Sample Requirements and Considerations for Future Chronologic Investigations in Earth-based Laboratories of Samples Cached During the Mars 2020 Mission

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Image Credit: Ehlmann et al., 2016
<table>
<thead>
<tr>
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<th>Objectives Proposed by International MSR Objectives and Samples Team (iMOST)</th>
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<tbody>
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<td>1</td>
<td>Interpret the primary geologic processes and history that formed the martian geologic record, with an emphasis on the role of water.</td>
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<td>2</td>
<td>Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.</td>
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<td>3</td>
<td>Quantitatively determine the evolutionary timeline of Mars.</td>
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<td>4</td>
<td>Constrain the inventory of martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.</td>
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<td>5</td>
<td>Reconstruct the processes that have affected the origin and modification of the interior, including the crust, mantle, core and the evolution of the martian dynamo.</td>
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<td>6</td>
<td>Understand and quantify the potential martian environmental hazards to future human exploration and the terrestrial biosphere.</td>
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<td>7</td>
<td>Evaluate the type and distribution of <em>in situ</em> resources to support potential future Mars exploration.</td>
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Objectives Proposed by International MSR Objectives and Samples Team (iMOST)

Chronological investigations are at the core of most scientific objectives for MSR: How, why & when?

1. History (through time) of geologic processes
2. History (through time) of biologic activity (if any)
3. Evolutionary timeline of Mars
4. Volatile inventory as a function of time
5. Evolution (through time) of the martian dynamo
Objective 3: Quantitatively Determine the Evolutionary Timeline of Mars

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<th>KEY OPEN QUESTIONS: OBJECTIVE 3</th>
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<td>How does the impact flux on Mars compare to that on the Moon, and was there a period of late heavy bombardment on Mars?</td>
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<td>When did Mars’ early dynamo shut down?</td>
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<td>What were the accretionary building blocks of Mars, and how long did the processes of crust formation and metal-silicate segregation (core formation) take?</td>
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<td>What was the duration of igneous activity on the surface of Mars?</td>
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<td>What are the timescales of aqueous, hydrothermal and sedimentary processes (including rates of burial, uplift and erosion of surfaces) on Mars?</td>
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Common Radiometric Dating Systems

- $^{40}\text{Ar}/^{39}\text{Ar}$ ($t_{1/2}$ $\sim$ 1.25 Ga)
- $^{87}\text{Rb}-^{87}\text{Sr}$ ($t_{1/2}$ $\sim$ 49 Ma)
- $^{147}\text{Sm}-^{143}\text{Nd}$ ($t_{1/2}$ $\sim$ 105 Ga)
- $^{176}\text{Lu}-^{176}\text{Hf}$ ($t_{1/2}$ $\sim$ 37 Ga)
- $^{238}\text{U}-^{206}\text{Pb}$ ($t_{1/2}$ $\sim$ 4.5 Ga)
- $^{235}\text{U}-^{207}\text{Pb}$ ($t_{1/2}$ $\sim$ 704 Ma)
Common Radiometric Dating Systems: Minimum Requirements

Even with the best analytical capabilities in Earth-based laboratories, a meaningful age may be obtained if, and only if, there was:

• **Complete equilibration** of the isotopes of the daughter element prior to the parent/daughter fractionation event (i.e., event that is being dated); condition is typically met by igneous rocks.

• **No disturbance** of the parent-daughter isotope system after it achieved closure subsequent to the parent/daughter fractionation event.
  - Closure temperatures are different for different chronometers and different phases; the same rock may yield different ages for different chronometers depending on its thermal history.
  - Secondary processes like *weathering* and *metamorphism* can seriously disturb the parent-daughter isotope system – no age information may be possible.
Example of $^{40}\text{Ar}/^{39}\text{Ar}$ Dating: Nakhlite clinopyroxenites

- Sample mass requirement: Typically ~10-100 mg sample with a K-bearing phase (e.g., feldspar); separated single grain analysis is feasible
Example of $^{87}\text{Rb}-^{87}\text{Sr}$ & $^{147}\text{Sm}-^{143}\text{Nd}$ Dating: Zagami basaltic shergottite

- Sample mass requirement: Typically ~100s of mg, up to a few grams

Borg et al., 2005
Mineral Separation Protocol for Combined Rb-Sr, Sm-Nd and U-Pb Analyses

Borg et al., 2005
Example of Application of Short-lived Chronometers to Martian Meteorites

$^{146}\text{Sm} \rightarrow ^{142}\text{Nd} \ (t_{1/2} \sim 68 \text{ Ma})$

$^{182}\text{Hf} \rightarrow ^{182}\text{W} \ (t_{1/2} \sim 9 \text{ Ma})$

Kruijer et al., 2017
Application of Short-lived Chronometers

Accretion and Early Differentiation History of Mars from Martian Meteorites

- I-Pu-Xe: $^{129}\text{I} \rightarrow ^{129}\text{Xe}$ ($t_{1/2} \sim 16$ Ma)
- $^{244}\text{Pu} \rightarrow$ Fission Xe ($t_{1/2} \sim 80$ Ma)
- $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$ ($t_{1/2} \sim 68$ Ma)
- $^{182}\text{Hf} \rightarrow ^{182}\text{W}$ ($t_{1/2} \sim 9$ Ma)

- Provide “relative” model ages
- High precision data typically require large (gram-sized) bulk samples

Kruijer et al., 2017
Relative Assessment of Mars 2020 Landing Sites in the Context of Chronological Investigations

• Jezero: Late Noachian/Early Hesperian fluvial/deltaic sediment deposition into a crater lake; a mafic floor unit overlies most of the basin fill.
  • Pro: The mafic floor unit ("volcanic floor") estimated to be ~3.5 Ga and could provide lower bound for volcanic activity in crater
  • Con: The mafic floor unit is of uncertain origin & may not be datable.
Relative Assessment of Mars 2020 Landing Sites in the Context of Chronological Investigations

• NE Syrtis: Exposures span ≥400 Ma (Early/Mid Noachian onwards), include 4 water-related habitable environments and 3 igneous units.
  • Pro: Most ancient section, with three distinct (likely) igneous datable units.
  • Con: 1-2 of the igneous units may be weathered and/or metamorphosed.
Relative Assessment of Mars 2020 Landing Sites in the Context of Chronological Investigations

• Midway: Compromise site between NE Syrtis and Jezero, features NE Syrtis-type terrain & drivable to Jezero.
  • Pro: Ancient (Early Noachian) section, with two distinct (likely) igneous datable units.
  • Con: 1-2 of the igneous units may be weathered and/or metamorphosed.

Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ehlmann & Mustard, 2012)
Relative Assessment of Mars 2020 Landing Sites in the Context of Chronological Investigations

- Columbia Hills: Multiple igneous units (≤~4 Ga) and several types of evidence of aqueous processes (hydrothermal environment; evaporative precipitates?).
  - Pro: Well-characterized site with multiple datable units
  - Con: Small-scale stratigraphy that cannot be correlated in time with other globally significant units
Summary

Sample Requirements

• Relatively fresh (unmetamorphosed, minimally weathered) igneous lithology with more than 2 phases that fractionate parent/daughter elements
  • Multiple chronometers on the same samples are required to determine unambiguous ages
• Currently, 10s of mg up to few grams of sample is required for the highest precision isotope analyses
• Extensive processing in Earth-based laboratories will likely be required to obtain meaningful age constraints
• Coordinated analyses for different investigation types (e.g., petrological, chronological and paleointensity) on the same samples will be required to achieve high priority science objectives

Landing Site Considerations

• Landing site must contain igneous lithologies (preferably ones that may be correlated in time at large areal scales) that are relatively unweathered
  • NE Syrtis and Columbia Hills likely present the best opportunities for collecting datable samples
  • Midway may be a good compromise for sampling the “best” sedimentary and igneous lithologies