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


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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

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 must be adapted for Mars
Where do we look for rock-hosted life?

<table>
<thead>
<tr>
<th>Icy Worlds</th>
<th>Earth</th>
<th>Mars</th>
</tr>
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<tbody>
<tr>
<td>basaltic crust</td>
<td>marine sediments</td>
<td>shallow subsurface</td>
</tr>
<tr>
<td>not at current finalist landing sites</td>
<td></td>
<td>recorded in the rocks of Midway and NE Syrtis</td>
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Onstott et al., in review, Astrobio

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.

- Follow the interfaces
  - Redox
  - Permeability

Increasing porosity/permeability
Increasing redox energy flux
Increasing biomass

$10^7$ cells/cm²
$10^3$ - $10^5$ cells/gram

H₂, CH₄-rich fluid filled fault/fissure
redox transition zone

Fe³⁺, SO₄²⁻, NO₃⁻ bearing oxidized matrix rock

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.

Modern seafloor seds.

Buried seafloor seds. (products of photosynthate consumed)

No cell counts in granite block

Impact-fractured rock
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 CH₄ production, and unique isotope signals from methanogens using H₂ & 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 prep).

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
Isotopic and organic biosignatures (lipids) preserved in carbonates

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

- Squalene $\delta^{13}$C ~ 14‰
- PMI $\delta^{13}$C ~ 10‰

Extracted hydrocarbons

Methanogen lipid-derived hydrocarbons

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

Biomarker: Bacterial (sulfate-reducer?) core lipids

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

Terrestrial carbonated serpentinites, Chimaera seeps, Turkey

SE serpentine
V carbonate vein

Zwicker et al. (2018)

Rempfert et al. (in prep)

Hydroxyarchaeol with PE headgroup

Archaeal intact lipids

Klein et al. (2015)

Slide provided by A. Templeton, K. Rempfert

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.

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

Fluorescence showing DNA
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
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
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

<table>
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<tr>
<th>Step</th>
<th>Spatial Scale</th>
<th>Key Measurement Requirements</th>
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<tbody>
<tr>
<td>1. Identify rocks with ancient subsurface habitats</td>
<td>&lt;100 m sampling</td>
<td>Ability to identify water-related mineral deposits from orbit, determine stratigraphic context</td>
</tr>
<tr>
<td>2. Locate interfaces that represent favorable locations for rock life</td>
<td>Meter- to cm-scale</td>
<td>Ability to identify redox and permeability interfaces by identification of distinct lithologic units</td>
</tr>
<tr>
<td>3. Search for mineralization from fluid flow at interfaces</td>
<td>Centimeter- and millimeter-scale</td>
<td>Ability to identify silica, carbonate, sulfate, phyllosilicate, and oxides that may mineralize microbial life</td>
</tr>
<tr>
<td>4. Search for organics, mineralization, and isotopic anomalies at the interface</td>
<td>&lt;100 µm sampling</td>
<td>Ability to detect organics, chemical, mineralogic, and/or isotopic differences between interface rocks and surrounding rocks indicative of biosignatures</td>
</tr>
<tr>
<td>5. Map putative biosignatures in 3-dimensions, tracking chemical and organic variations with texture</td>
<td>&lt;1 µm sampling in 3-D</td>
<td>Ability to identify microbial textures and distinguish biotic and abiotic processes to definitively confirm fossil rock-hosted life</td>
</tr>
</tbody>
</table>

Done! NE Syrtis, Midway (thanks orbiters! + more to come with CaSSIS)

Mastcam-Z, Supercam (+ RIMFAX)

Mastcam-Z, Supercam, PIXL, SHERLOC

PIXL, SHERLOC

Sample Return

The National Academies Has Also Recommended the Search for Subsurface Life

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.
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 $>10^6 \text{ cells/cm}^3$ (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. $\geq 3$ opportunities in 3 different rock units from three different time periods
Fossil record of subsurface life


Figure by R. L. Harris, Z. Garvin, and D. Nisson
Pathways Utilized by Subsurface Chemotrophs Evolved Long Before Those Used By Phototrophs

Cyanobacteria

Stem => Crown
(PSII)

LUCA
Acetyl-CoA Pathway

GNS

1.2 Ga Akinete Calibration

1.6 Ga Akinete Calibration
Preserved Biosignatures of Rock-Hosted Life: 100Ma Carbonate/Serpentine-Hosted Example from Deep Carbonate-Serpentine Interface

Klein et al. 2015, PNAS Fossil Lost City Hydrothermal System, deep rocks. 125 - 113Ma)

Lipid analysis samples standard

standard standard
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 microtubules in zones of hydrothermal alteration

Organics co-located with morphology

Redox patterns consistent with metabolism

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

Sapers et al., 2015, Geology; Sapers et al., 2015, EPSL
Scaling the Exploration Strategy

Seeking boundaries and interfaces at all spatial scales

from orbit

Landscape-scale

Hand sample

Microscopy

Thin section
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

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

Figure by H. Sapers

Onstott et al., in review, Astrobio
Microenvironment Feedback

Methylation
As, Se, Te, Sn, Pb, Hg

Fixation, volatilization
organic C → CO₂

Chemolithotrophic leaching
H⁺, pH changes, Fe(III), SO₄²⁻

Redox (im)mobilization
(Fe(III) - Fe(II)
Mn(IV) - Mn(II))

Chemo-organotrophic leaching
H⁺, siderophores, organic acids, metabolites

Biocorrosion

Mineral bioweathering biominalization

Biosorption

Metals

Chemistry determines colonization
Colonization affects chemistry

to create biosignatures