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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

Objectives Proposed by International MSR Objectives and Samples Team (iMOST)

1	Interpret the primary geologic processes and history that formed the martian geologic record, with an emphasis on the role of water
2	Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life
3	Quantitatively determine the evolutionary timeline of Mars.
4	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.
5	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.
6	Understand and quantify the potential martian environmental hazards to future human exploration and the terrestrial biosphere.
7	Evaluate the type and distribution of *in situ* resources to support potential future Mars exploration.

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

1. History (through time) of geologic processes
2. History (through time) of biologic activity (if any)
3. <u>Evolutionary timeline of Mars</u>
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

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

Common Radiometric Dating Systems

- $^{40}Ar/^{39}Ar$ ($t_{1/2}$ ~1.25 Ga)
- ^{87}Rb-^{87}Sr ($t_{1/2}$ ~49 Ma)
- ^{147}Sm-^{143}Nd ($t_{1/2}$ ~105 Ga)
- ^{176}Lu-^{176}Hf ($t_{1/2}$ ~37 Ga)
- ^{238}U-^{206}Pb ($t_{1/2}$ ~4.5 Ga)
  ^{235}U-^{207}Pb ($t_{1/2}$ ~704 Ma)

NWA 8159: Augite-rich basaltic shergottite

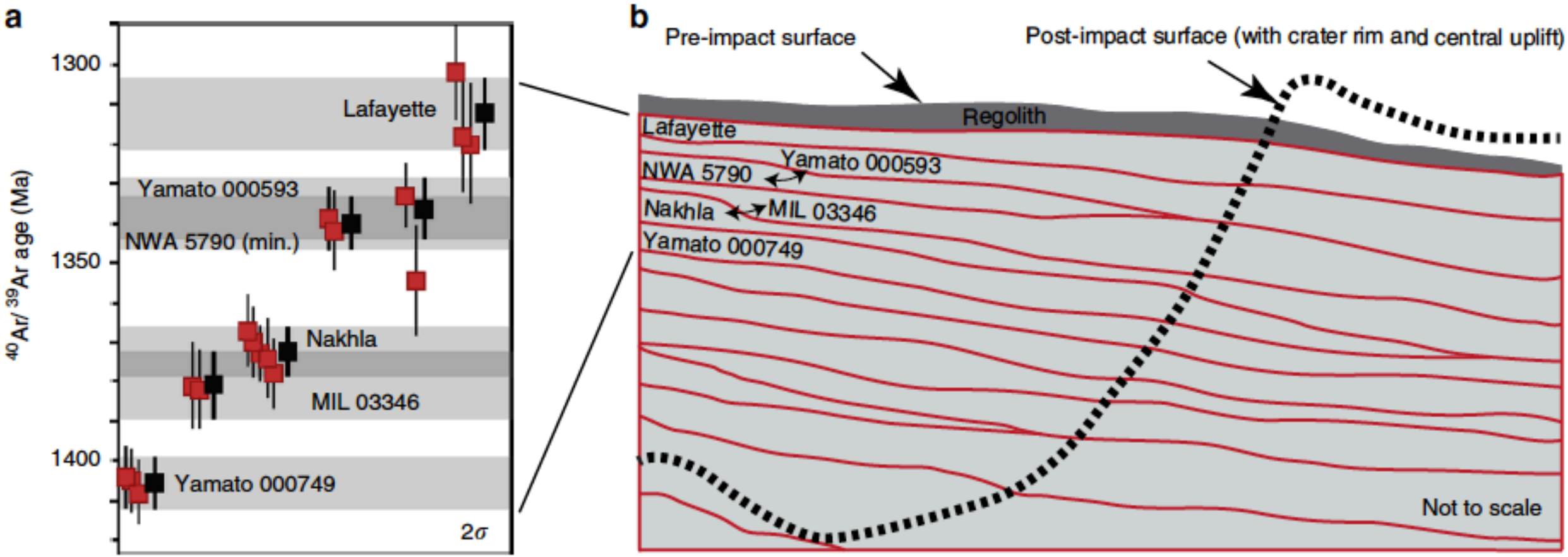
Herd et al., 2017

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.

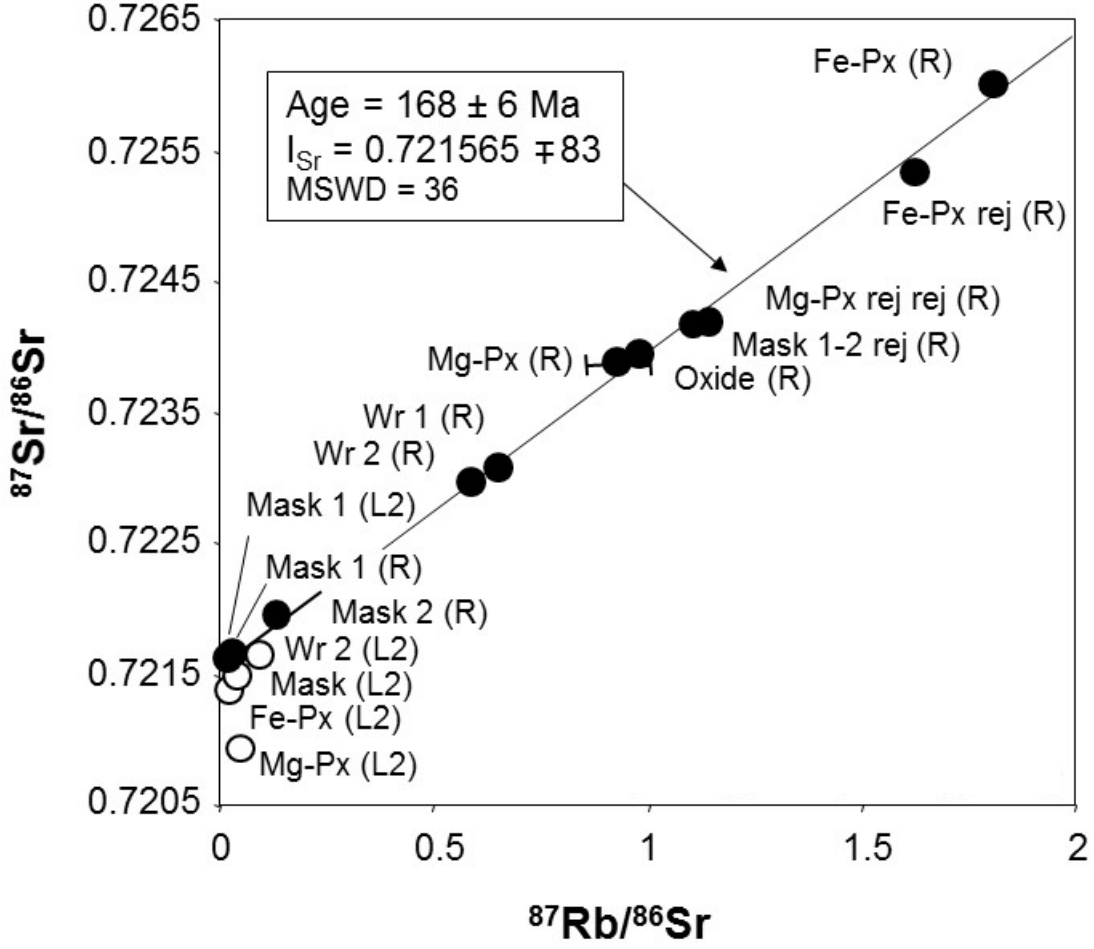
Example of $^{40}Ar/^{39}Ar$ Dating: Nakhlite clinopyrxenites

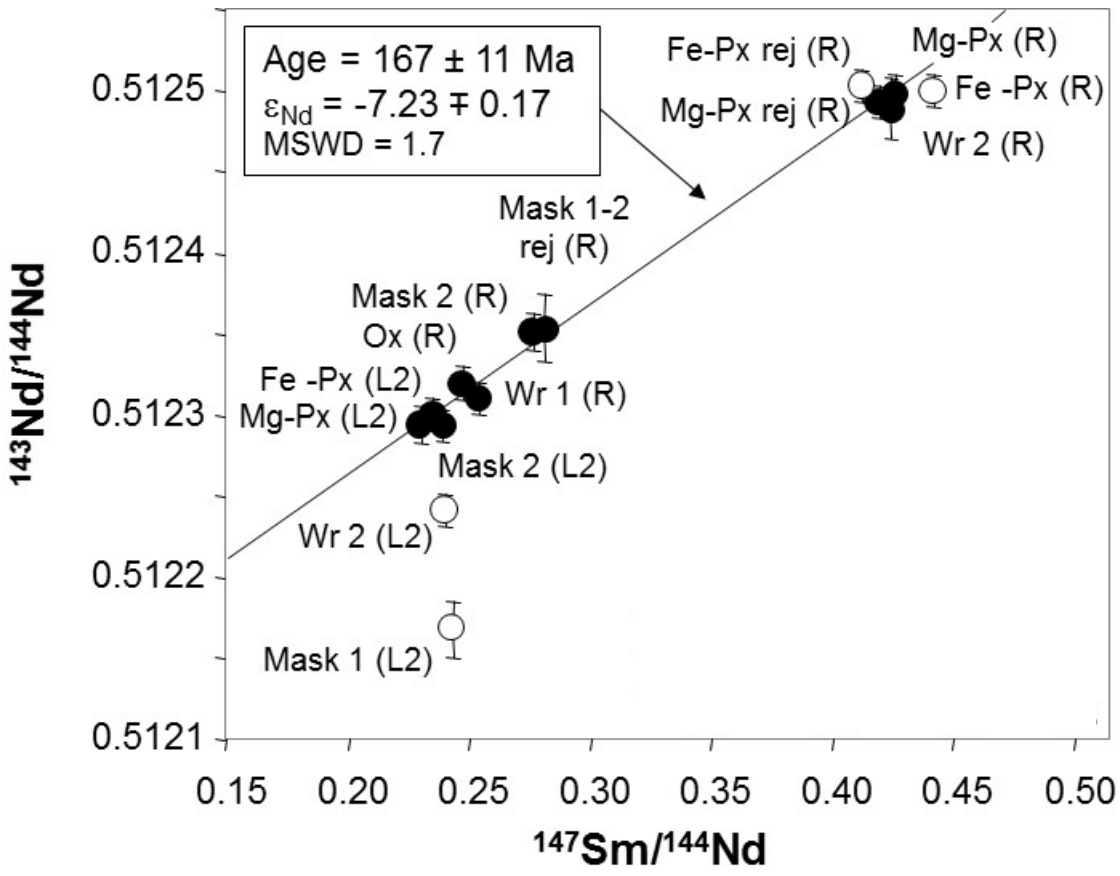


- Sample mass requirement: Typically ~10-100 mg sample with a K-bearing phase (e.g., feldspar); separated single grain analysis is feasible

Cohen et al., 2017

Example of ^{87}Rb-^{87}Sr & ^{147}Sm-^{143}Nd Dating: Zagami basaltic shergottite

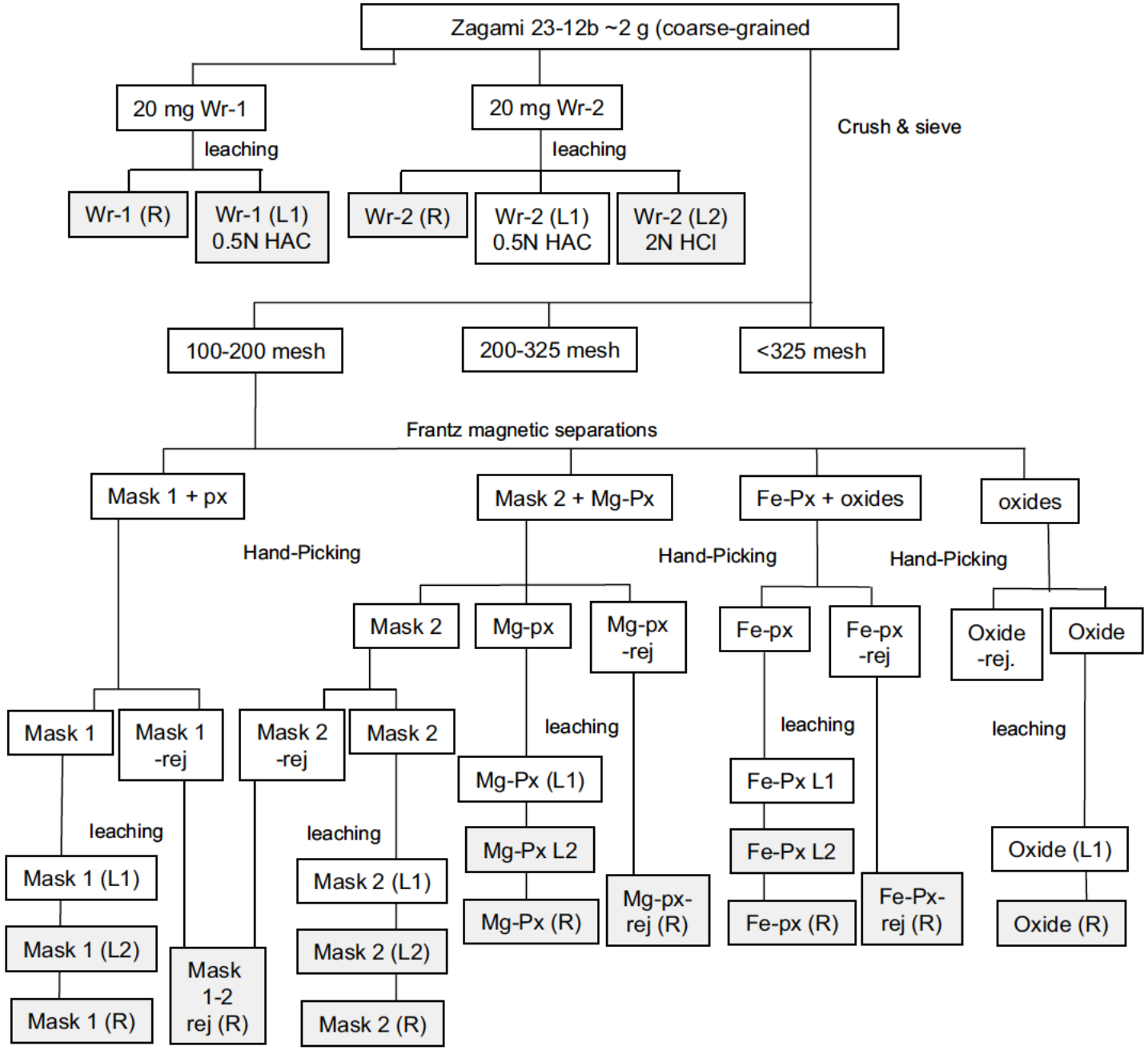




- Sample mass requirement: Typically ~100s of mg, up to a few grams

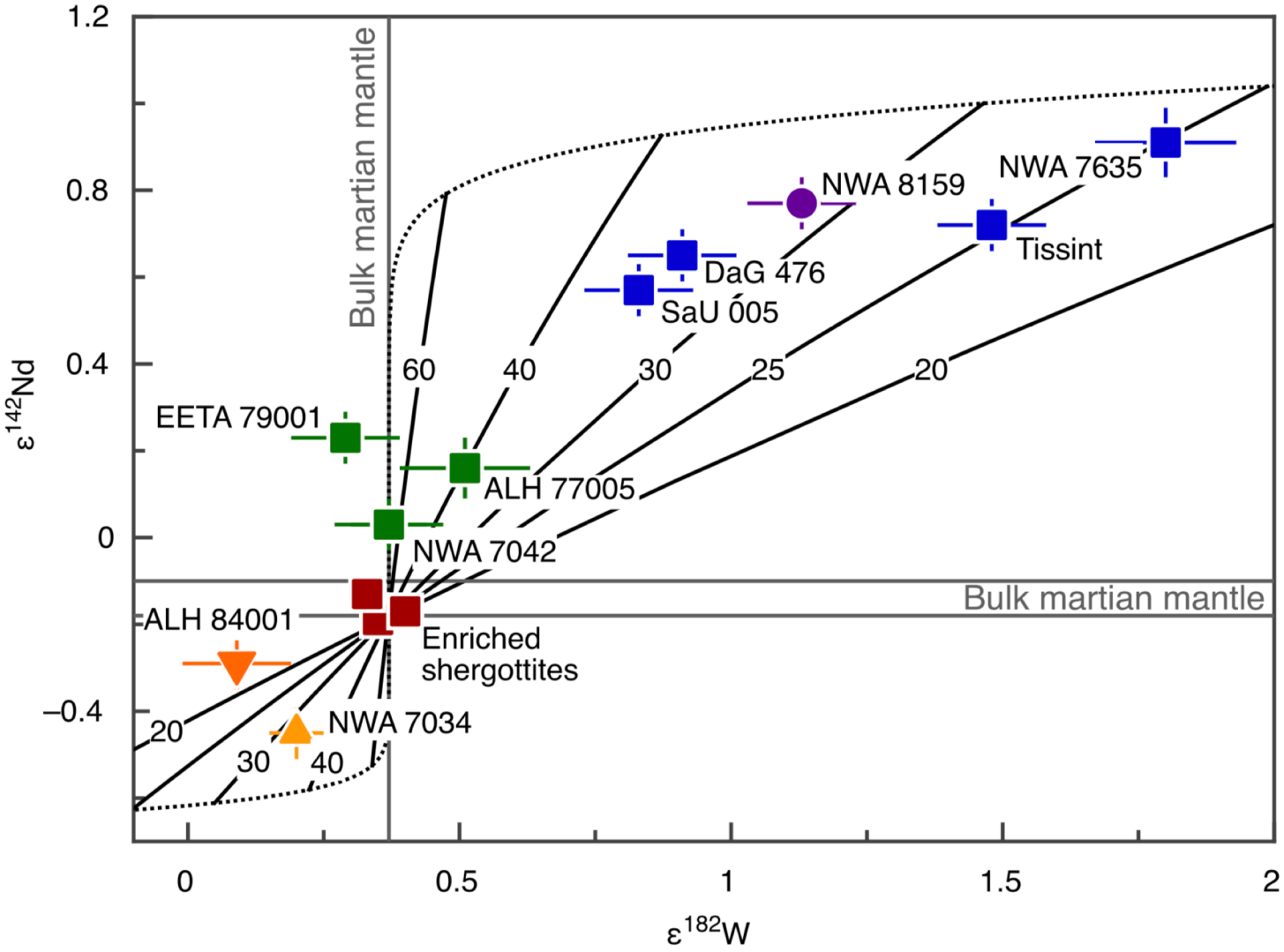
Borg et al., 2005

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



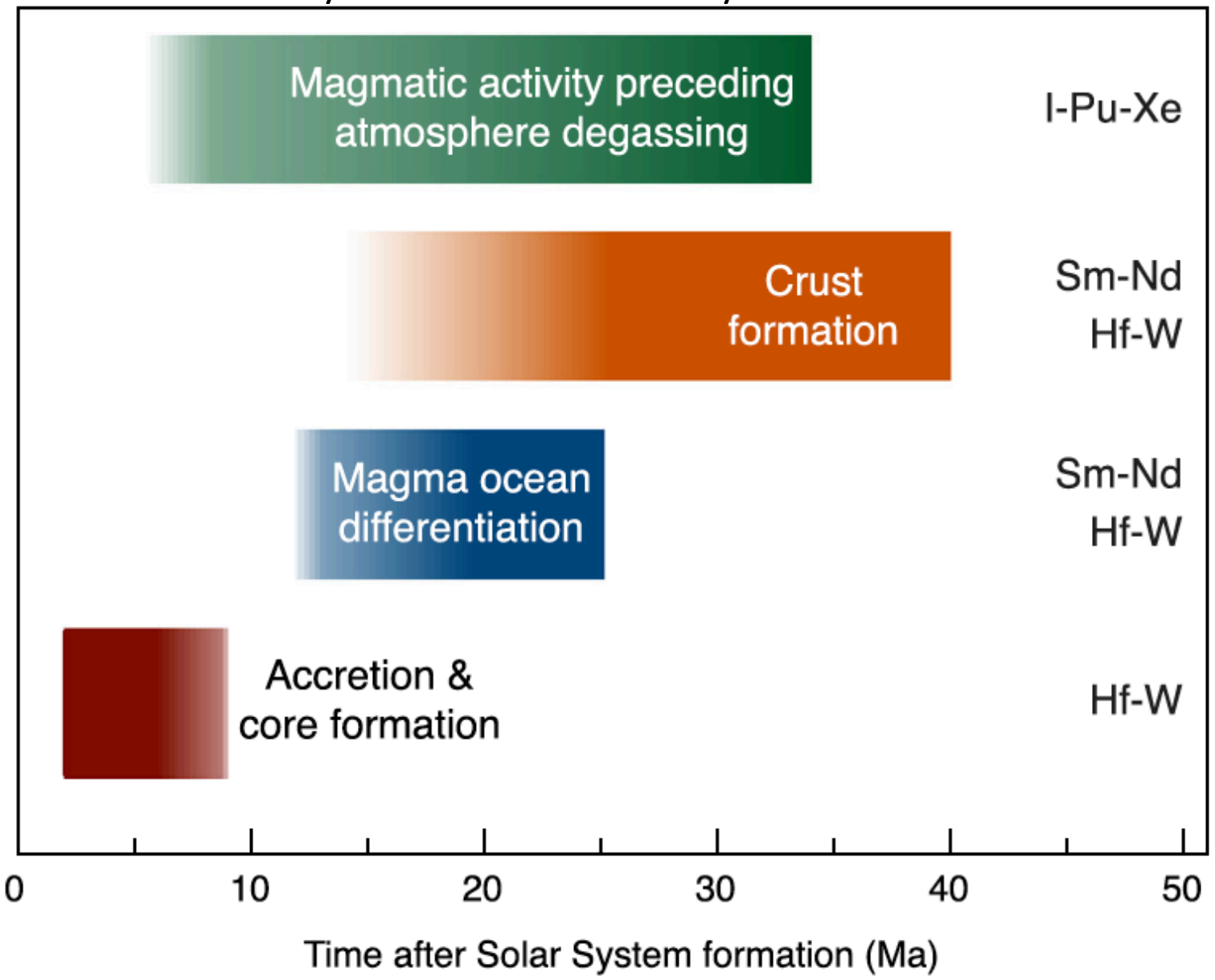
$^{146}Sm \rightarrow {}^{142}Nd$ ($t_{1/2}$ ~68 Ma)

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

Kruijer et al., 2017

Application of Short-lived Chronometers

Accretion and Early Differentiation History of Mars from Martian Meteorites



$^{129}I \rightarrow {}^{129}Xe$ ($t_{1/2}$ ~16 Ma)

$^{244}Pu \rightarrow$ Fission Xe ($t_{1/2}$ ~80 Ma)

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

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

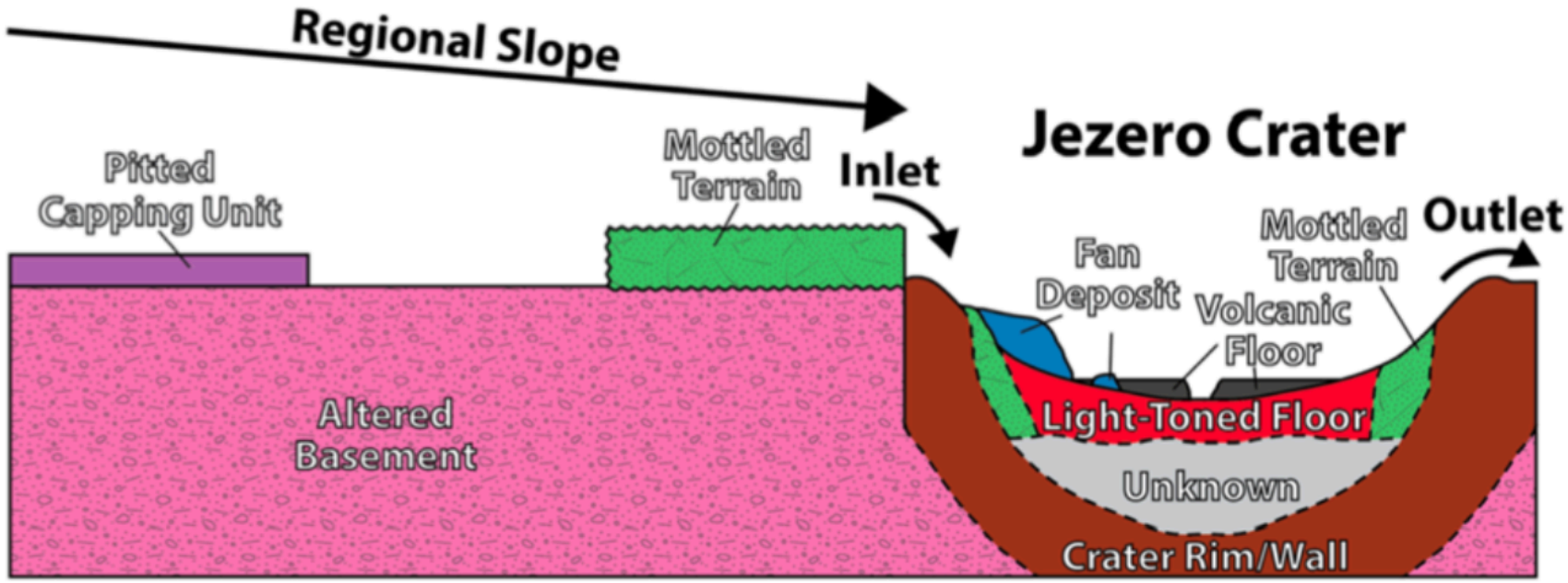
- Provide “relative” model ages
- High precision data typically require large (gram-sized) bulk samples

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.

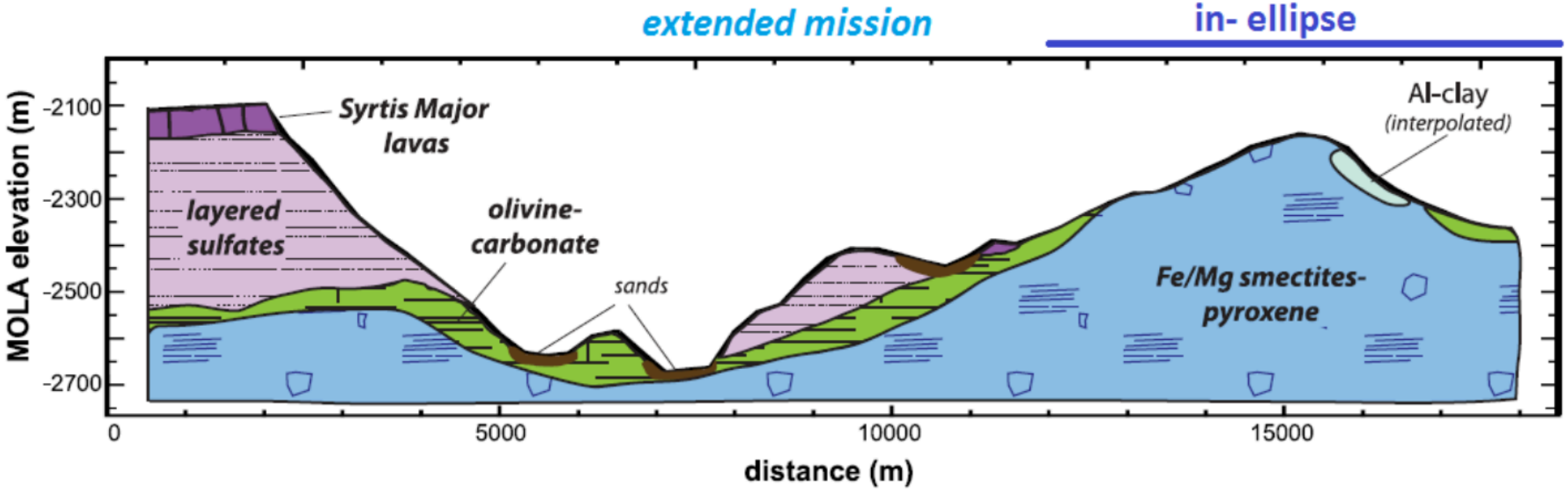
Regional (~3x ellipse) Stratigraphic Column Figure (ref: Goudge et al, 2015)



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.

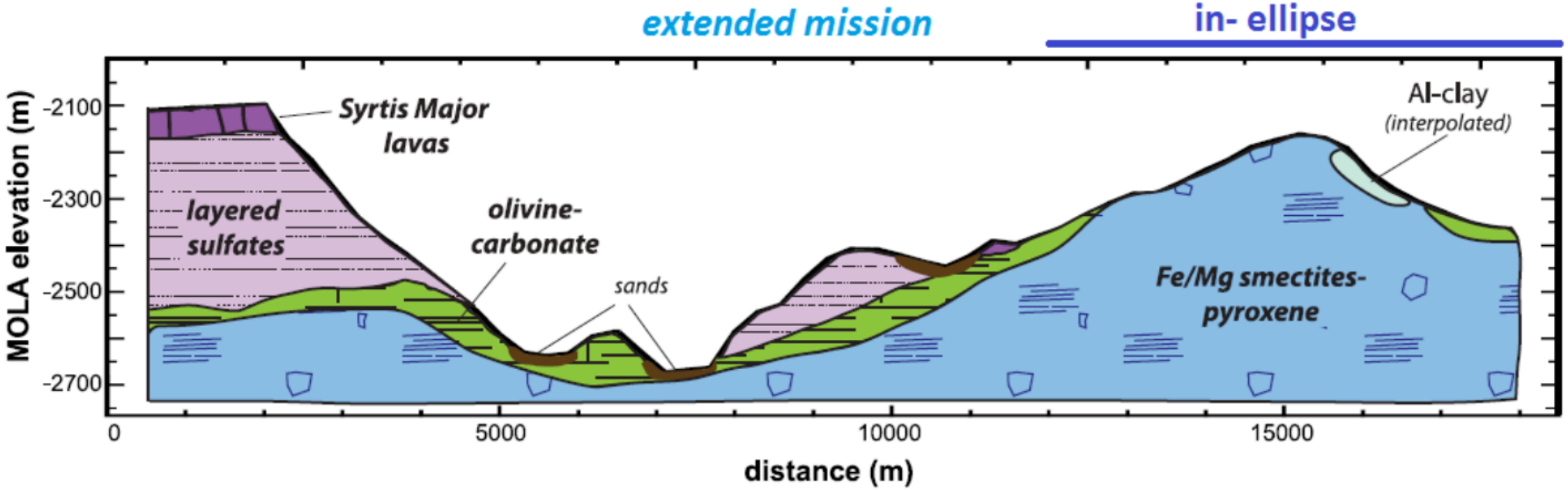
Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ehlmann & Mustard, 2012)



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.

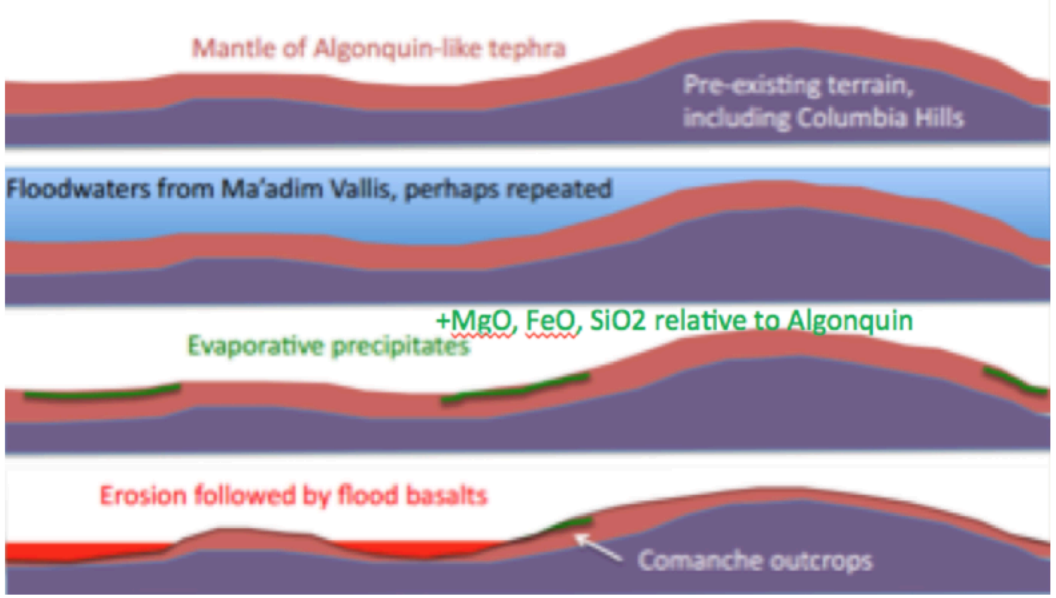
Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ehlmann & Mustard, 2012)



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

Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ruff et al. 2014; Lewis et al. 2008)



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