MEPAG meeting #33

Summary Report of the Working Group on Finding Signs of Past Rock-Hosted Life

on Behalf of the Rock-Hosted Life Working Group

Bethany Ehlmann (Caltech & JPL), TC Onstott (Princeton), Max Coleman (JPL), Jeff Marlow (Harvard), Paul Niles (NASA JSC), Haley Sapers (Caltech)

February 22, 2017

Working Group on Finding Signs of Rock-Hosted Life: History & Motivation

Orbiter and rover data from the last decade of Mars missions show widespread and time-persistent groundwater-related environments. Several candidate Mars2020 sites have accessible "rock-hosted" habitats for life, which, if on Earth today, would be inhabited (e.g., aquifers in volcanic rock, aquifers in sedimentary rock)

The 2nd Mars-2020 Landing Site Workshop (August 2015) had many questions about rock-hosted life, especially *past* rock-hosted life, e.g.,

- ➢ "What is the astrobiological potential of the subsurface?"
- ➢ "How much biomass?"
- ➢ "What are the biosignatures of rock life?"

The May 2016 Biosignature Analogs workshop did not have the participation needed to enable answering these questions

We set out to answer these and other questions, with funding from NASA HQ (M. Meyer, M. Voytek) and logistical support from the NASA Astrobiology Institute and the JPL Mars Program Office - thank you!

- ➢ 4 Community Webinars, recorded
- ➢ In-person meeting of invited experts at Caltech, February 6-7, 2017
- ➢ Dissemination: 3rd Mars Landing Site Workshop Presentation, MEPAG Presentation, a summary publication to be submitted to *Astrobiology or Frontiers* (TBC) in April

For more detailed information, go to http://web.gps.caltech.edu/~rocklife2017/

Successful, Well-Attended Community Webinar Series

Advertised on LPI, PEN, NAI, and C-DEBI email newsletter lists;
typically 50-60 independent logins each webinar

See recordings, presentations, reading lists archived
http://web.gps.caltech.edu/~rocklife2017/

Telecon 1:
Martian Environments, Facies, and Ages: Evidence for Rock-Hosted Waters
December 19, 8:30AM PST

Telecon 2: Metabolisms and Niches for Terrestrial Rock-Hosted Life
December 20, 8:30AM PST

Telecon 3: Paleo-Rock-Hosted Life Biosignature Detection & Characterization
January 13, 8:30AM PST

Telecon 4: Advanced Instrumentation Techniques for Finding Biosignatures
January 23, 9:30AM PST

International Team of On-Site Participants and Contributors to Webinars

Abigail Allwood	JPL
Jan Amend	USC
Luther Beegle	JPL
Roh Bhartia	JPL
Penny Boston	NASA Ames
Charles Cockell	University of Edinburgh
Max Coleman (Org.)	JPL
Bethany Ehlmann (Org.)	Caltech, JPL
Danny Glavin	NASA Goddard
Lindsay Hays	JPL
Keyron Hickman-Lewis (student)	*CNRS-Orleans*
Kai-Uwe Hinrichs	Univ. of Bremen
Joel Hurowitz	Stony Brook University
Magnus Ivarsson	Swedish Museum of Natural History
Sean Loyd	Cal State University Fullerton
Sarah Stewart Johnson	Georgetown University
Issaku Kohl	UCLA
Sean Loyd	Cal State University Fullerton
Jeff Marlow (Org.)	Harvard University
Benedicte Menez	IPGP
Joe Michalski	University of Hong Kong
Anna Neubeck	Stockholm University
Paul Niles (Org.)	NASA Johnson
Tullis Onstott (Org.)	Princeton University
Maggie Osburn	Northwestern University
Aaron Regberg	NASA Johnson
Cecilia Sanders (student)	*Caltech*
Haley Sapers (Org.)	Caltech, JPL, USC
Barbara Sherwood-Lollar	University of Toronto
Greg Slater	McMaster University
Nathan Stein (student)	*Caltech*
Alexis Templeton	University of Colorado
Greg Wanger	JPL
Frances Westall	CNRS-Orleans
Reto Wiesendanger (student)	*University of Bern*
Ken Williford	JPL
Boswell Wing	University of Colorado
Ed Young	UCLA
Jon Zaloumis (student)	*Arizona State University*

International Team of On-Site Participants and Contributors to Webinars

- A total of 39 scientists, including:
  - 5 students
  - 7 early career researchers

- Areas of expertise:
  - Earth deep biosphere
  - Earth ancient life in the rock record
  - Mars environments
  - Advanced instrument techniques
  - Astrobiology
  - Mars 2020 science
  - Mars 2020 instruments

Why Focus on An Exploration Strategy for Martian Rock-Hosted Life? - The Science Drivers

One hypothesis is that the record of ancient Martian life might look much like some aspects of the presently-known early terrestrial record (~3.0-3.7 Ga), i.e., mineralized, (+/-oxygenic) photosynthetic mats, forming laminated structures in near-shore, marine facies on a mostly ocean world.

By 3.5 Ga, Mars' surface environment had evolved to conditions different and more challenging to life (vs. Earth)

- Earth had had an ocean in continuous existence for 1 Ga. Mars did not.
  - Instead, 8 southern highlands landing sites under consideration had subsurface aquifers and/or systems of episodic lakes/rivers fed by runoff from precipitation or ice melt.
- Mars lost much of its radiation protection early (3.9-4.1 Ga). Loss of magnetic field; thin atmosphere (~1 bar or less)

Martian surface habitats at candidate landing sites are both more episodic and more extreme than age-equivalent surface habitats on the Earth. Early Martian organisms at the surface faced

- Cold (at least seasonally sub-freezing temperatures)
- Surface aridity
- Surface radiation doses many times higher than that present on the early Earth
- Low pN_2 limiting nitrogen uptake

There is thus a "risk" photosynthetic life would have been rare to absent

On the other hand, **subsurface environments were comparatively stable.** Data from orbital and landed missions suggest **widespread subsurface waters.** Consequently, **rock-hosted habitats showing evidence of persistent water warrant attention in the search for Martian life.**

How Knowledge of Terrestrial Life Leads to an Exploration Strategy

What do we know about terrestrial rock-hosted life?

Taxonomic biodiversity varies from location to location and environment to environment from simple to extremely complex, but functional diversity has common components.

- Primary Production - The **primary producers are chemolithotrophs many of which use H_2** that is produced by multiple abiotic processes (e.g. serpentinization, radiolysis, cataclastic reactions). Metal/sulfide oxidizers also leach/oxidize minerals and glass.

- Syntrophy - Complexity appears to build upon recycling of metabolic products to reduce thermodynamic limitations and increase activity between organisms at the same trophic level

- Mobility: Subsurface microorganisms are mobile and will migrate to new food sources or comrades.

- Evolution: Subsurface microorganisms and communities evolve through selection and gene transfer to gain functional diversity.

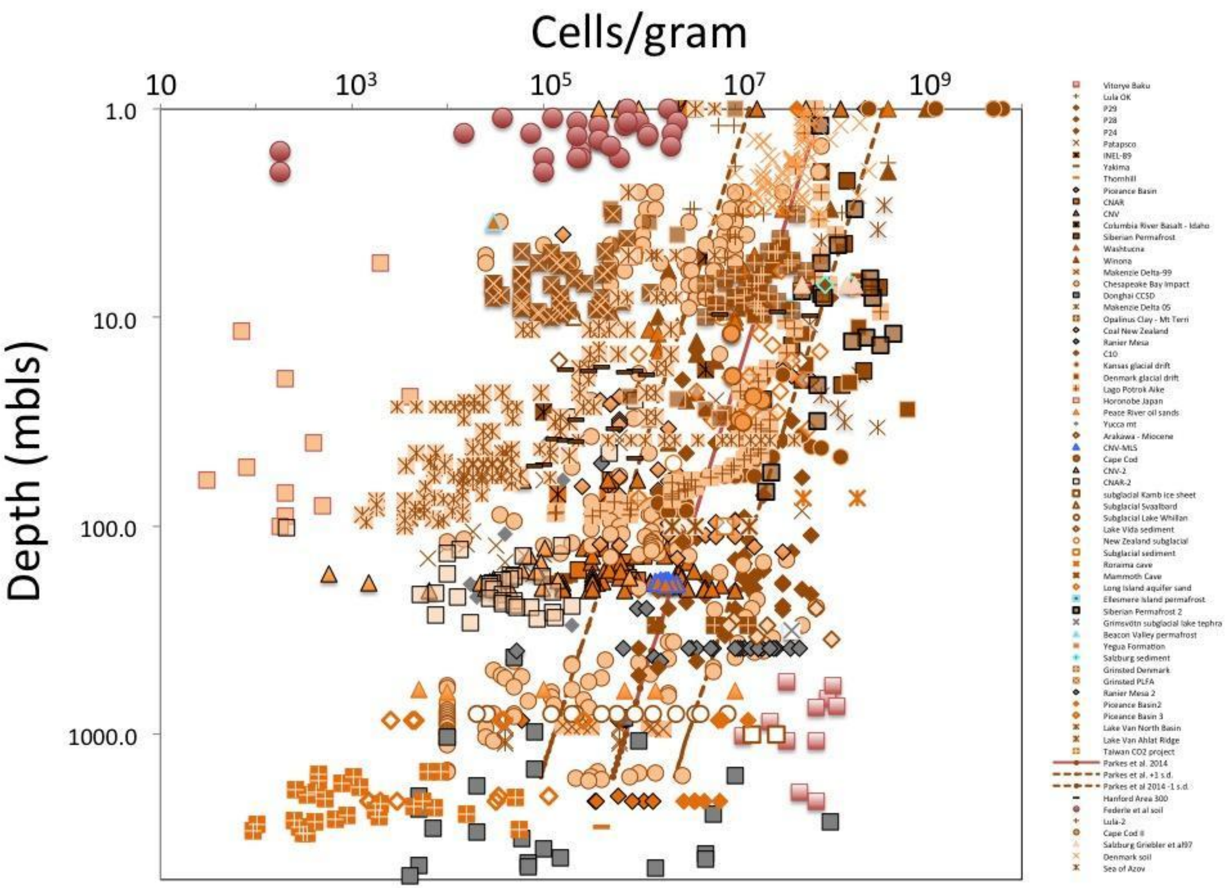
Biomass concentration varies from <10 cells/cm^3 to >10^9 cells/cm^3.

- Deep subsurface biomass abundance is similar for sedimentary, igneous and metamorphic rocks and usually does not correlate with organic carbon content of rock (with exception of seafloor sediments).

- High cell concentrations and microbial activity occur at redox interfaces where nutrient fluxes (both diffusive and advective, energy and essential trace elements) are greatest.

for more information see telecon #2 its reading list on website

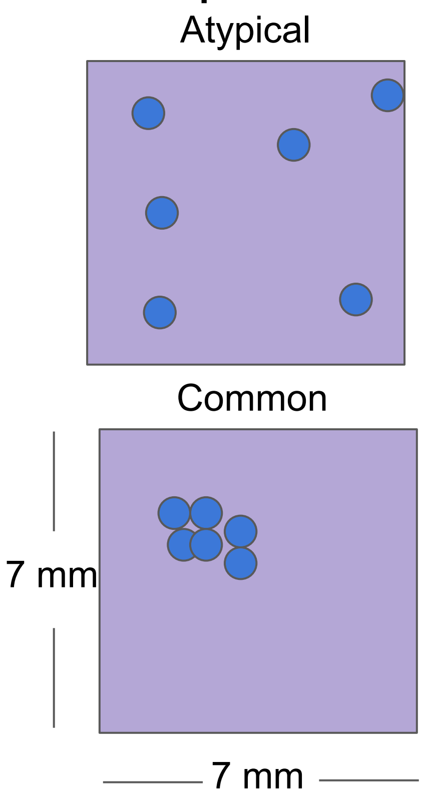
What do we know about terrestrial rock-hosted life?



Brown = sedimentary rocks;
Gray = igneous and metamorphic rocks

compiled from the literature by TC Onstott (see webinar #2)

Schematic Spatial Distribution



Key point **1 SHERLOC detection requires 10 cells in a pixel; equivalent over volume of observation is 10^3 cells/gm**

Exploration Strategy for Rock-Hosted Life

Seek – redox interfaces at a range of spatial scales because redox disequilibria drives metabolism

- ➢ This could start at the orbital scale by identifying lithological boundaries and continue to the rover scale and down even to the PIXL/SHERLOC scale (e.g. sulfate deposits adjacent to serpentinite) or small scale diffusive redox gradients (no fluid flow, just diffusive exchange, alteration haloes).

Seek - lithologic interfaces that indicate high permeability zones for focused fluid flow

- ➢ Fault zones, dykes swarms, fracture networks, connected vesicles.

Most subsurface cell concentrations, if like Earth and clustered, would be detectable (detection in 50-µm SHERLOC pixel requires 10 cells; over volume of observation is 10^3 cells/gm)

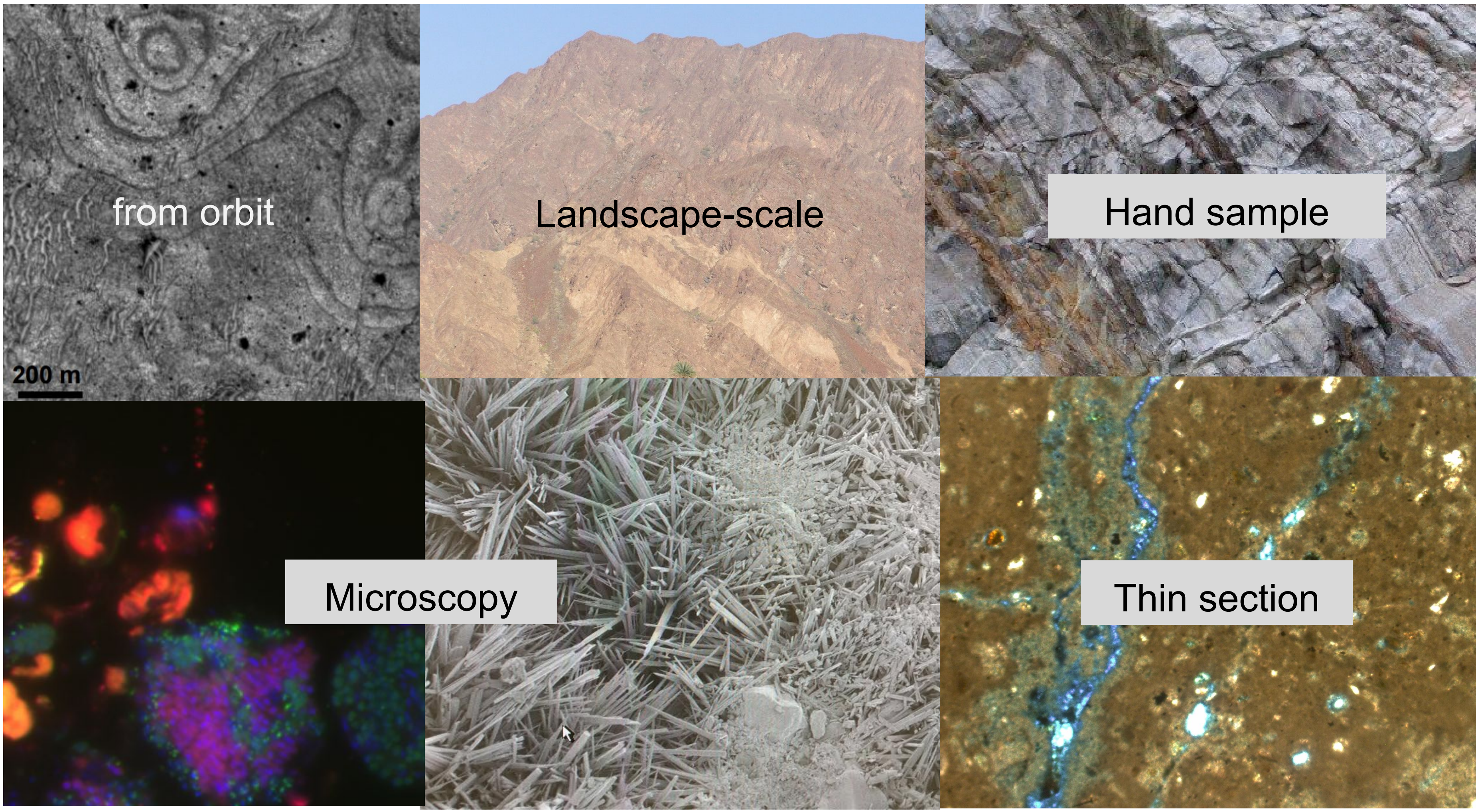
Products of life are more volumetrically significant than life itself (detectable by PIXL and SHERLOC**)**

- ➢ Sulfide, carbonate, oxides and other mineral by products
- ➢ Gas trapped in fluid inclusions
- ➢ Organics

Model scales spatially from landscape-scale, to hand-scale, to microscopic

Scaling the Exploration Strategy

Seeking boundaries and interfaces at all spatial scales



Examples of Biosignatures and the Exploration Strategy from Terrestrial Data

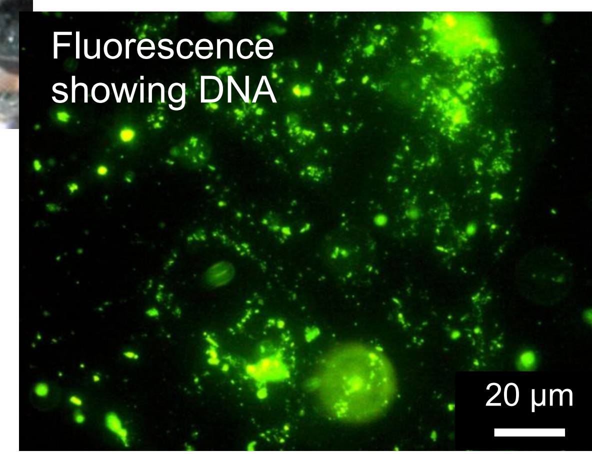
(See the posted Mars 3rd Workshop presentation and Telecons #2 and #3 for more examples)

How biosignatures are preserved for rock-hosted life: Example, Clay/Fe-ox. Mineralization

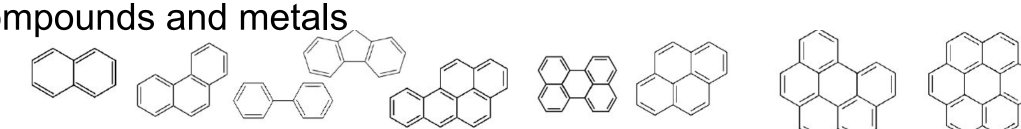
Trias et al, Nat Com under rev.; Moore, Ménez, Gérard, in prep.

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

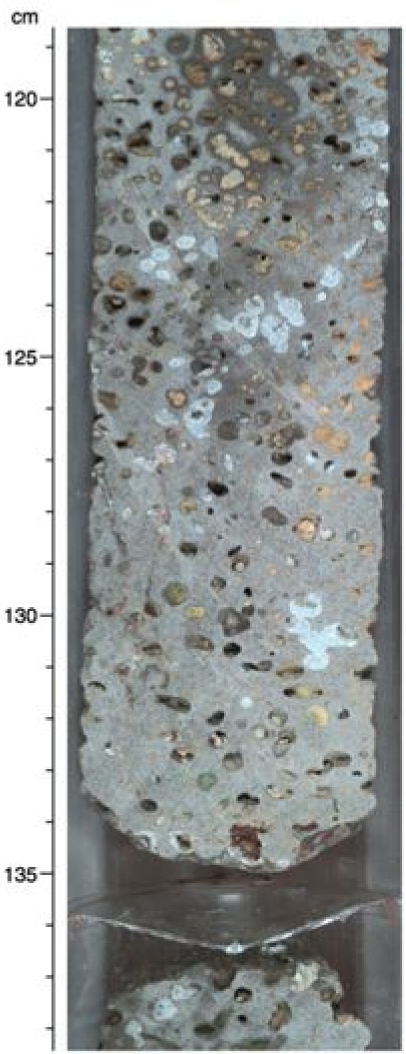
Here, microbial activity facilitates the creation of permeability by dissolution of primary materials (contrast with the “self-sealing” idea of mineralization in hydrothermal systems)

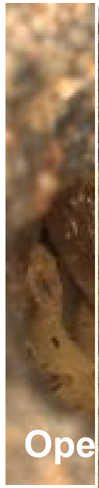


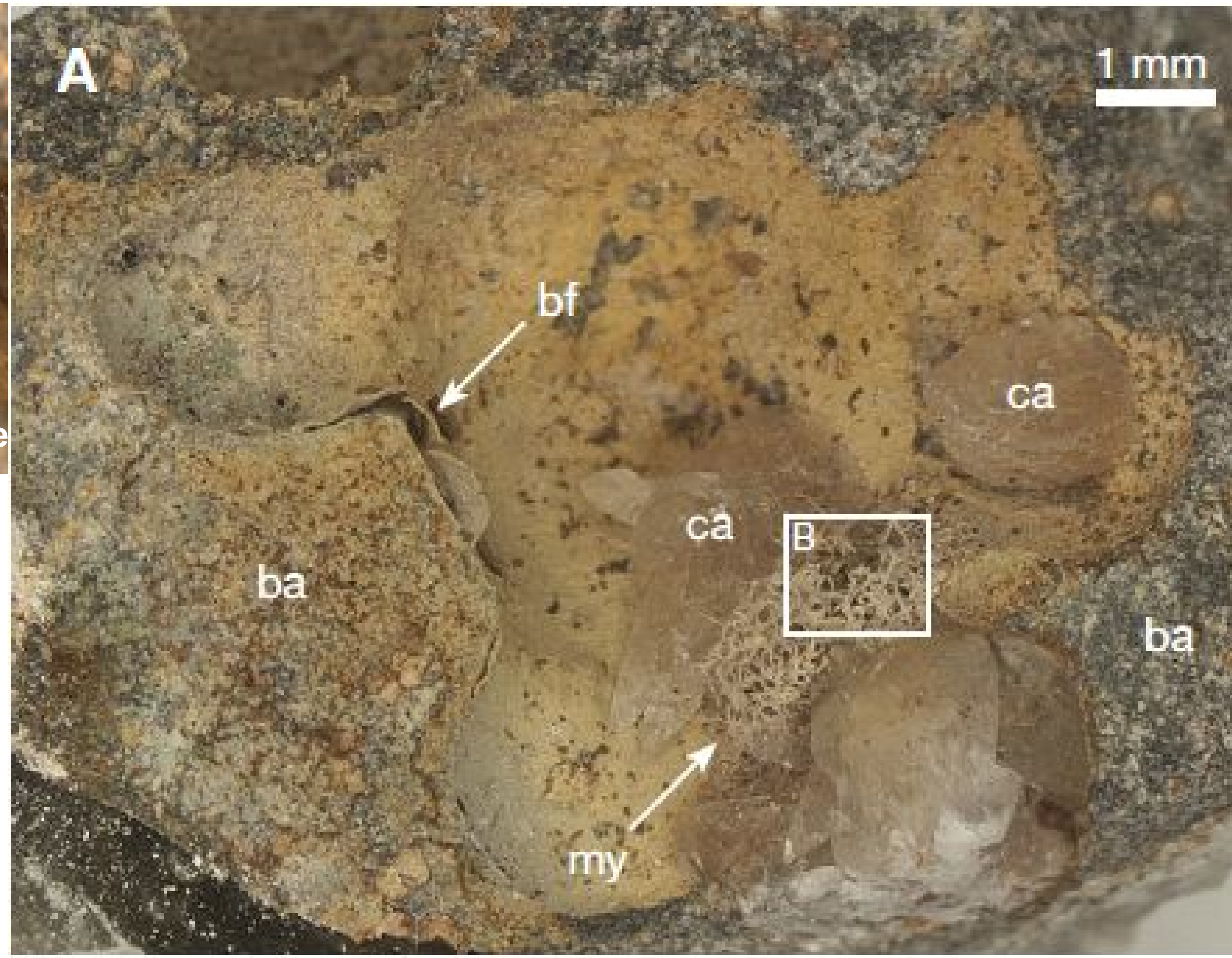
Feed-zones (made of fracture and rubbles) provided flow pathway for CO_2 charged ground waters
Dissolving the rock and feeding microbes (including iron-oxidizers) with aromatic compounds and metals



Preserved Biosignatures of Rock-Hosted Life: Example, <u>Ancient</u> Colonized Basalt

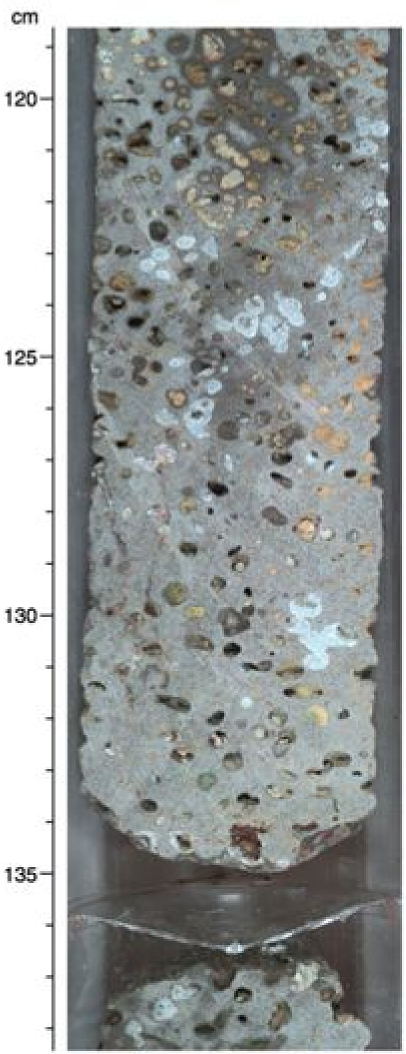


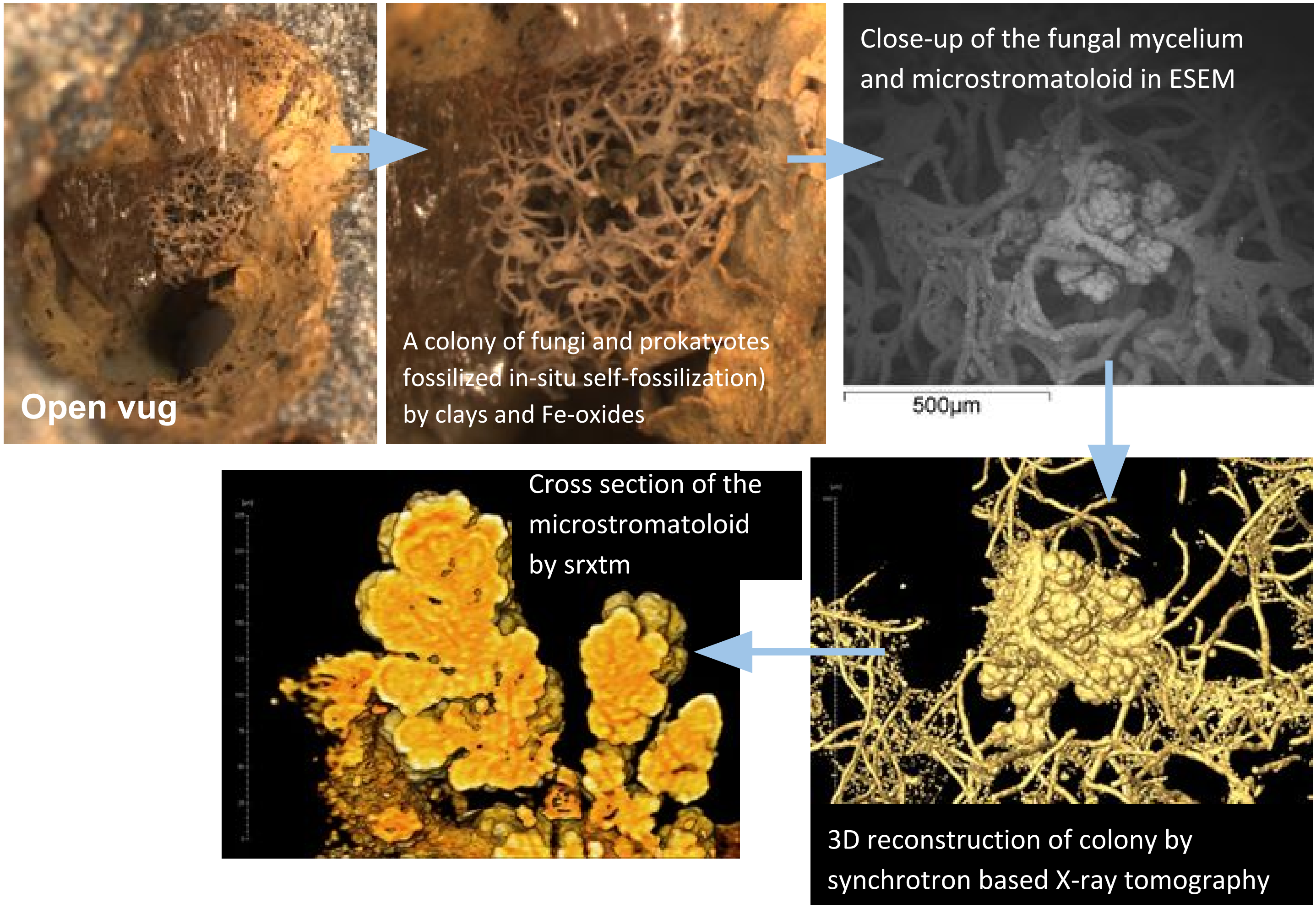




<u>Fossilized</u> prokaryotes and heterotrophic fungal colonies in basaltic subsurface basalt (8-43 Myr old) *Bengtson et al., Geobiology, 2014; Ivarsson et al., PLoS One, 2015*

Preserved Biosignatures of Rock-Hosted Life: Example, Ancient Colonized Basalt

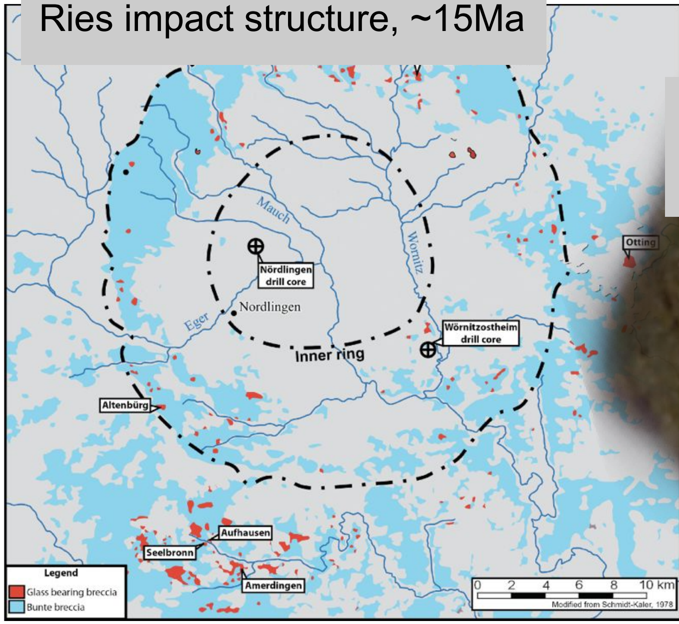




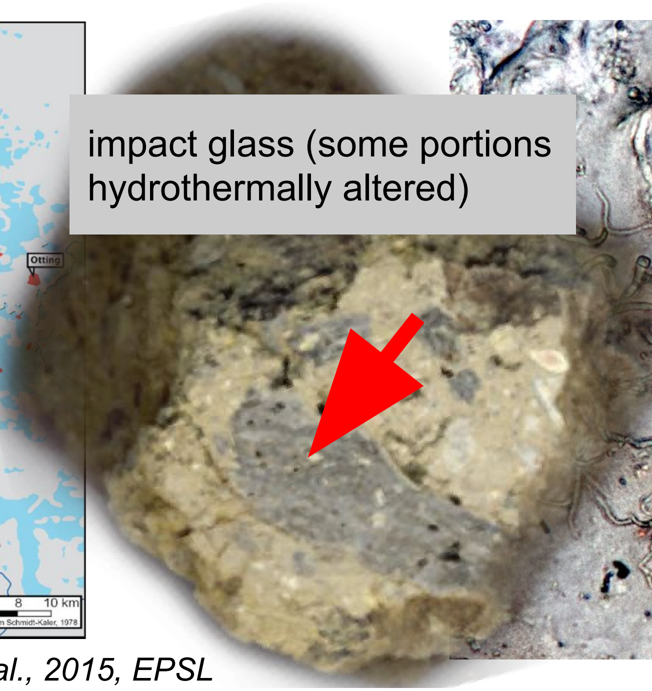
Fossilized prokaryotes and heterotrophic fungal colonies in basaltic subsurface basalt (8-43 Myr old) *Bengtson et al., Geobiology, 2014; Ivarsson et al., PLoS One, 2015*

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

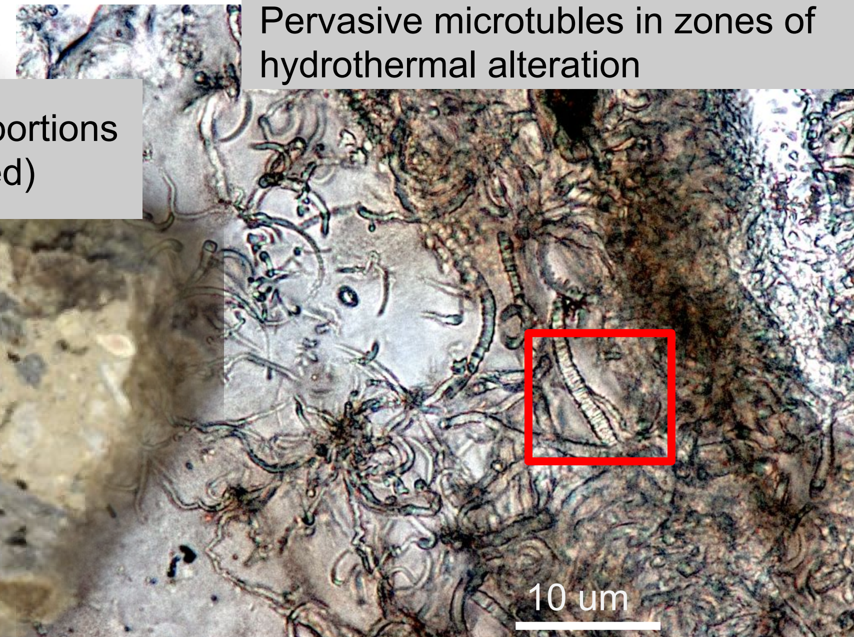
Ries impact structure, ~15Ma



impact glass (some portions hydrothermally altered)

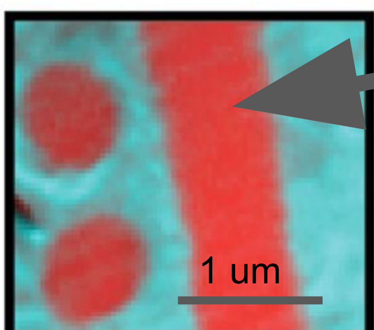


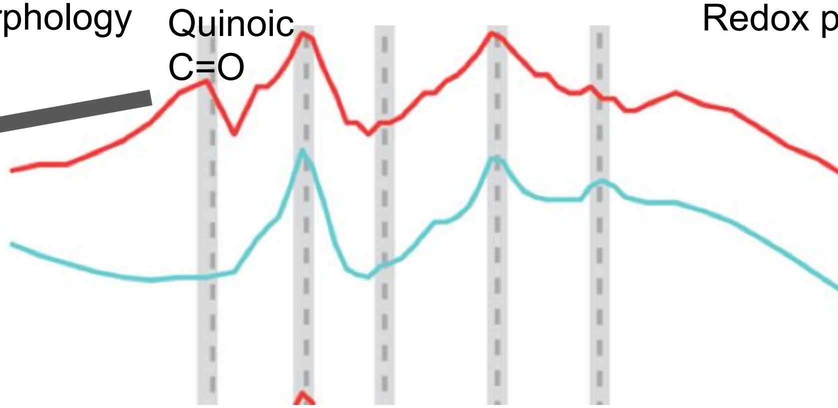
Pervasive microtubules in zones of hydrothermal alteration



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

Organics co-located with morphology

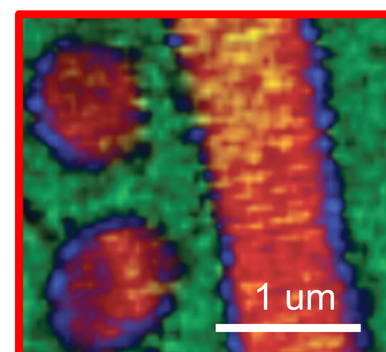




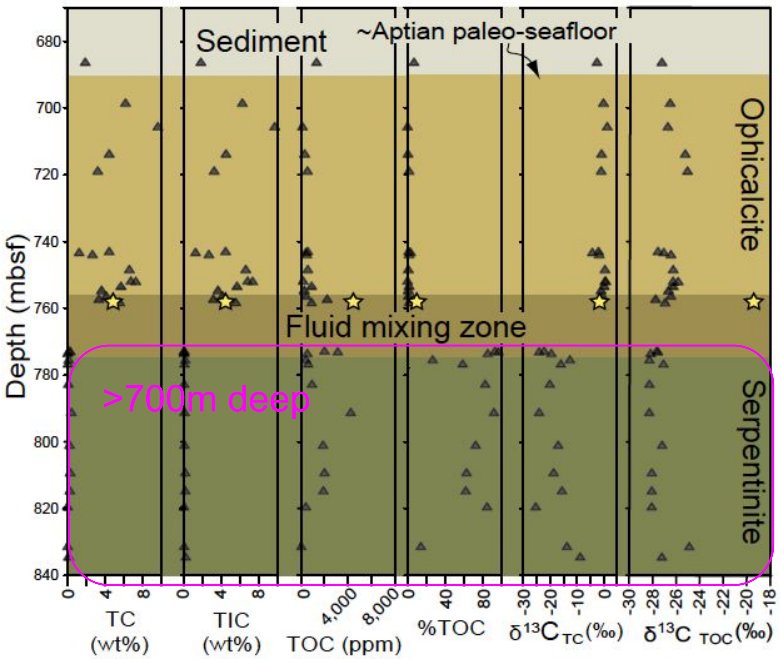
C K-edge NEXAFS

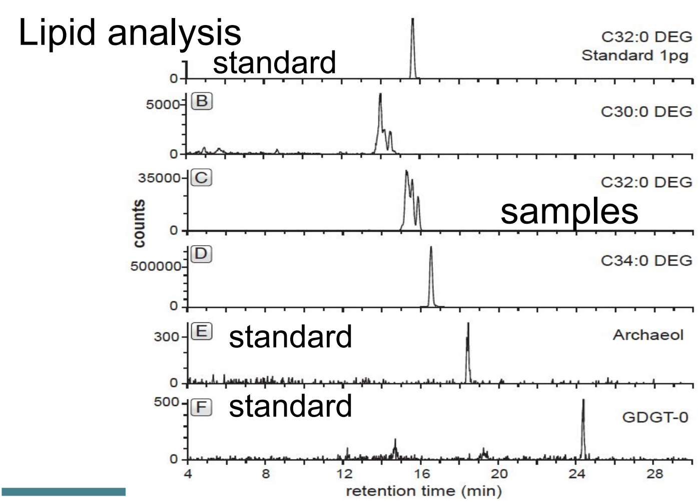
~Energy (eV) *283.5 285 286.5 288.5 290.3*

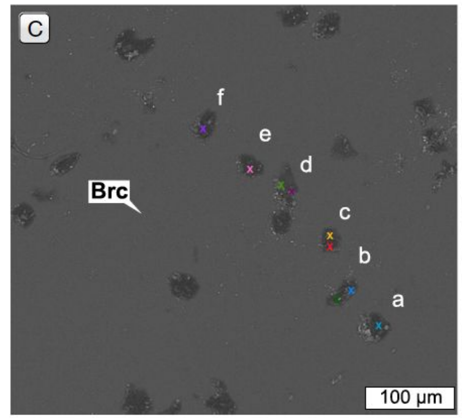
Redox patterns consistent with metabolism

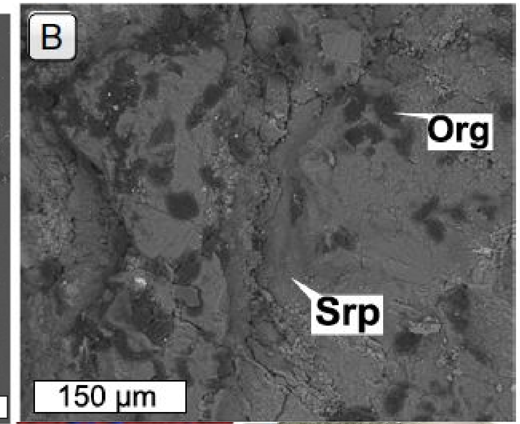


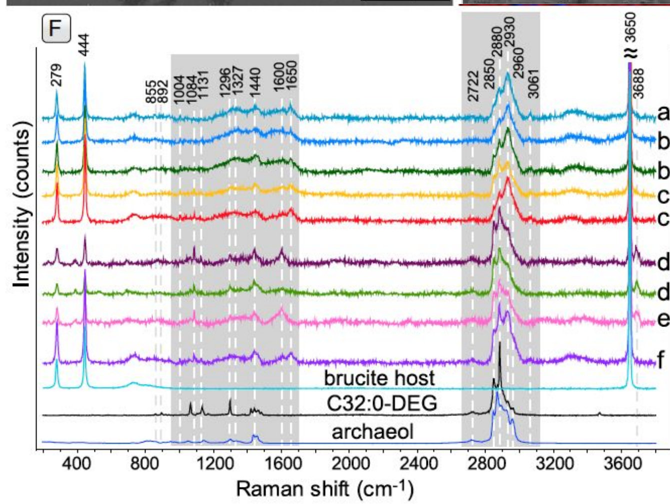
Preserved Biosignatures of Rock-Hosted Life: Example from Deep Carbonate-Serpentine Interface

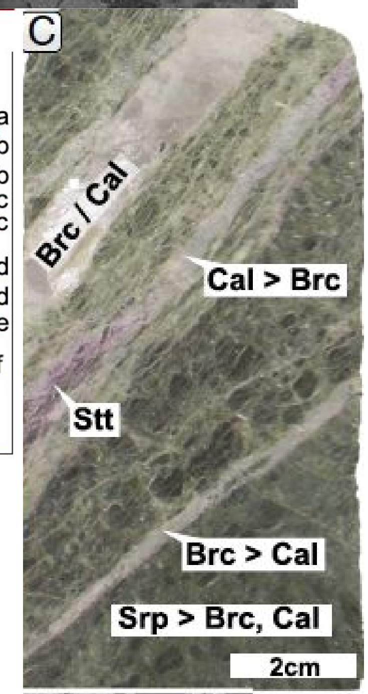












<u>Fossil</u> Lost City Hydrothermal System, deep rocks (125 - 113 Ma)

Klein et al. 2015, PNAS

Summary: How the Exploration Strategy Leads to Biosignatures in the Examples

Blue=this presentation
For others see 3rd workshop

Initial Observables	Biosignatures
Redox interface, local concentration of trace metals	*$\delta^{34}S$ evidence in framboids (potential)*
Fracture Interface, Clay/Fe oxides, Abiotic Organics	DNA discovery
Mineralized vesicles, Complex spongiform textures Fe/Mn oxides, microstromatolite	cell-like morphologies, organic matter
Interface between altered and unaltered amorphous material	microtubules w/ biogenic characteristics, redox gradients/organics co-located w/ tubules, spectral signatures of redox-active cofactors (quinones)
Redox interface with carbonate mineralization at methane seep, pyrite, organics	aromatic and aliphatic amino acids, DNA
Mineral interface of serpentine and carbonate, organics	lipids, $\delta^{13}C$ evidence

Characteristics to Look for From Orbit and Rover

Mineral assemblages that indicate habitable waters. Present at all sites

Where to look for the surface expression of the subsurface?
Answer: Ample at some of the landing sites due to faulting and erosion into deep rock units
  e.g., Olivine-carbonate/serpentine contacts and zones of discharging waters
  e.g., Fe/Mg clays in mineralized fractures within basalts indicating the roots of springs
  e.g., Fe redox reaction zones | e.g., Fe sulfide aqueous precipitates

Given heterogeneity (and sometimes low abundance), how are you sure you've sampled the right places?
Answer: **Seek the interfaces**. Seek specific chemolithologic signatures; they are larger than the biomass itself. Sample prospective areas and also employ payload for organics.

How do you know the millions-of-years-old, already discovered rock-hosted life biosignatures are preserved over billions of years?
Answer: A geologically less active (no high T metamorphism) and less inhabited planet (no/few modern microbes eating of paleo rock-hosted life) makes rock-hosted life preservation easier on Mars than on Earth. **The race is currently on on Earth to find the oldest rock-hosted life. The oldest rock-hosted life biosignature is 125 Ma [Klein et al. 2015]; oldest potential (debated) biosignature 3.5 Ga [Staudigal et al., 2008].** The preservation mechanism is mineral entombment/formation (e.g., in silica, carbonate, or clay). Organics can be preserved, minerals, e.g. sulfide, record a biogenic metabolism. ***Same principles as surface life preservation.***

Findings & Recommendations

- **Ancient Mars aqueous environments included stable, spatially widespread, long lived habitats** within rocks. Mars surface was more harsh than time-equivalent ancient environments on Earth (no magnetic field, atmosphere was thin, obliquity cycled, arid, sometimes freezing)
  - **Aquifers in crystalline rock, aquifers in sedimentary rock warrant significant attention in exploration for Martian biosignatures**

- **The Exploration Strategy for Rock-Hosted Life is well-understood: "Seek the Interfaces" (redox and paleo-permeability),** has been demonstrated on Earth, and should be conducted at scales ranging from orbit to microscopic. Also,
  - The metabolic waste products (minerals) of rock-hosted life are more numerous that the life itself and are most likely to be identified by the rover
  - The spatial clustering of organisms means they are detectable at ~10^3 cells/gram
  - Mars-2020 type instrument measurements can yield potential biosignatures and are a guidepost for sampling for sophisticated, e.g., lipid and isotopic biosignatures work on Earth that would confirm life

- Future investigations of terrestrial analogs – concerted effort ongoing (NAI, NSF, Agouron)
  - Further needed exploration will **continue to step backward in time to equivalent Archaean habitats both to look for rock-hosted life biosignatures and to understand the factors that overprint them on Earth**, leading to determination of the sweet spot of preservation.

Extras

Specific Objectives and Methods

Our objectives are to develop an end-to-end (living organism to biosignature) understanding of potential traces of past rock hosted life and then

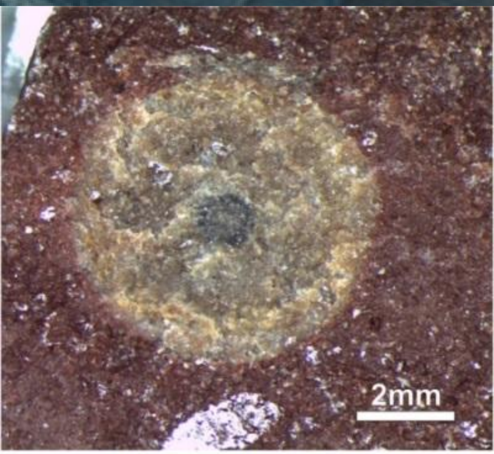
1. articulate the suite of biosignatures produced by paleo rock-hosted life
2. establish which facies types may preserve them
3. describe measurements can Mars-2020 can make *in situ* to identify potential biosignatures and collect samples with a high probability for hosting biosignatures, identifiable in terrestrial laboratories
4. disseminate findings via presentation at the 3rd Mars Landing Site workshop, a peer-reviewed publication

Key Challenges for Earth Rock-Hosted Life Analogs

- ➢ High temperature alteration of the older rocks by metamorphism
- ➢ Modern rock-hosted life is common and modern terrestrial organisms eat their older ancestors in the rock for key nutrients. Consequently, most research so far has focus on the relatively near-term past

- ➢ Mars may be better for preservation of ancient rock-hosted life!

Zones to target for Potential Biosignatures: Example, sedimentary aquifer Fe-redox interfaces

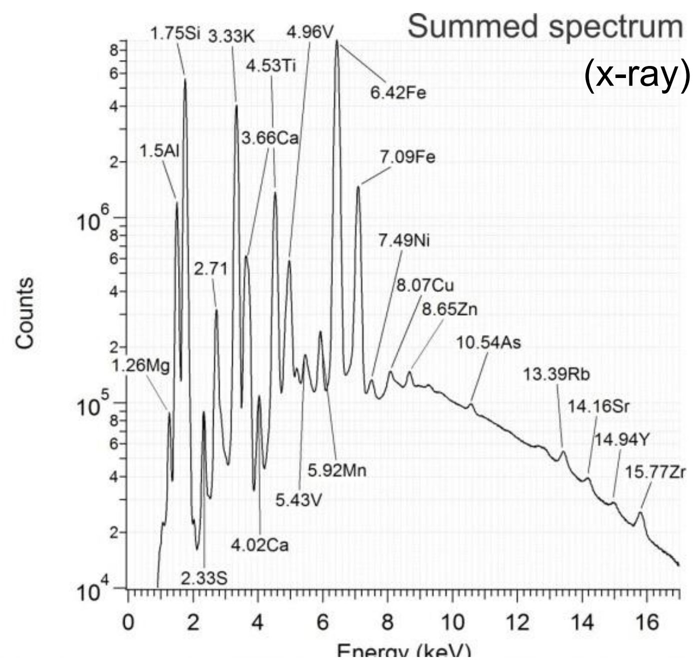


Sample courtesy *Spinks et al. 2010, J. Astrobio.*

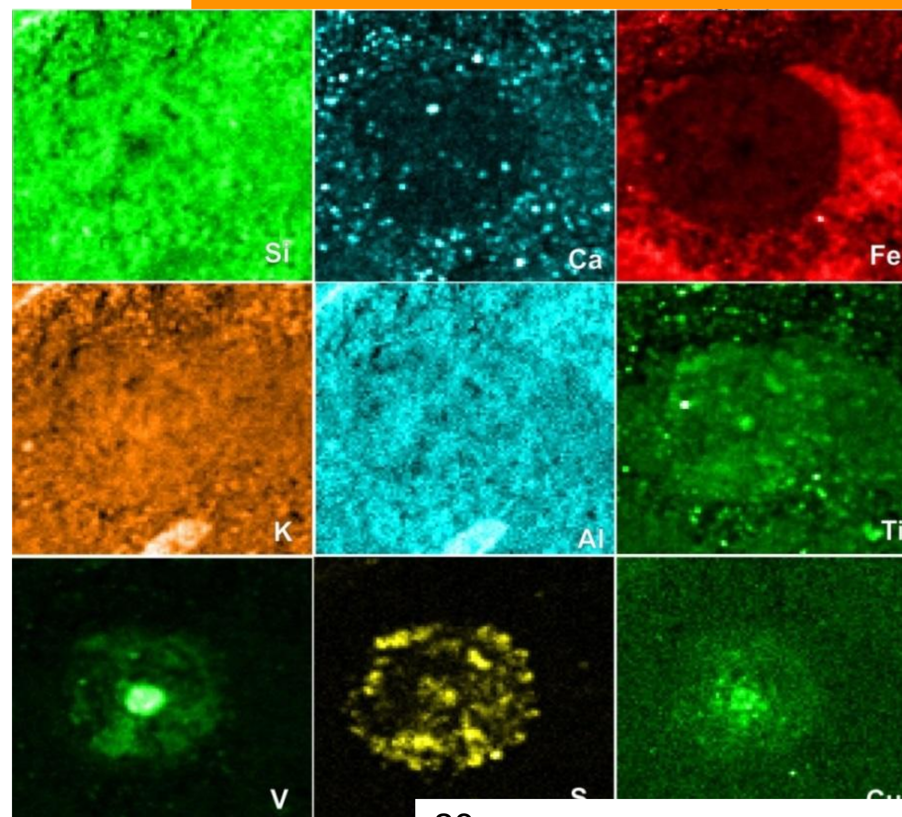
Proterozoic vanadium-enriched reduction spot from sandstone aquifer

PIXL map of 12x12mm area shows concentration of biologically significant elements

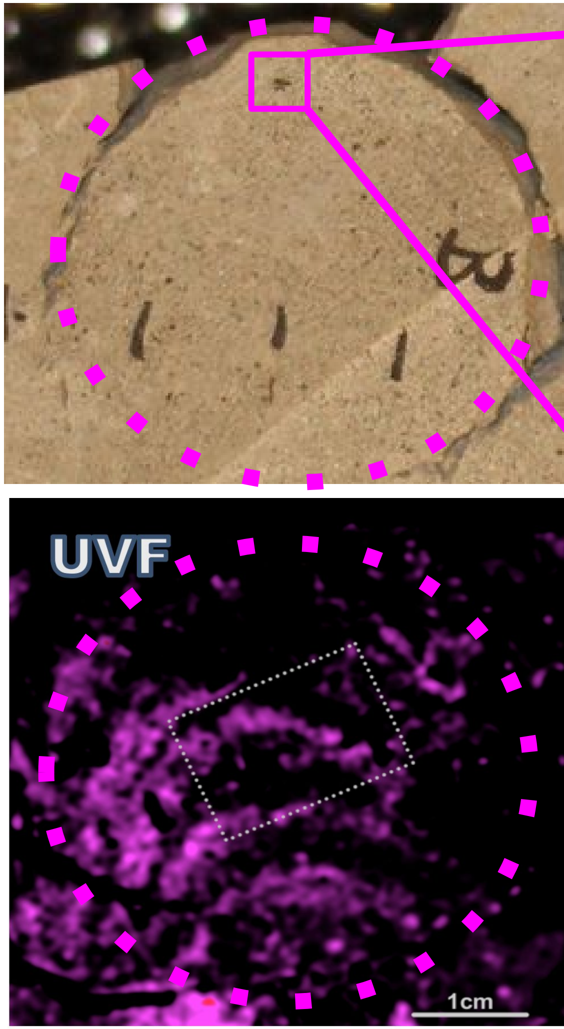
Data courtesy of the PIXL team

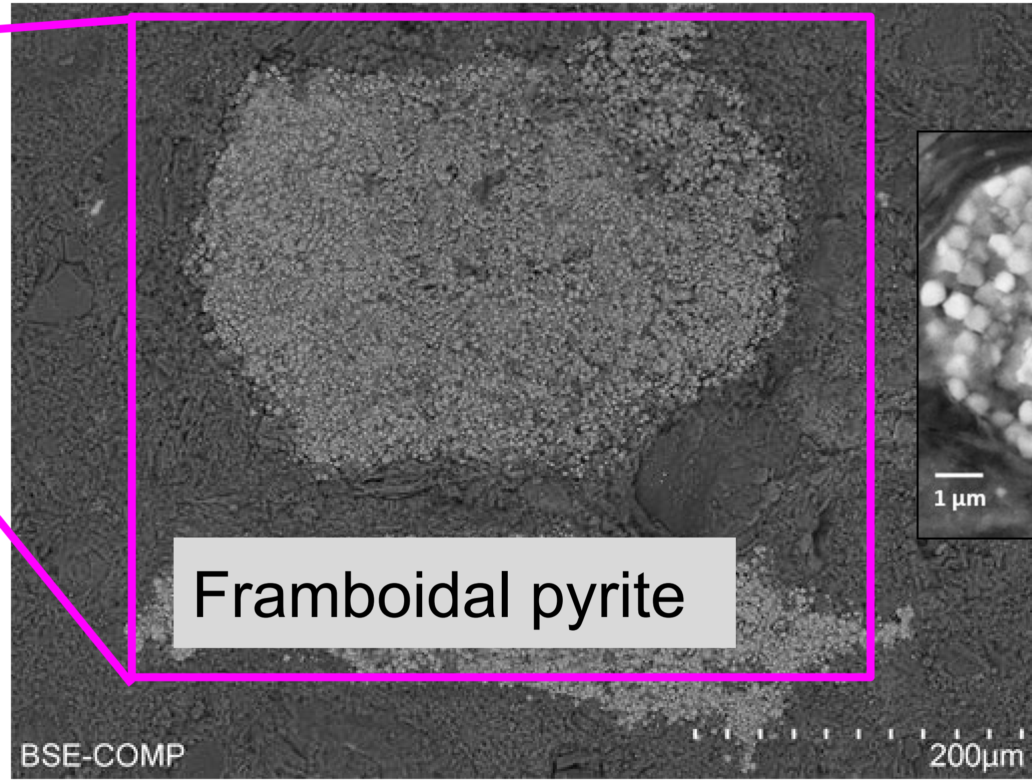


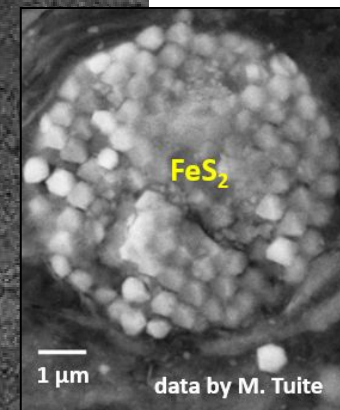
PIXL breadboard science results



Preserved Biosignatures of Rock-Hosted Life: Example, Fe-sulfide mineralization







ex., pyrite framboid

Pyrites (incl. framboidal) are a possible indicator of an 'active' sulfur cycle in the presence of organics (as indicated by DUV fluorescence). Sulfides indicate need for further examination for organics and collection

data courtesy of G. Wanger/SHERLOC team

Abundant, active endolithic communities in these rocks. *Marlow et al., Nature Comm., 2014*

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Redox interface with carbonate mineralization at methane seep, pyrite, organics	aromatic and aliphatic amino acids, DNA
Mineral interface of serpentine and carbonate, organics	lipids, d13C evidence