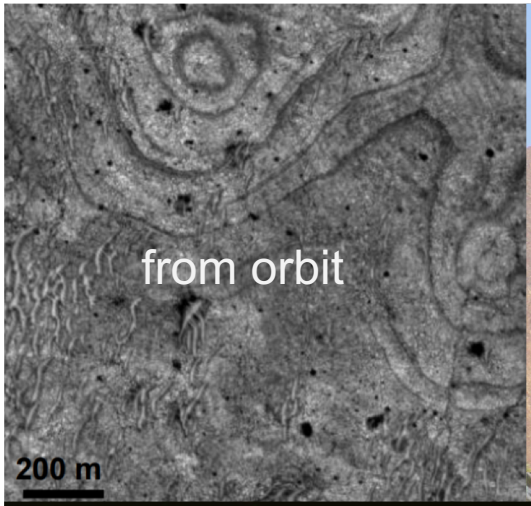


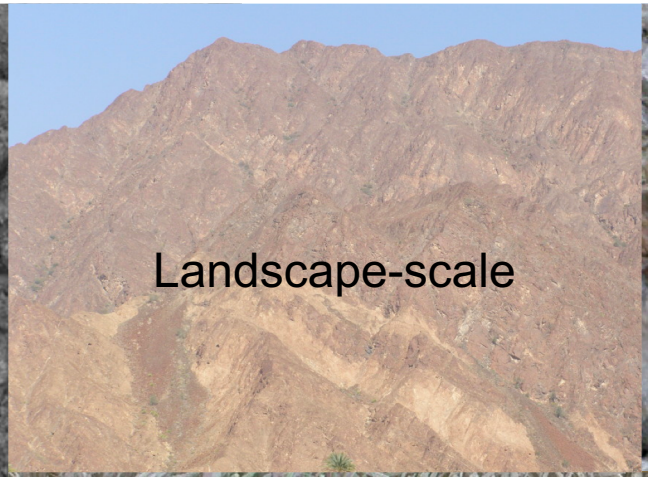
Fe(III)
Fe(II)
Fe(III)
Fe(II)

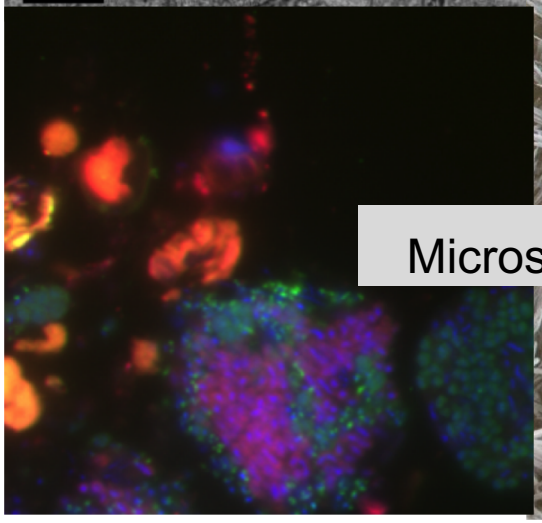
Fe L_3-edge

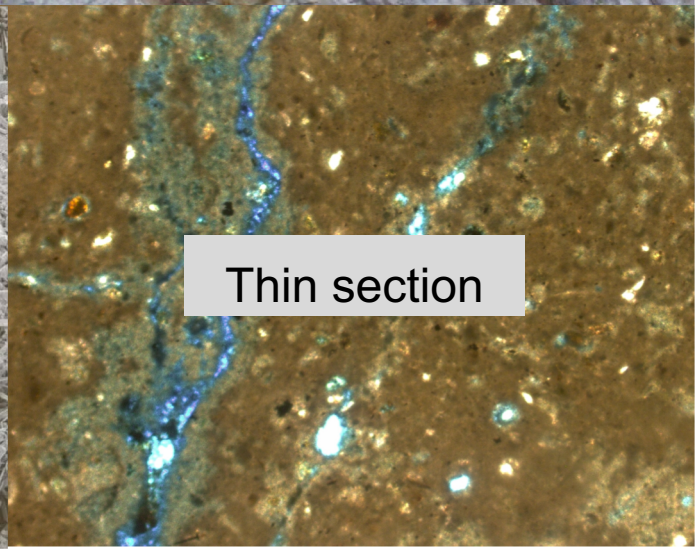
Scaling the Exploration Strategy

Seeking boundaries and interfaces at all spatial scales









Example from Cecilia Sanders work

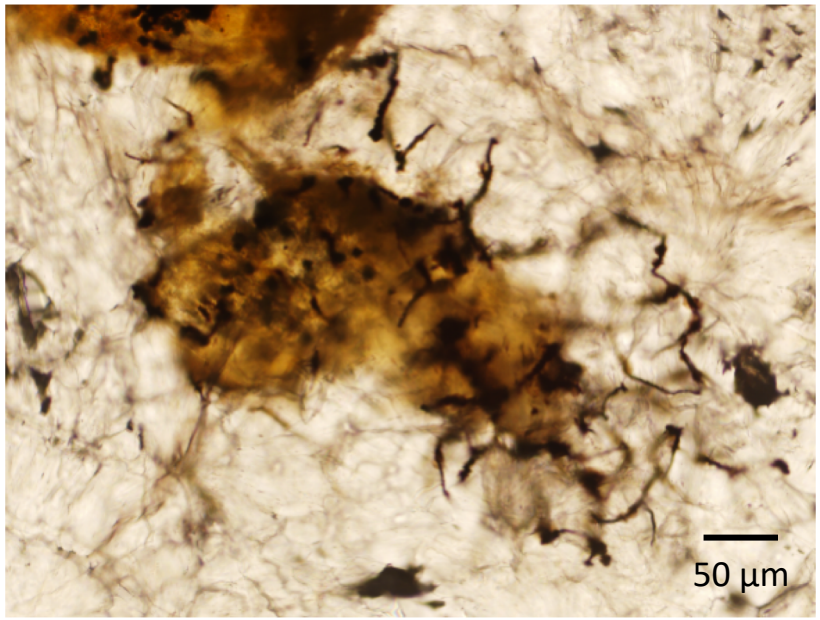
- Placeholder for graphics from cultivation experiments by Cecilia Sanders, Victoria Orphan, Bethany Ehlmann
- Biofilms
- Isotopically distinct pyrite

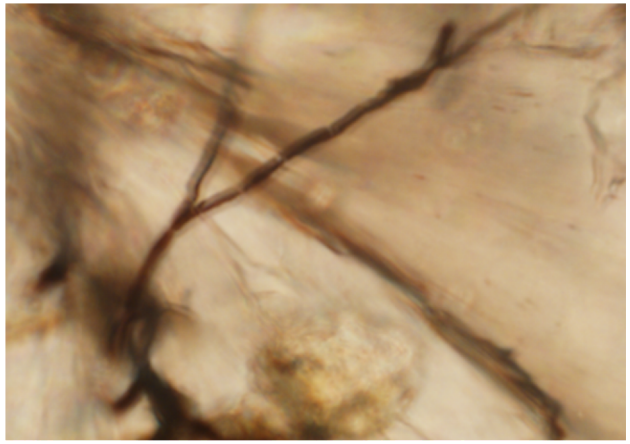
Among the Oldest: 2Ga Fossil Rock Life

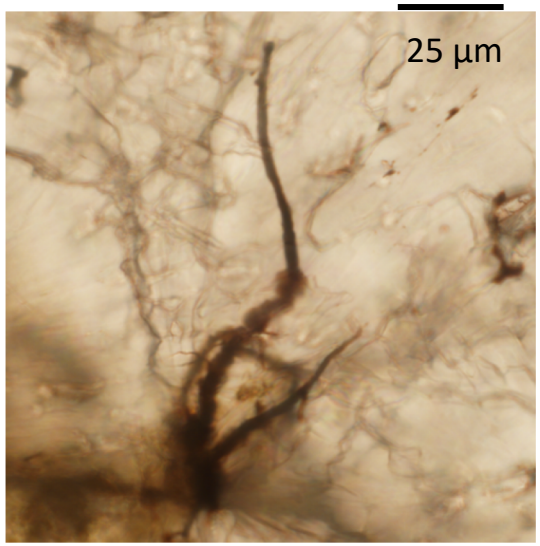
Vesicular basalt (2.4 Ga), Ongeluk formation, South Africa. Overview of a vesicle with filamentous fossils, and a tomographic reconstruction of the network.

Bengtson et al., 2017, Nat Comm.

Fossil Life in Olivine-Derived Carbonate



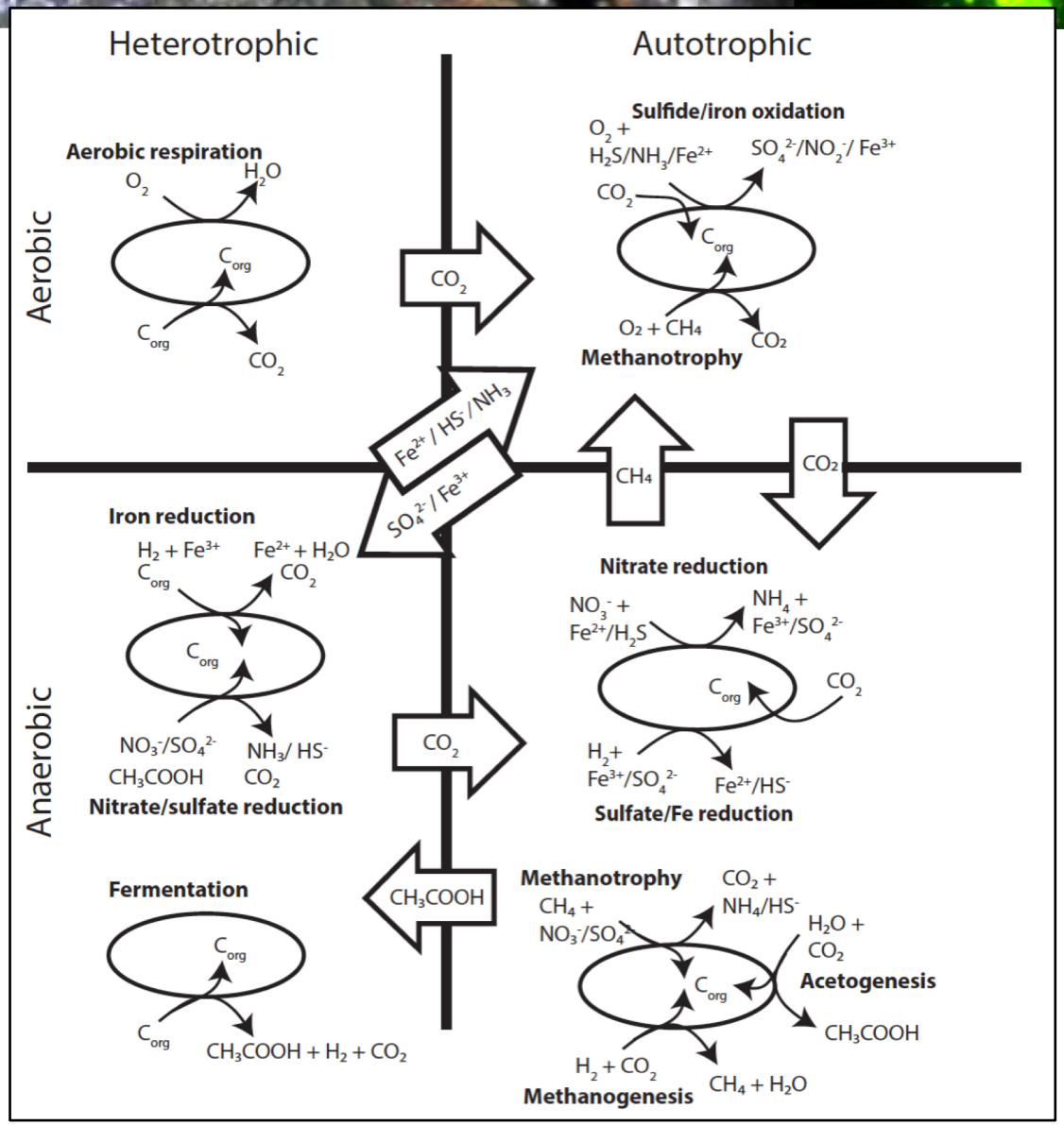




25 µm

Fossilized filamentous microorganisms in carbonate filled vein in ultra mafic rocks from the Mid-Atlantic Ridge.
Ivarsson et al., 2018.

Metabolisms of rock-hosted life



Onstott et al., in review, Astrobio

Figure by H. Sapers

MICROENVIRONMENT FEEDBACK

to create biosignatures

fixation, volatilization

organic C → CO_2

Methylation

As, Se, Te, Sn, Pb, Hg

Chemolithotrophic leaching

H+, pH changes, Fe(III), SO_4^{2-}

Chemo-organotrophic leaching

H+, siderophores, organic acids, metabolites

Redox (im)mobilization

(Fe(III) - Fe(II)
Mn(IV) - Mn(II)

mineral bioweathering biomineralization

Biocorrosion
Biosoption

Metals

chemistry determines colonization
colonization affects chemistry