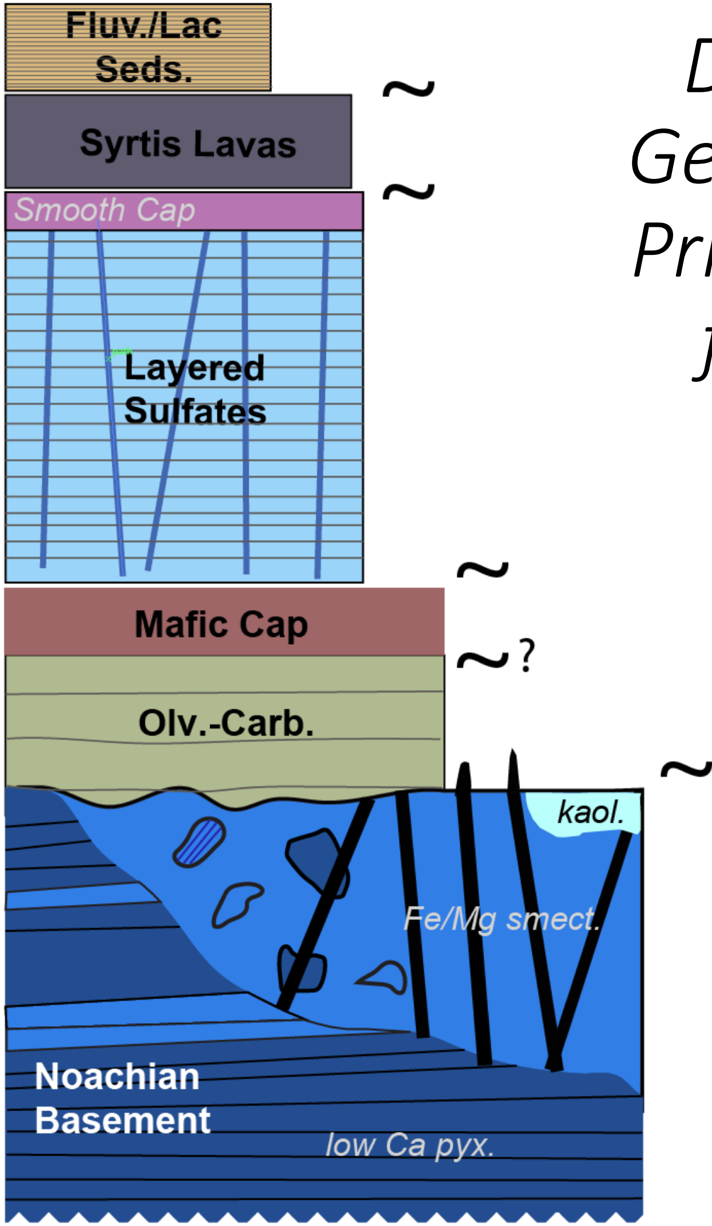
stratigraphy after Mangold et al., 2007; updated by Bramble et al., 2017 and Quinn & Ehlmann, 2018 (graphics by Ehlmann & Kremer)

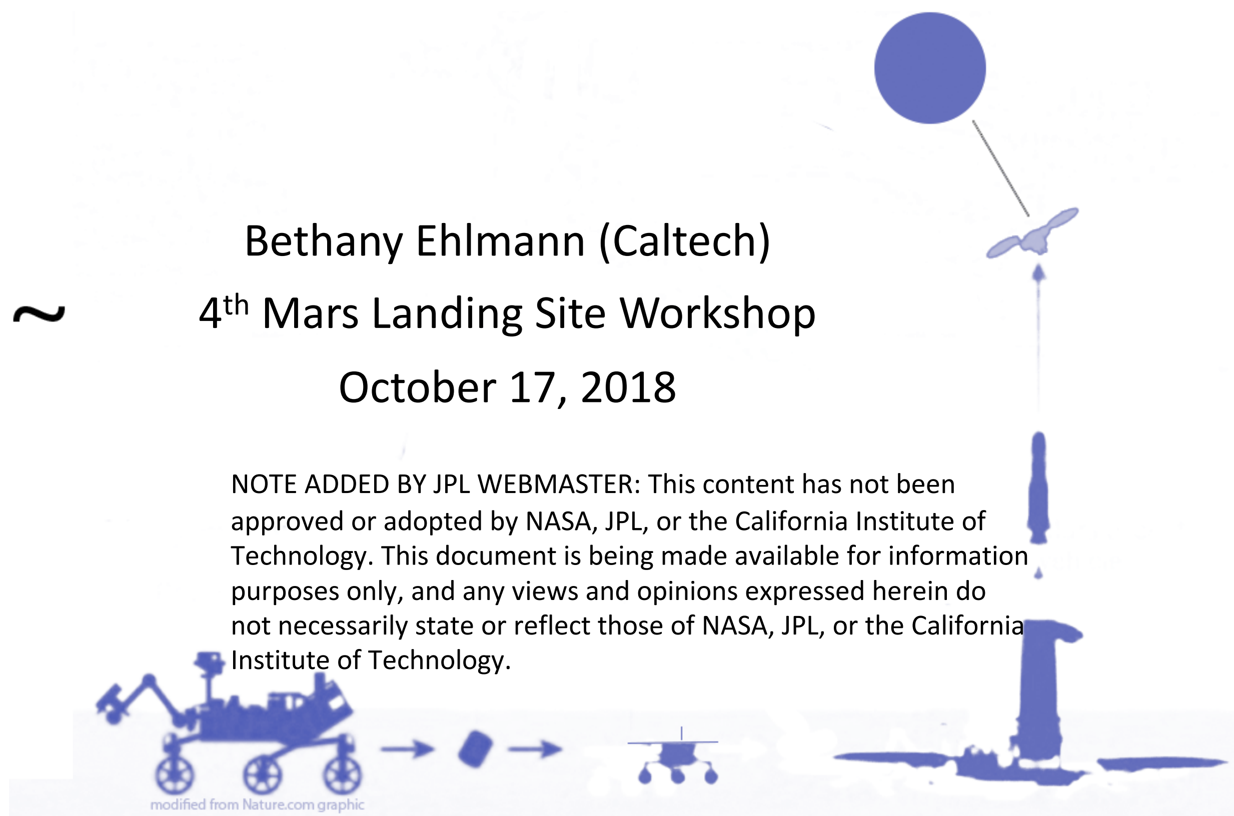


Mapping the Decadal Survey Drivers for Sample Return to Geologic Units Accessible in the Primary and Extended Missions from NE Syrtis and Midway

Bethany Ehlmann (Caltech)

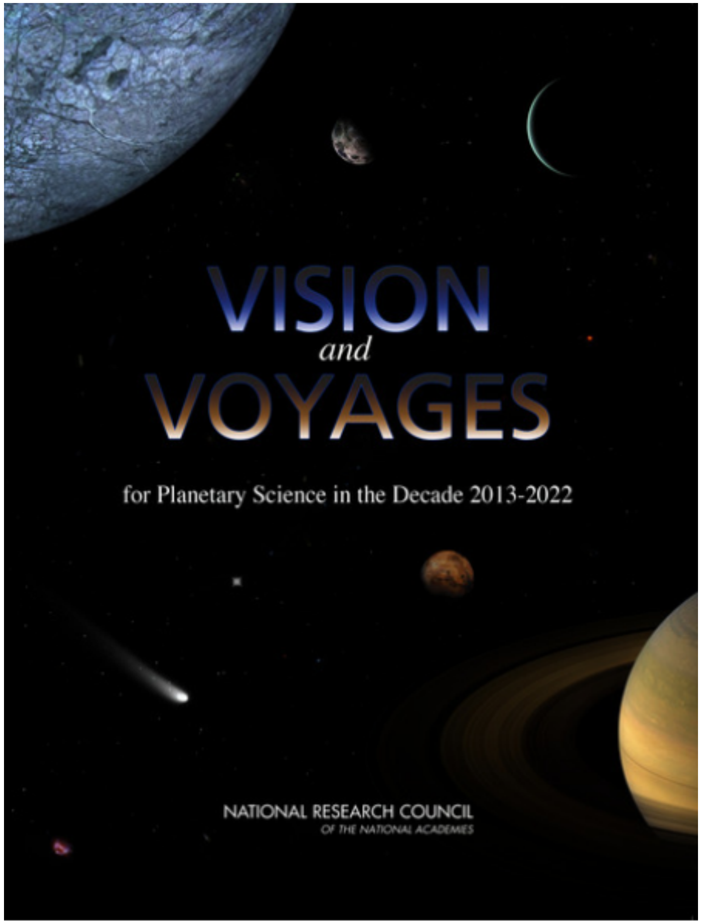
4^{th} Mars Landing Site Workshop

October 17, 2018



The Premise and the Thesis:

- Mars Sample Return is a huge investment for the planetary science community, indeed the entire ESA-NASA community
- The Decadal Survey prioritized a 3-mission sample return campaign because of anticipated merit of the in situ exploration coupled with return of a carefully selected sample cache
- It is our responsibility to be certain the cache we collect is provides the “Decadal-level Science” to justify this investment



This talk:

- *What is Decadal-level Science?*
- *How and Where can we achieve this?*

Thesis: Not all sites are created equal. We must visit and sample the Noachian stratigraphy to achieve Decadal-level science. This means land in NE Syrtis or Midway

What is Decadal-level science?

BOX 6.3
Sample Return Is the Next Step

The analysis of carefully selected and well-documented samples from a well-characterized site will provide the highest science return on investment for understanding Mars in the context of solar system evolution and for addressing the question of whether Mars has ever been an abode of life.

What is Decadal-level science?

BOX 6.3
Sample Return Is the Next Step

The analysis of carefully selected and well-documented samples from a well-characterized site will provide the highest science return on investment for understanding Mars in the context of solar system evolution and for addressing the question of whether Mars has ever been an abode of life.

Is analysis of samples required?

committee's recommendation is predicated on the assumption that collaboration with ESA will be maintained throughout the length of the Mars Sample Return campaign, offsetting some of NASA's costs. It is also important for the science return from the combined MAX-C/ExoMars mission to be significant even if the samples are never returned. Given the ambitious goals of MAX-C/ExoMars, this should be possible even if major descopes are neces-

Earth. It is widely accepted within the Mars science community that the highest science return on investment for understanding Mars as a planetary system will result from analysis of samples carefully selected from sites that have the highest scientific potential and that are returned to Earth for intensive study using advanced analytical techniques.

Important for the science return to be significant even if the samples are never returned

But highest science return on investment…. for ***understanding Mars as a planetary system***…will result from [samples] returned to Earth for intensive study

What is Decadal-level science?

BOX 6.3
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Is the search for life a major driver? Yes.

tion and evolution. Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life. The rocks from Mars that we have on Earth in the form of meteorites cannot provide an answer to this question. They are igneous rocks, whereas recent spacecraft observations have shown the occurrence on Mars of chemical sedimentary rocks of aqueous origin, and rocks that have been aqueously altered. It is these materials, none of which are found in meteorites, that provide the opportunity to study aqueous environments, potential prebiotic chemistry, and perhaps, the remains of early martian life.

Will address the question of whether the planet was ever an abode of life

What is Decadal-level science?

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Is understanding Mars evolution a major driver? Yes.

Sample Criteria

Selecting and preserving high-quality samples are essential to the success of the sample return effort. MEPAG identified 11 science objectives for Mars Sample Return (MSR) and specified the minimum criteria for a sample to meet these objectives.[7,8] The collection of Mars samples will be most valuable if they are collected as sample suites chosen to represent the diverse products of various planetary processes (particularly aqueous processes), and addressing the scientific objectives for MSR will require multiple sample suites. A full program of science investigations is expected to require samples equal to or greater

Most valuable if [samples] represent the **diverse products of various planetary processes**

What is Decadal-level science?

BOX 6.3
Sample Return Is the Next Step

The analysis of carefully selected and well-documented samples from a well-characterized site will provide the highest science return on investment for understanding Mars in the context of solar system evolution and for addressing the question of whether Mars has ever been an abode of life.

Is the search for life a major driver? Yes.

Is understanding Mars evolution a major driver? Yes.

Did the Decadal Survey think we could do both at one single landing site location? Yes

Key Decadal Drivers in the Search for Life

Site Selection and Context

Mars is a remarkably diverse planet with a wide range of aqueous environments preserved in its rock record. As a result of two decades of orbital and in situ exploration of Mars, a large number of excellent candidate sample return sites, where water played a major role in the surface evolution, have already been identified. Significantly, the geologic setting of these sites—as identified through mineralogic and stratigraphic mapping—indicates that there were major differences in water chemistry and temperature, weathering processes, and sediment transport and deposition processes across Mars, providing a diversity of environments from which to collect samples. The known sites also contain diverse sedimentary and igneous terrains within the roving range of existing spacecraft.

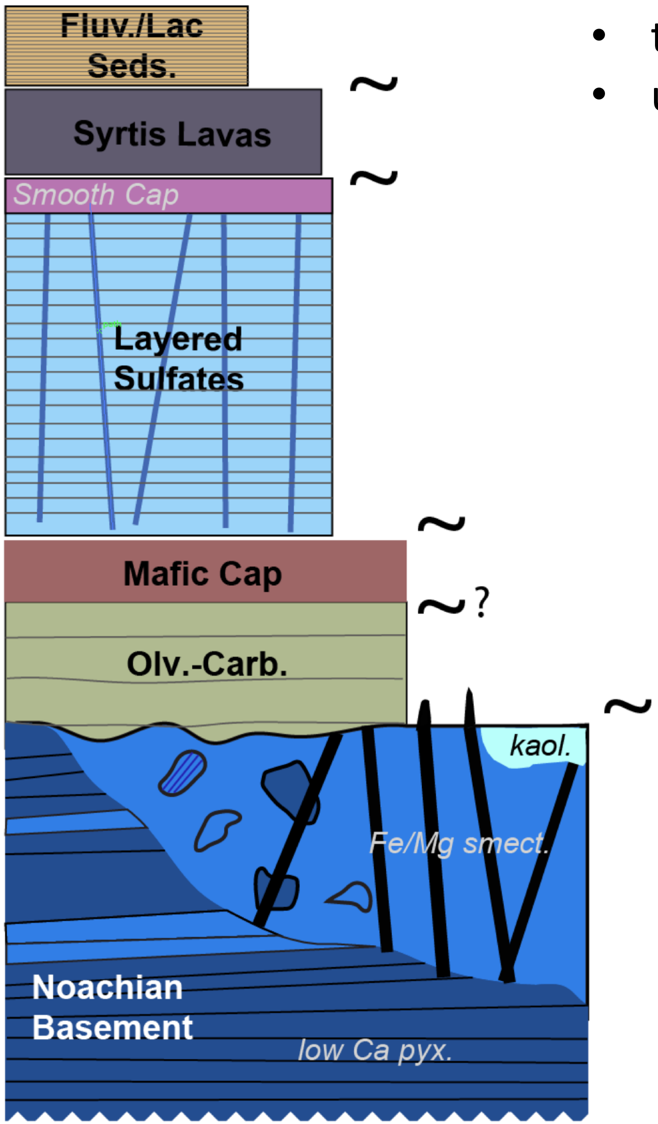
The site will be selected on the basis of compelling evidence in the orbital data for aqueous processes and a geologic context for the environment (e.g., fluvial, lacustrine, or hydrothermal). The sample-collection rover must have the necessary mobility and in situ capability to collect a diverse suite of samples based on stratigraphy, mineralogy, composition, and texture.[3,4] Some biosignature detection, such as a first-order identification of carbon compounds, should be included, but it does not need to be highly sophisticated because the samples will be studied in detail on Earth.[5,6]

Pick a site where

- *water played a major role with varied units recording water chemistry, temperature, weathering, sedimentation*
- *igneous and sedimentary in roving distance*
- *geologic context*

Basic in situ biosignature detection only: carbon compounds

Only NE Syrtis and Midway offer Decadal-level science



The complete package

- the search for life
- understanding Mars evolution

- Go to the Noachian: Mars at its most active and habitable
- Prioritizing life in the best, most stable habitats (aquifers) and diversify to maximize chances of discovery
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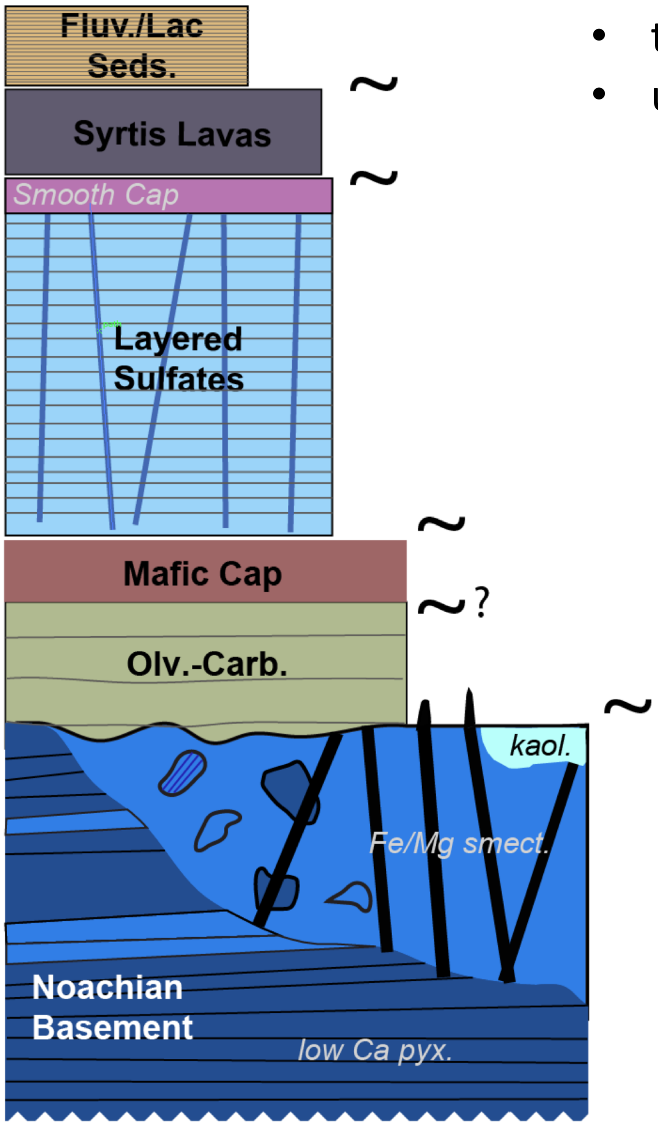

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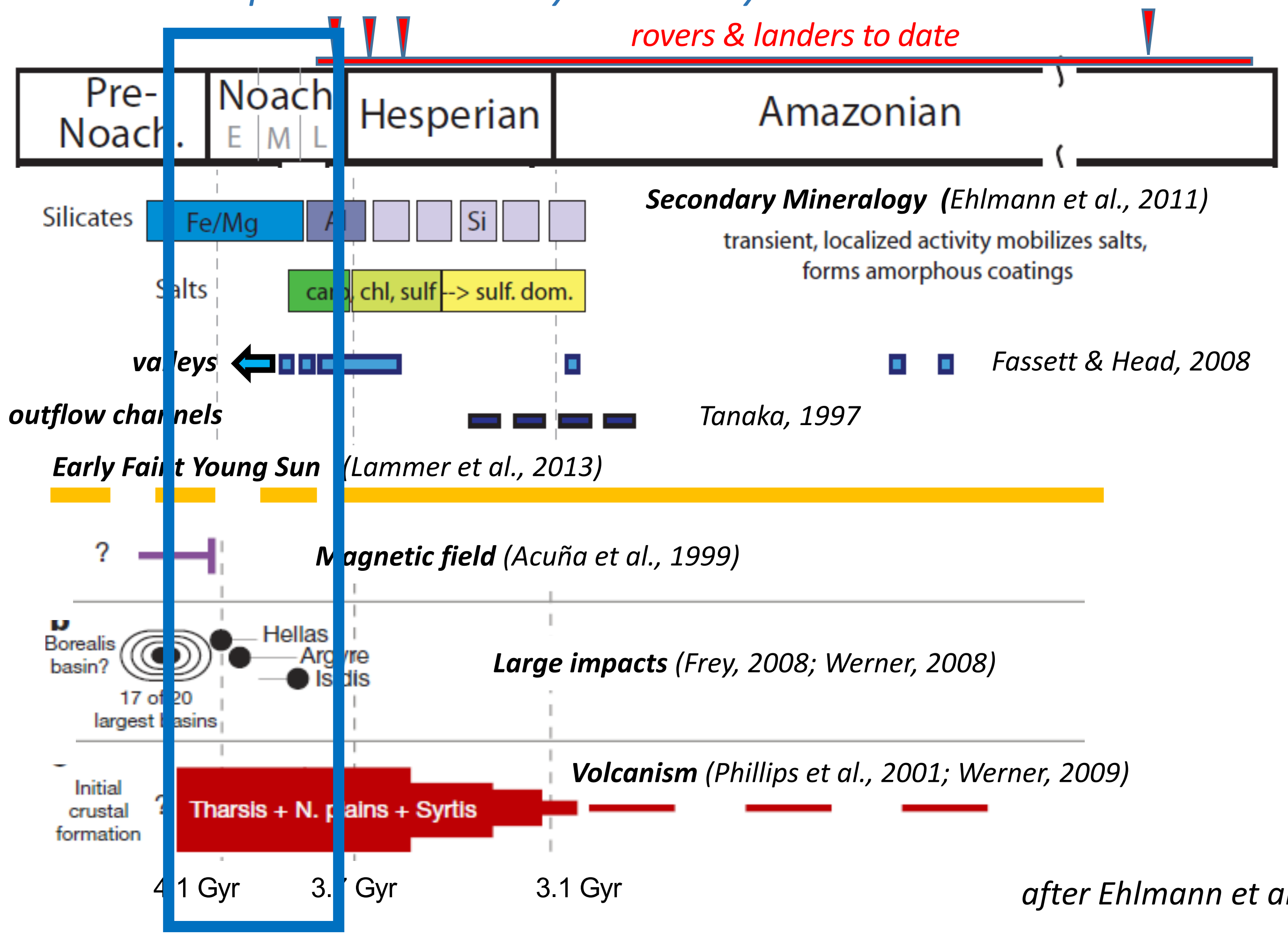
Go to the Noachian: Mars at its most active and habitable

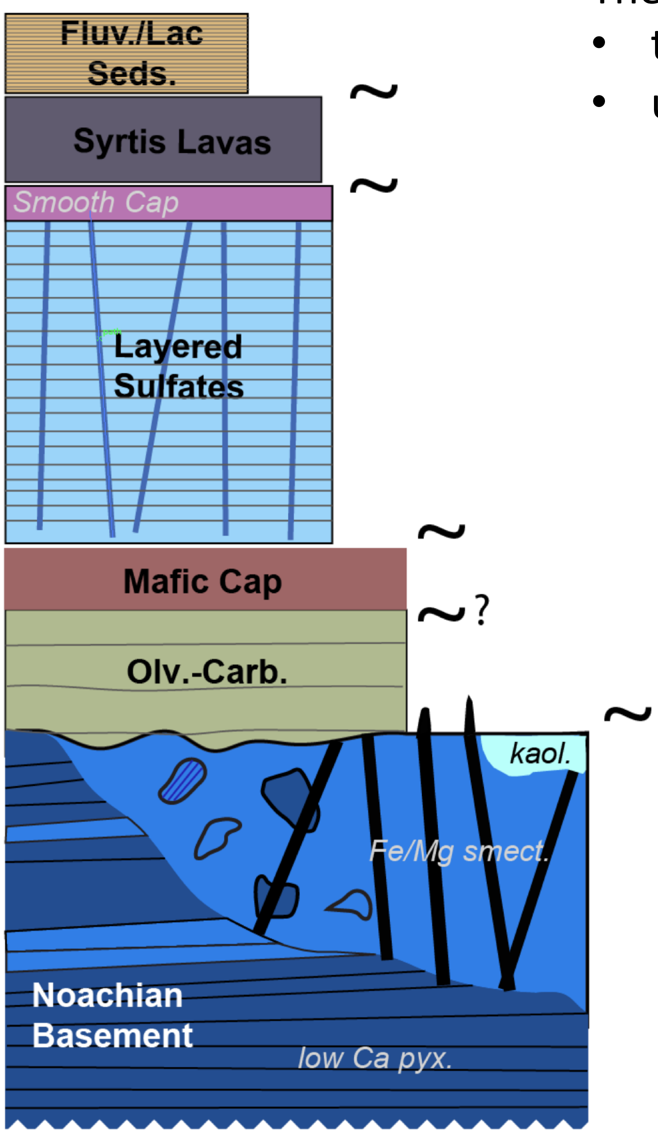
- Essential science covers early Mars history and big questions remain

Pre-Noachian to Hesperian at Midway and NE Syrtis



after Ehlmann et al., 2016

Only NE Syrtis and Midway offer Decadal-level science



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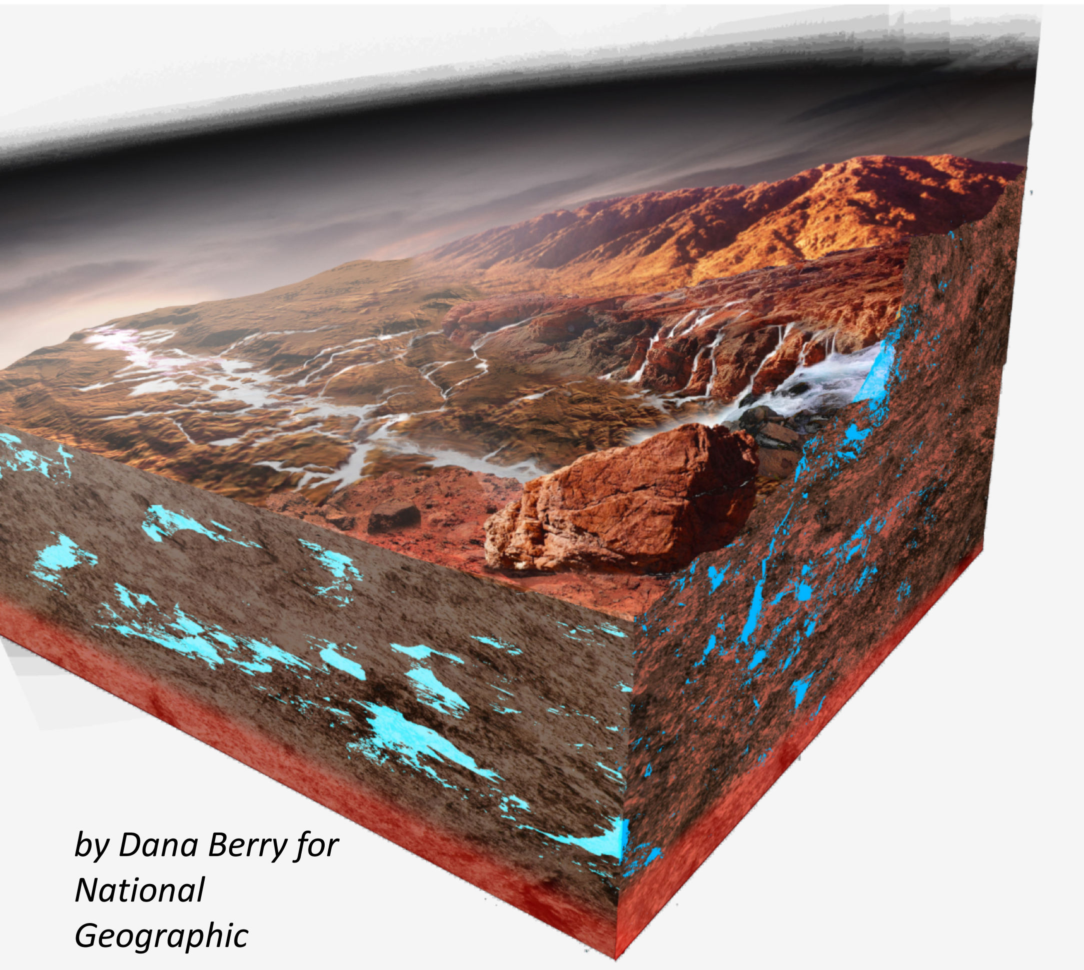
Search for Life: Prioritizing life in the best, most stable habitats (aquifers)

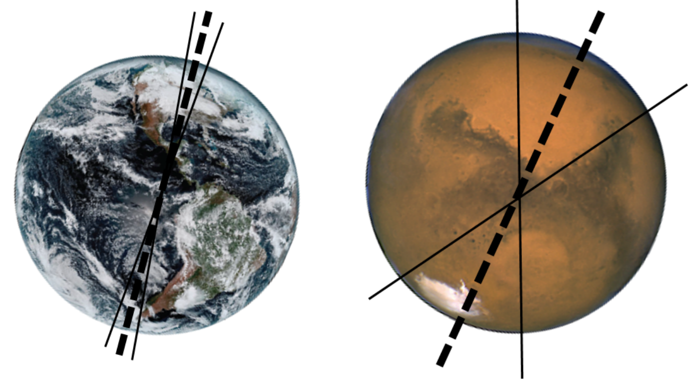
Fundamental Differences: Regardless of what you believe about early Mars climate, liquid water on early Mars was never stable at the surface for long time

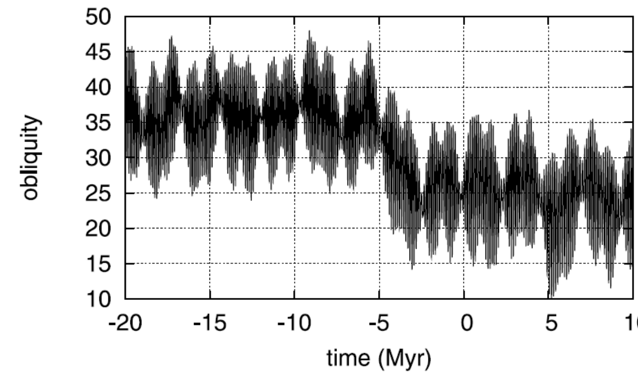


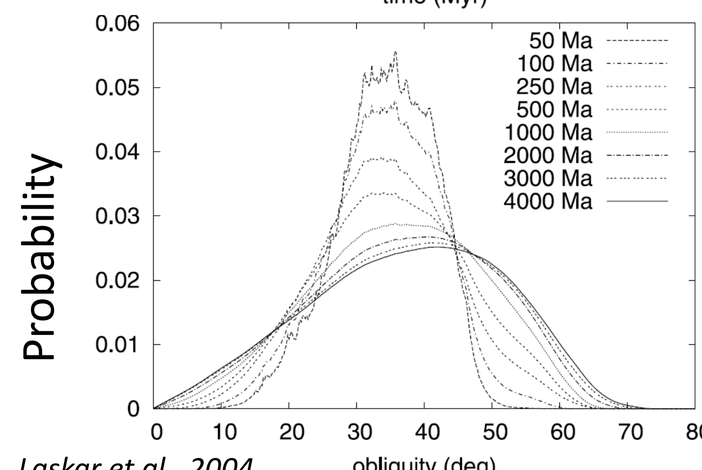
by Dana Berry for National Geographic

1° causes ice ages

10° - 60°







Laskar et al., 2004

Search for Life: Prioritizing life in the best, most stable habitats (aquifers)

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

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).

Search for Life: Prioritizing life in the best, most stable habitats (aquifers)

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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

Recommendation: NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances demonstrating the breadth and diversity of life in Earth's subsurface, the history and nature of subsurface fluids on Mars, and potential habitats for life on Ocean Worlds.

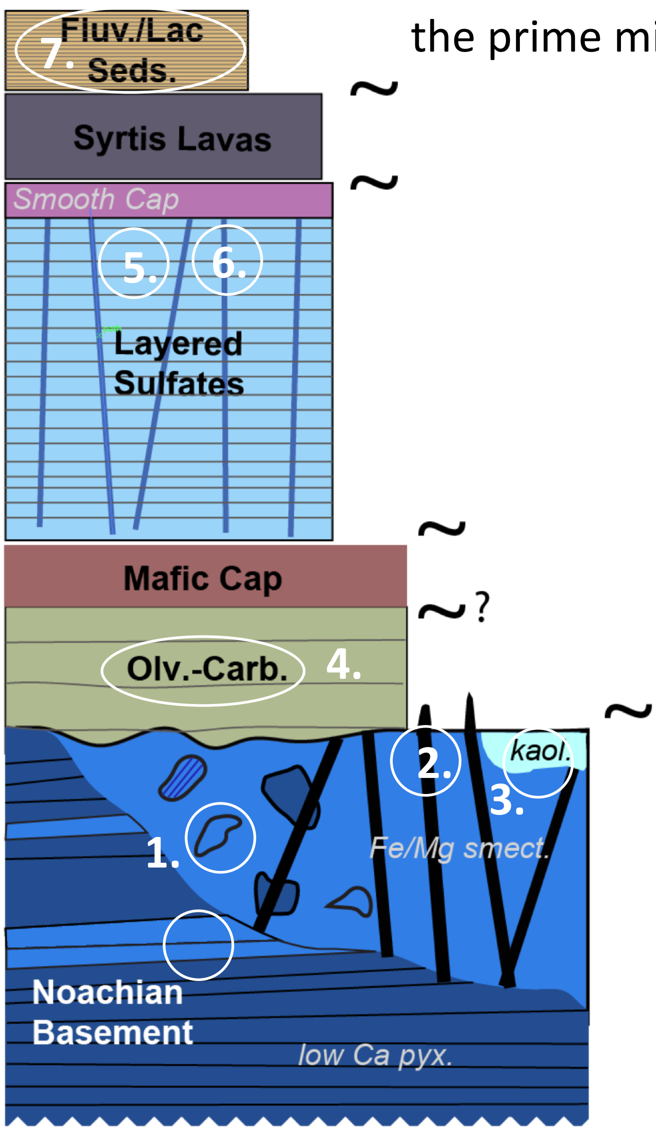
characterization of exoplanet atmospheres and the search for potential biosignatures for terrestrial exoplanets orbiting M-dwarf stars—a major theme identified as well in the Exoplanet Science Strategy (2018).

The National Academies of | SCIENCES ENGINEERING MEDICINE

7/19

see Onstott et al., next talk

Search for Life: Diversify to maximize chances of discovery

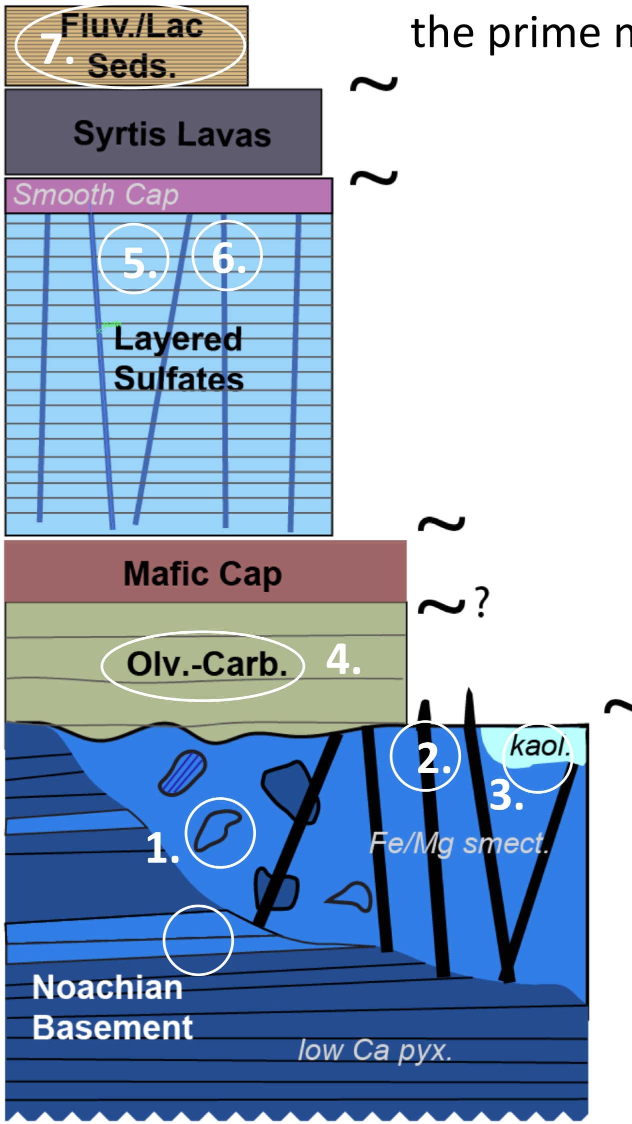


Noachian strata offer ≥4 habitable environments to sample for life in the prime mission and up to 7 in the extended mission

- ***1. Pre-Isidis clay rich material crust (Early Noach.):*** Rover will determine sedimentary vs. altered igneous and sample.
- ***2. Post-Isidis clay ridges (Mid Noachian):*** Rover will determine fluid chemistry, temperature of groundwaters and sample
- ***3. Kaolinite (Late Noachian?):*** Rover will determine groundwater vs. surface weathering origin, stratigraphic/contact relationships, and sample
- ***4. Carbonate (Mid/Late Noachian):*** Rover will determine serpentinization vs. carbonation processes by mineral assemblages and sample
- ***5. Sulfate sediments (Late Noachian):*** Rover will interpret depositional facies, water chemistry, and sample
- ***6. Jarosite-enriched ridges (Late Noach./Early Hesp.):*** Rover will determine fluid chemistry, temperature of groundwaters and sample
- ***7. Fluviolacustrine clay sediments (Late Hesp/Amaz.):*** Rover will determine depositional facies, lake chemistry, and sample

Search for Life: Diversify to maximize chances of discovery

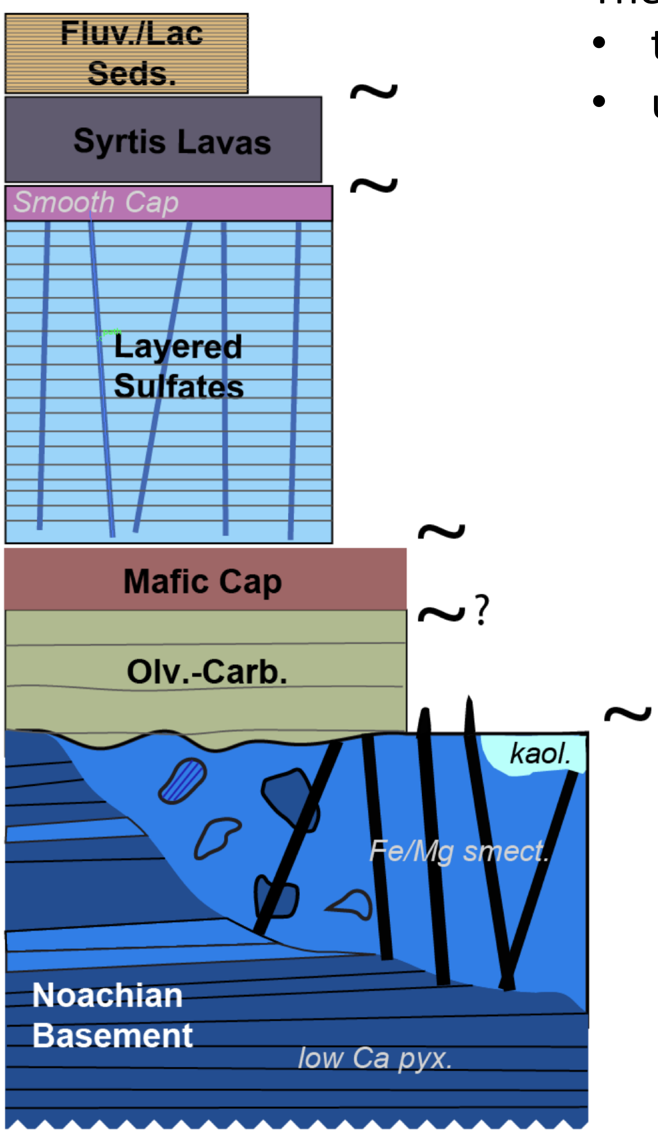
Noachian strata offer ≥4 habitable environments to sample for life in the prime mission and up to 7 in the extended mission



iMost Report Geology Objectives	Midway	NE Syrtis	Jezero	Gusev
	extended mission			
Sediments	✓	✓	✓	?
Hydrothermal	✓	✓		✓
Groundwater	✓	✓		
Subaerial	✓	✓		?
Igneous	✓	✓	?	✓

unparalleled habitable environmental diversity

Only NE Syrtis and Midway offer Decadal-level science



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Go Where You Can Test Important Hypotheses About Mars Processes

- Ex. 1: Igneous
- Ex. 2: Clay formation and habitability
- Ex. 3: Carbonate formation and atmospheric sequestration

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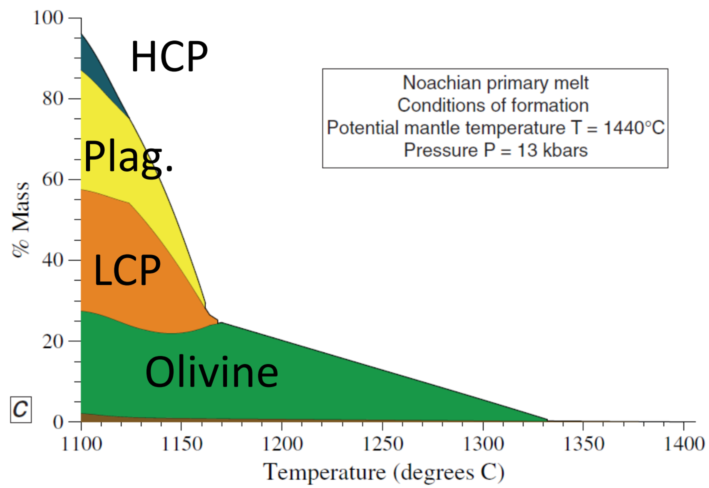
LETTER

doi:10.1038/nature09903

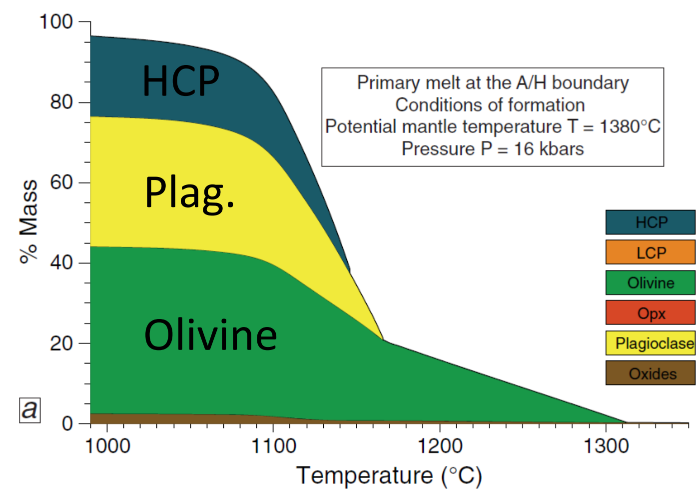
+2013

Thermal history of Mars inferred from orbital geochemistry of volcanic provinces

David Baratoux[1,2], Michael J. Toplis[1,2], Marc Monnereau[1,2] & Olivier Gasnault[1,2]



Noachian lava predicted composition



Am/Hesp. lava predicted composition

Baratoux et al., 2011; 2013

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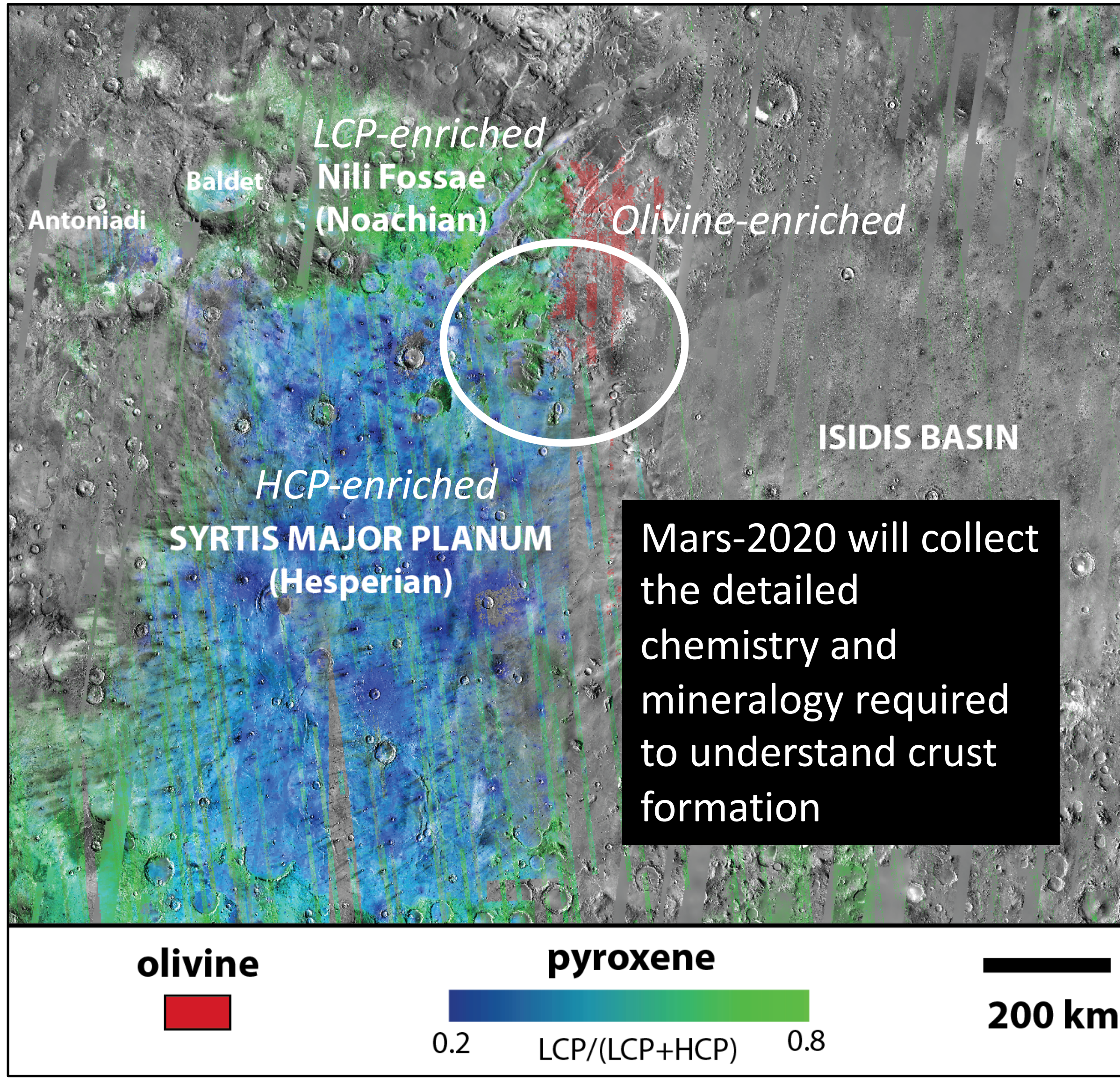

By P. Thollot in Ehlmann et al., 2009

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Vol 438|1 December 2005|doi:10.1038/nature04274 nature

ARTICLES

Phyllosilicates on Mars and implications for early martian climate

F. Poulet[1], J.-P. Bibring[1], J. F. Mustard[2], A. Gendrin[2], N. Mangold[3], Y. Langevin[1], R. E. Arvidson[4], B. Gondet[1], C. Gomez[1] & the Omega Team*

REVIEW

doi:10.1038/nature10582

Subsurface water and clay mineral formation during the early history of Mars

Bethany L. Ehlmann[1]†, John F. Mustard[2], Scott L. Murchie[3], Jean-Pierre Bibring[1], Alain Meunier[4], Abigail A. Fraeman[5] & Yves Langevin[1]

nature geoscience ARTICLES
PUBLISHED ONLINE: 9 SEPTEMBER 2012 | DOI: 10.1038/NGEO1572

Magmatic precipitation as a possible origin of Noachian clays on Mars

Alain Meunier[1]*, Sabine Petit[1], Bethany L. Ehlmann[2], Patrick Dudoignon[1], Frances Westall[3], Antoine Mas[1], Abderrazak El Albani[1] and Eric Ferrage[1]

LETTER

Primordial clays on Mars formed beneath a steam or supercritical atmosphere

Kevin M. Cannon[1,2], Stephen W. Parman[1] & John F. Mustard[1]

Go Where You Can Test Important Hypotheses About Mars Processes

- Ex. 1: Igneous
- Ex. 2: Clay formation and habitability
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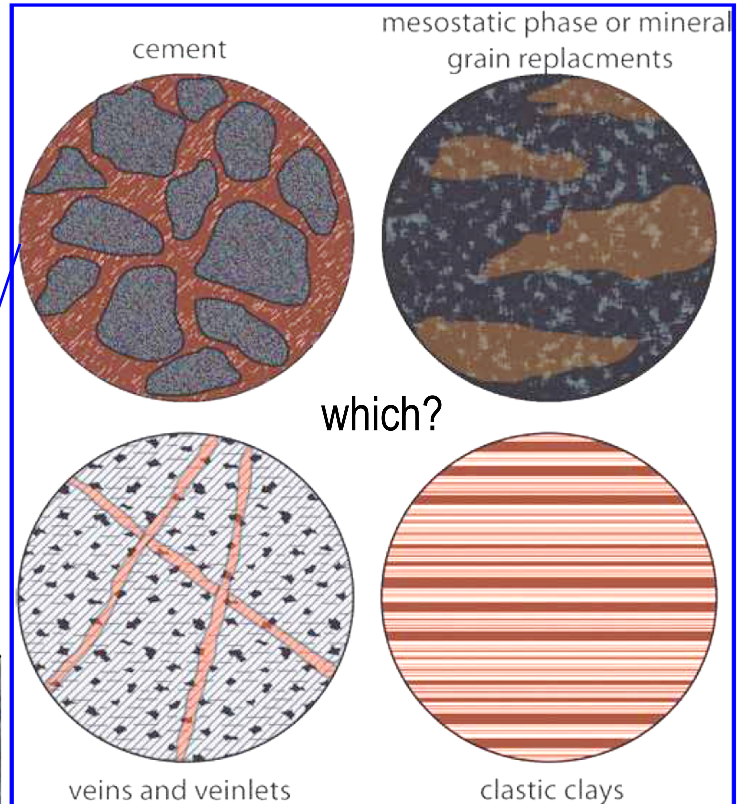
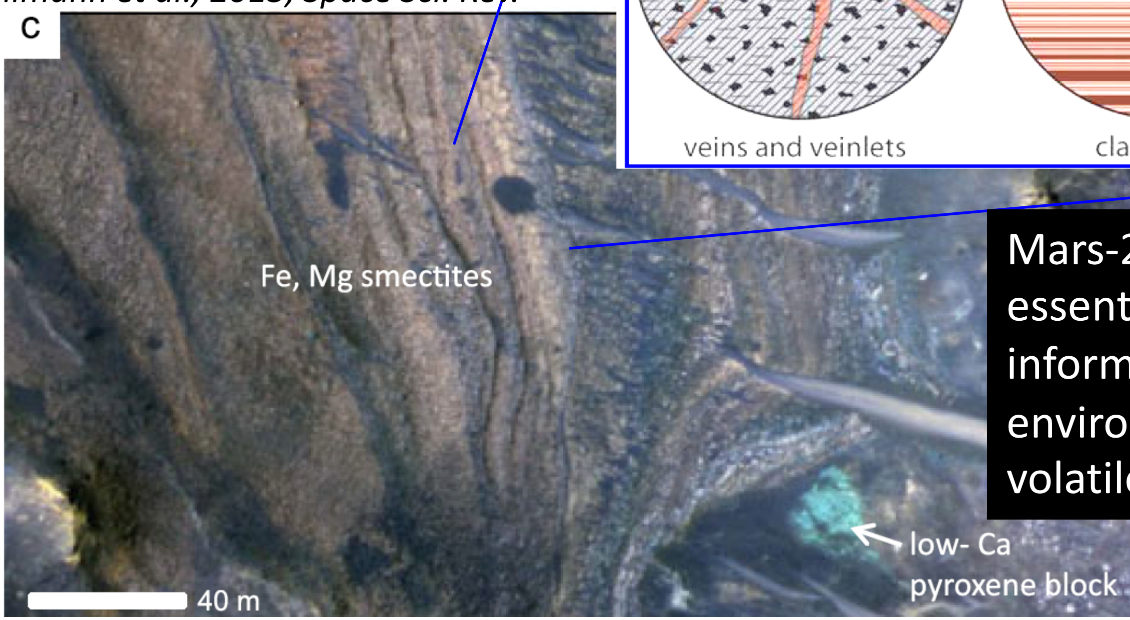
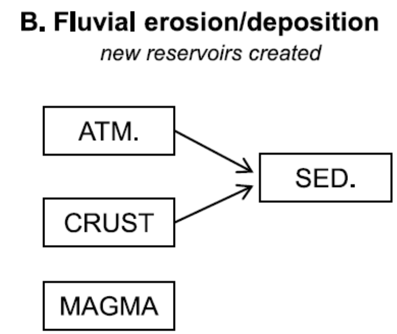


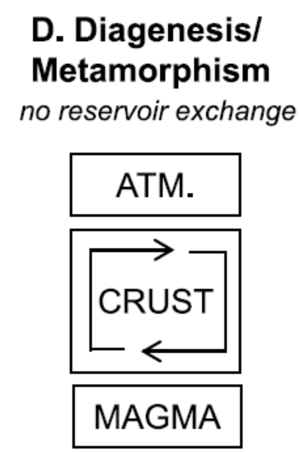
Michalski et al., 2010, Astrobio.

Ehlmann et al., 2013, Space Sci. Rev.



Mars-2020 collects essential information for environments and volatile cycling





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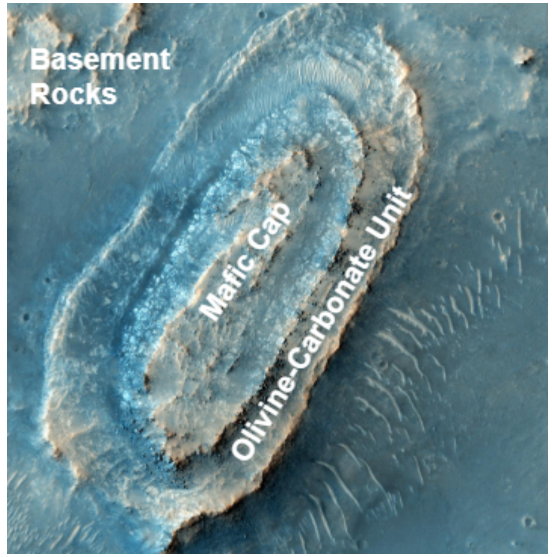
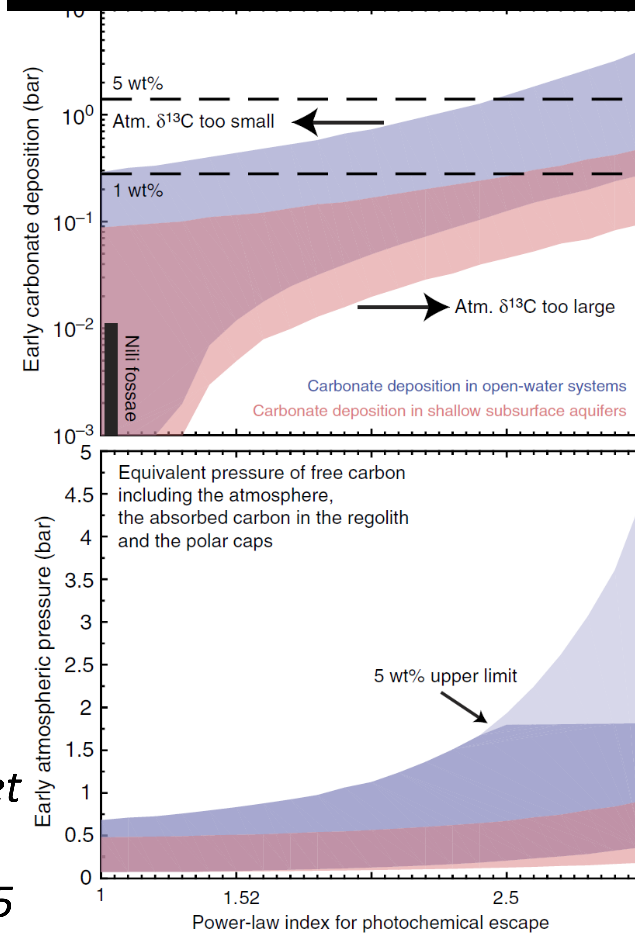
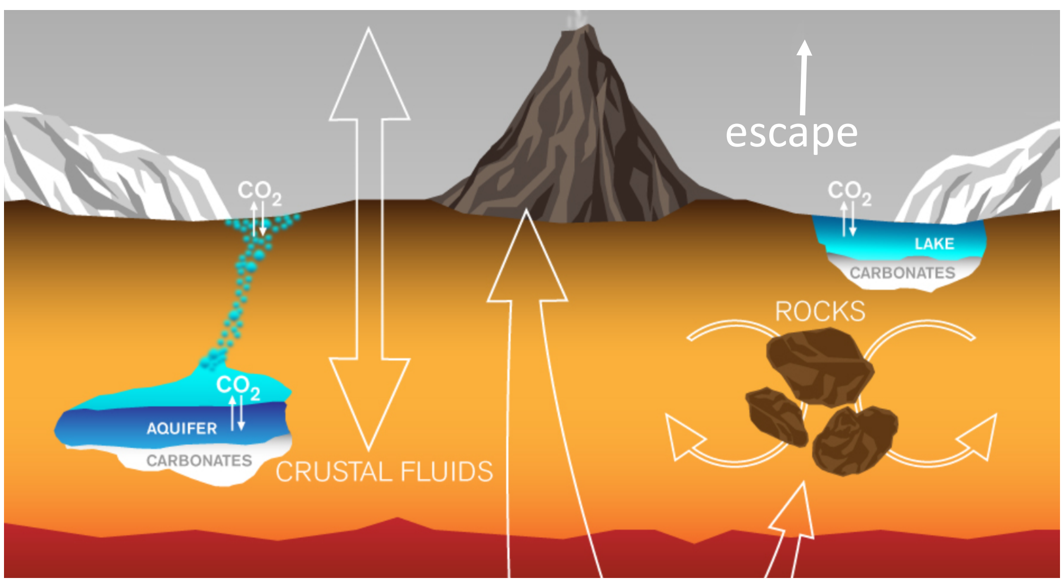


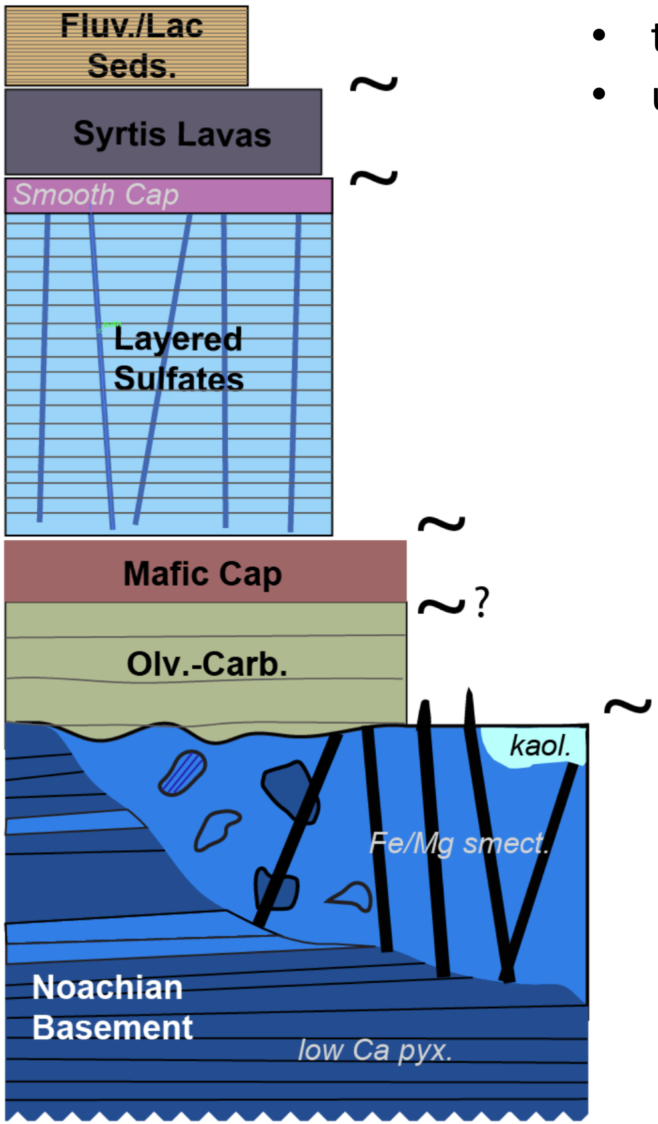
Mars-2020 collects essential information on carbonate formation: Open/closed sys. Fractionation factor? Matters for atmosphere loss calculations





Hu et al., 2015

Only NE Syrtis and Midway offer Decadal-level science



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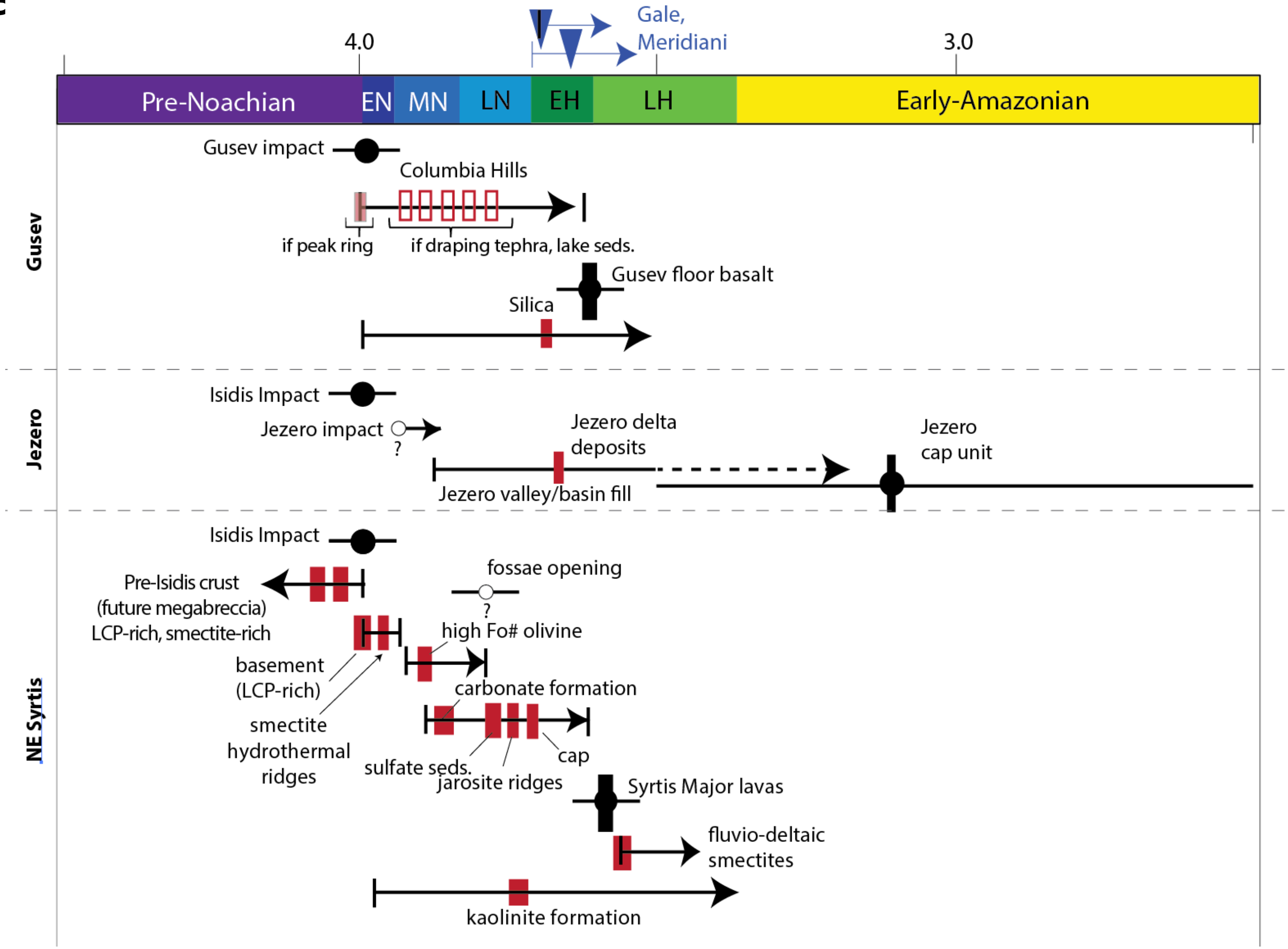
Midway and NE Syrtis offer a richer set of units sampling longer time in context



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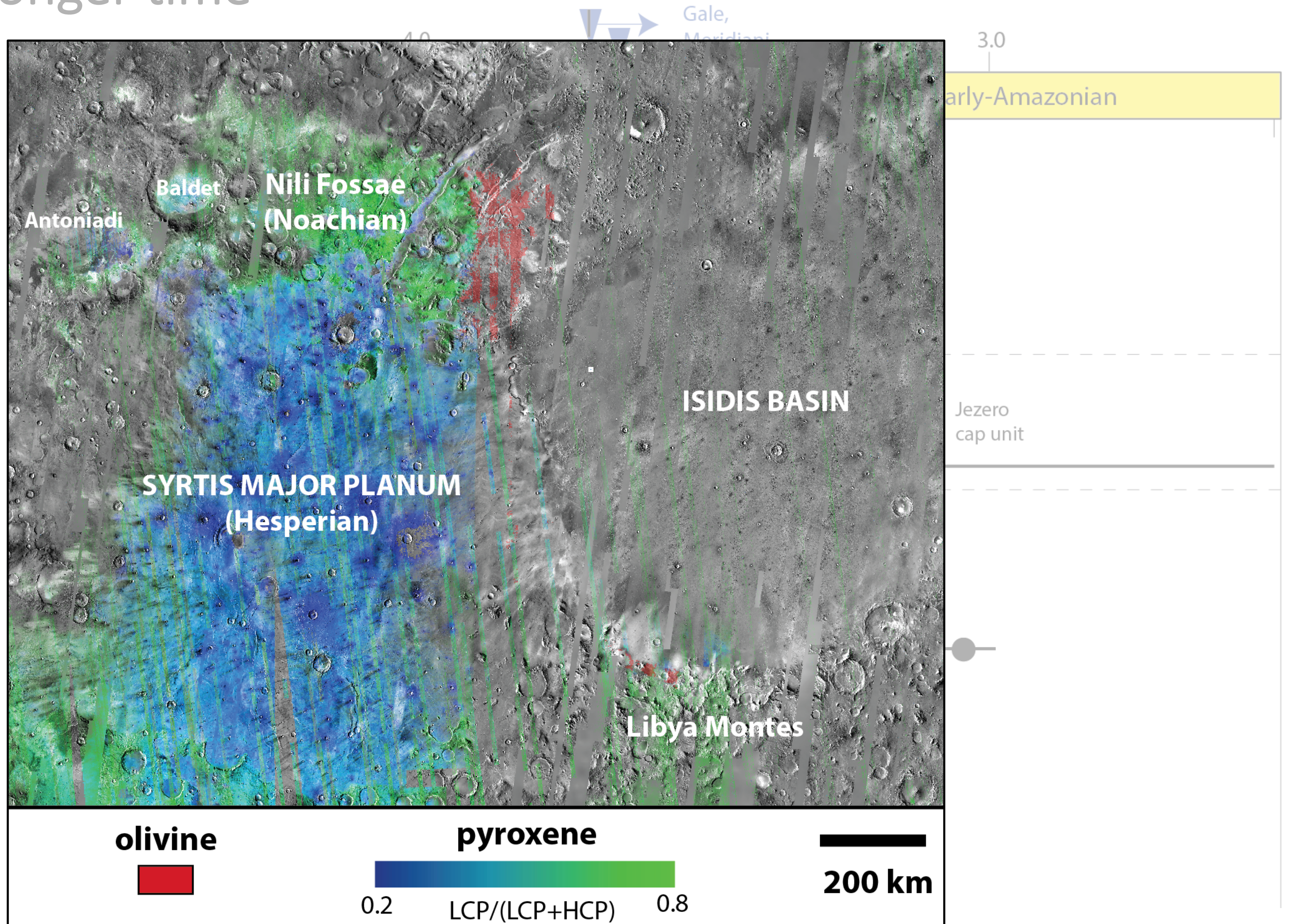

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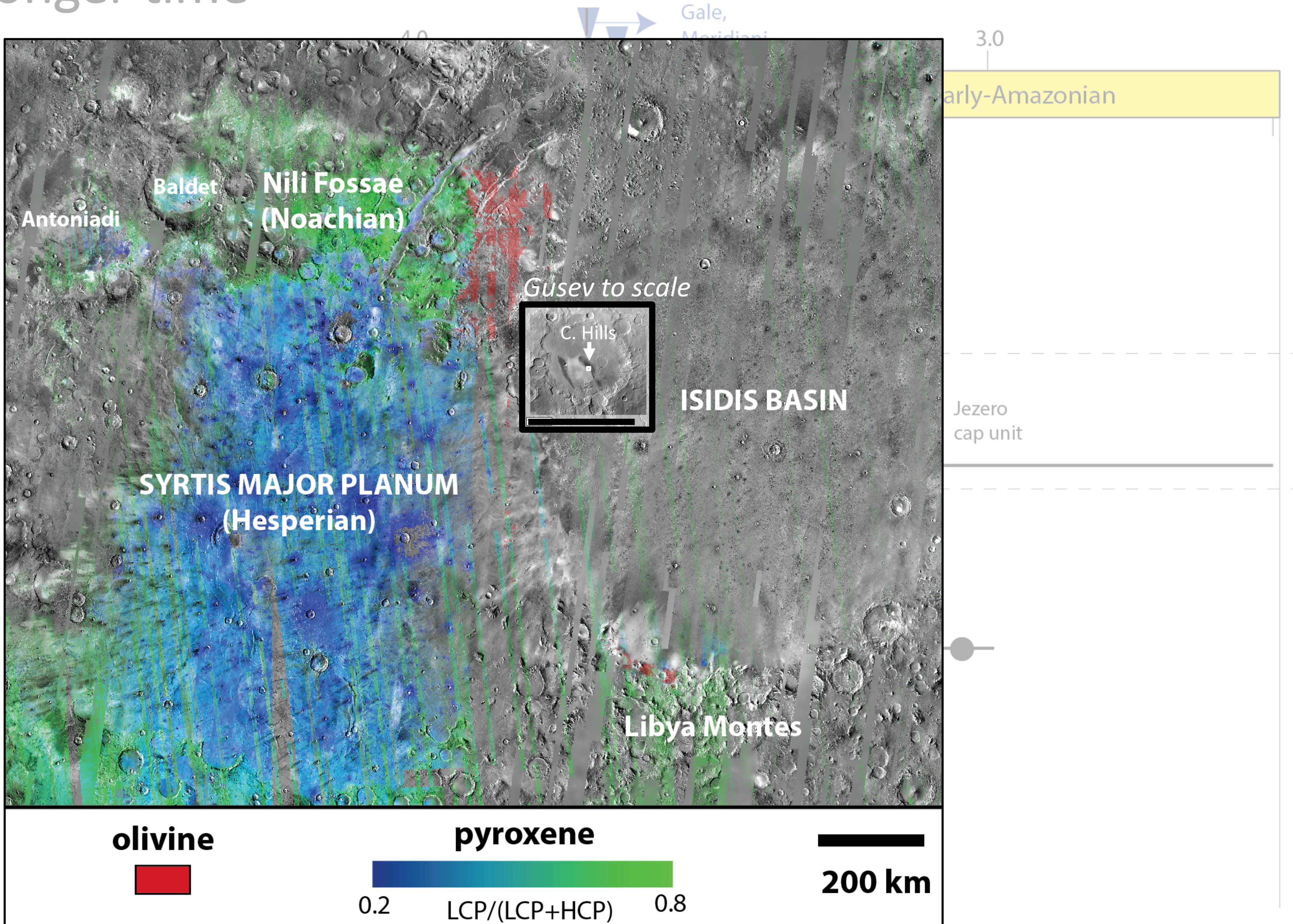
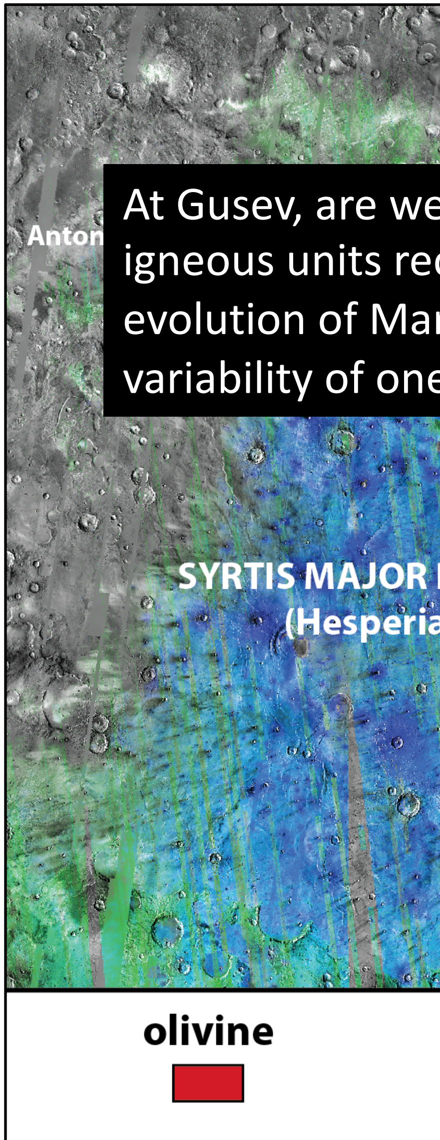
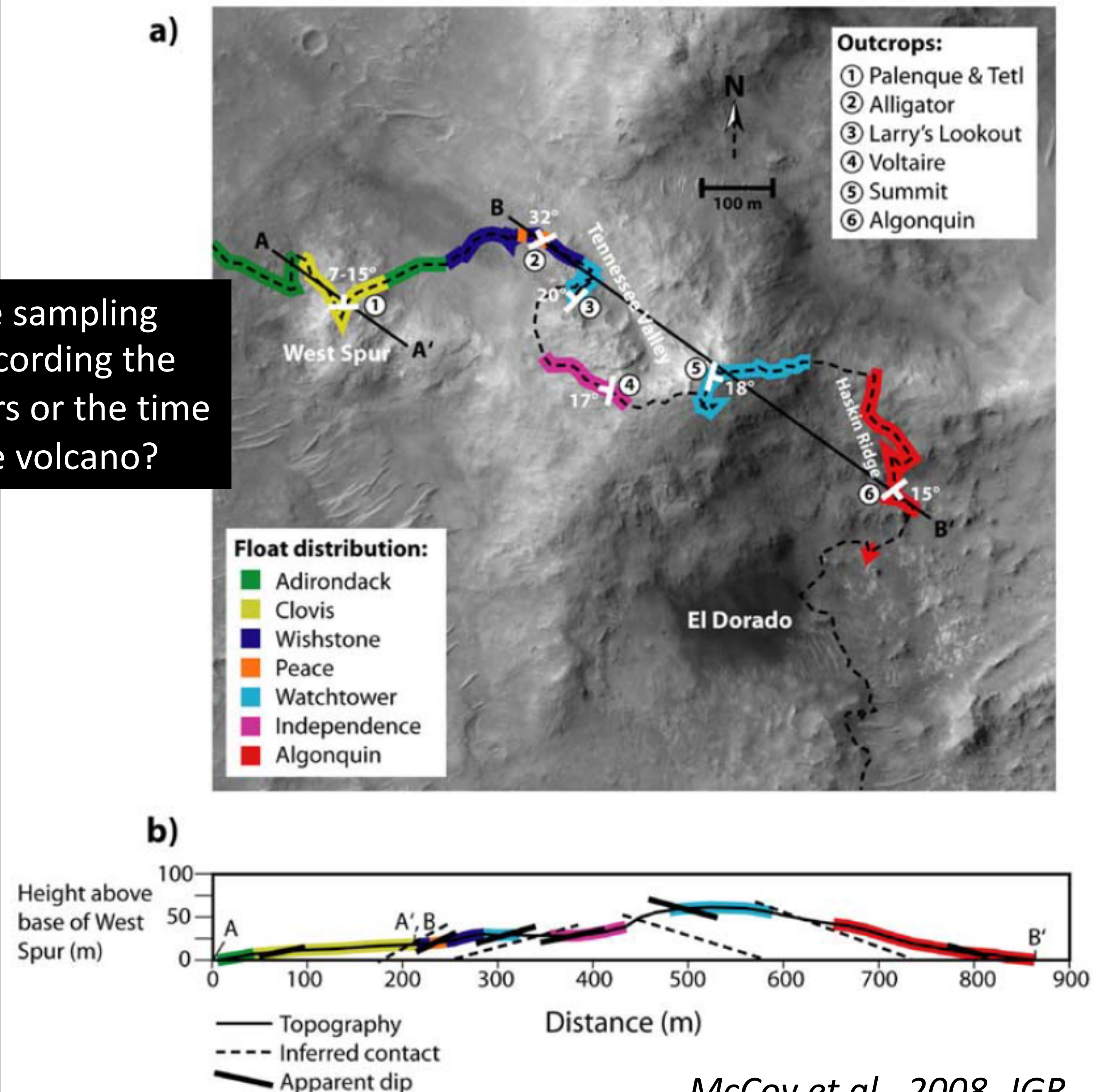


Midway and NE
longer time

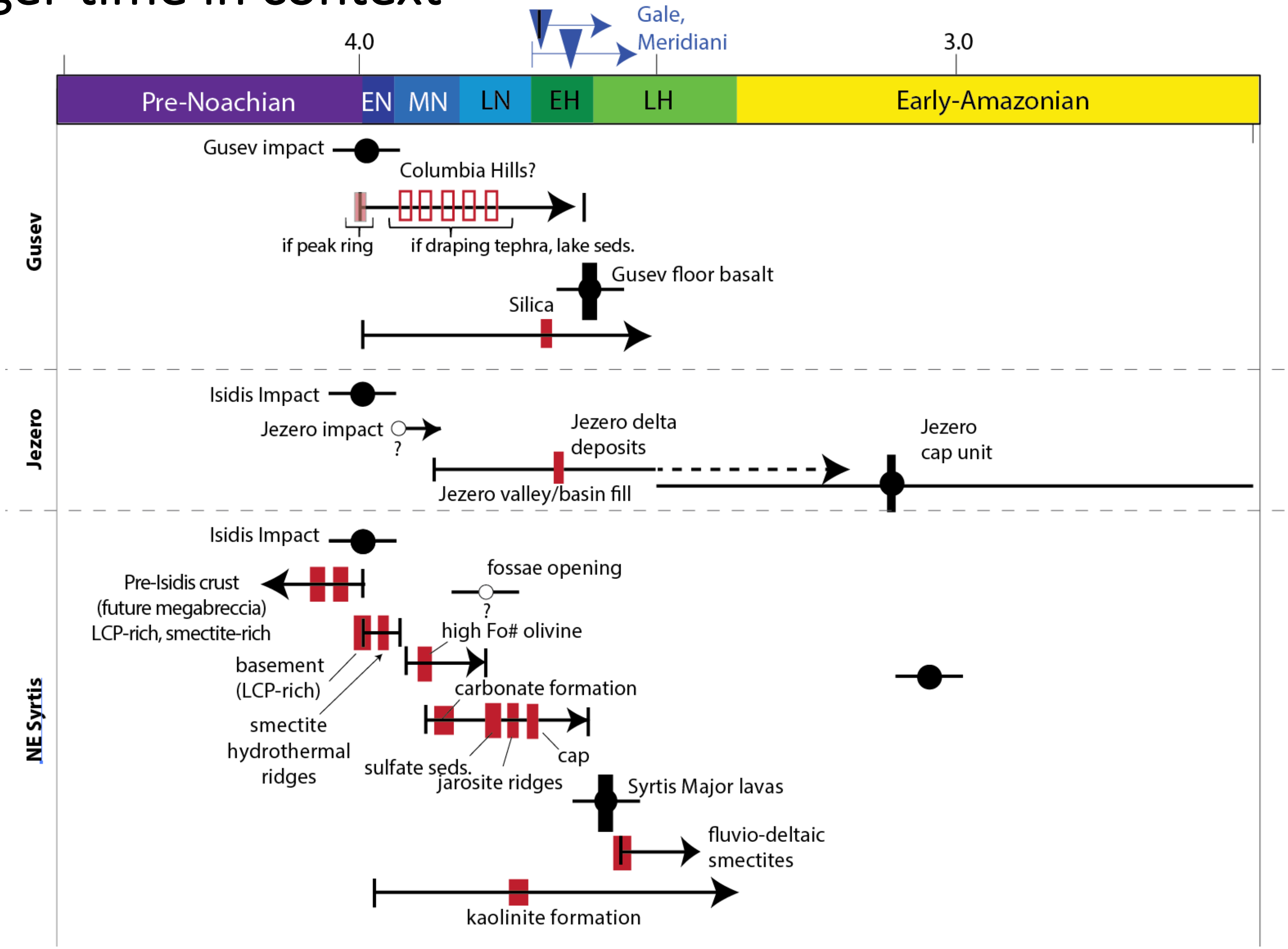


At Gusev, are we sampling igneous units recording the evolution of Mars or the time variability of one volcano?



McCoy et al., 2008, JGR

Midway and NE Syrtis offer a richer set of units sampling longer time in context



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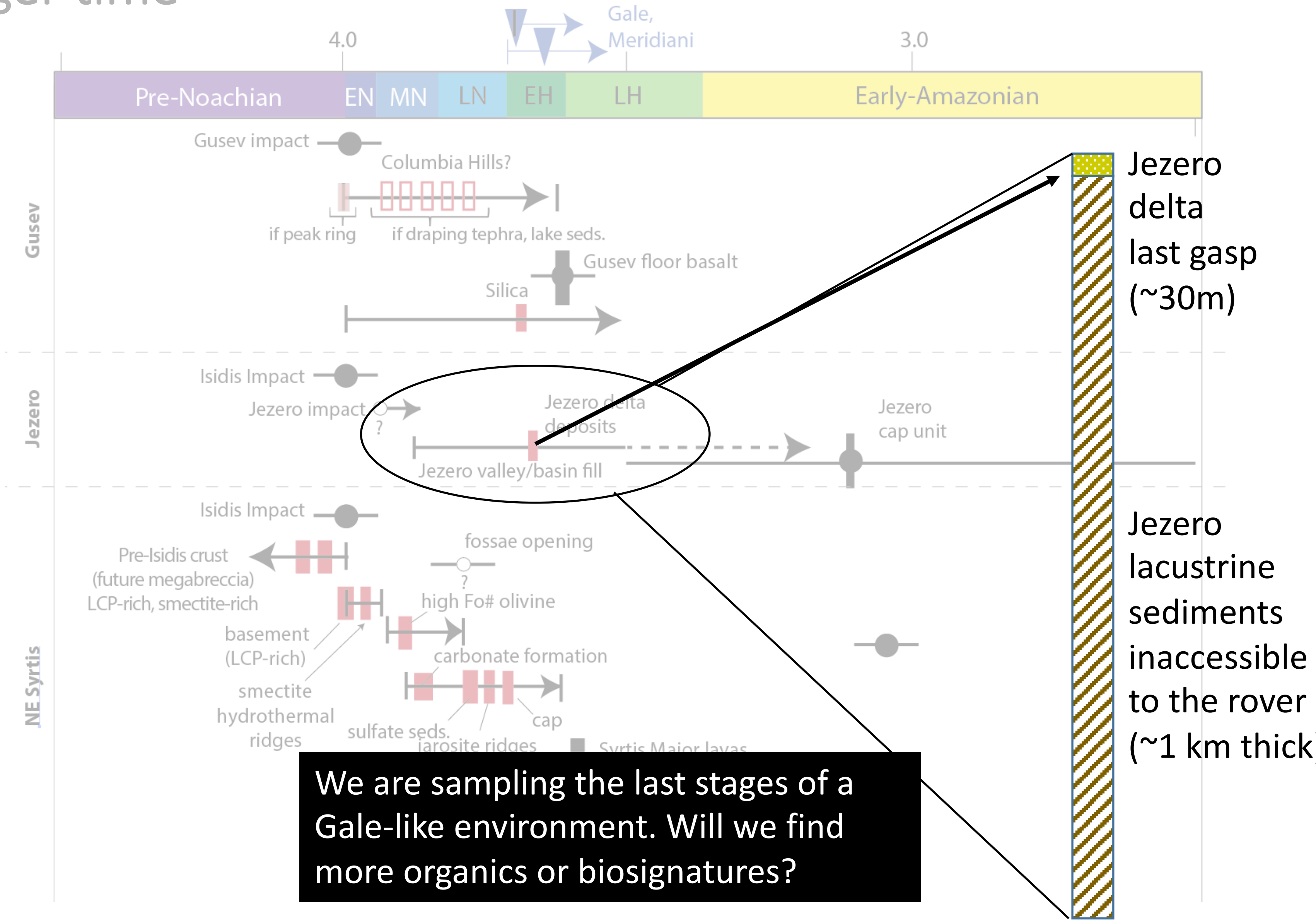
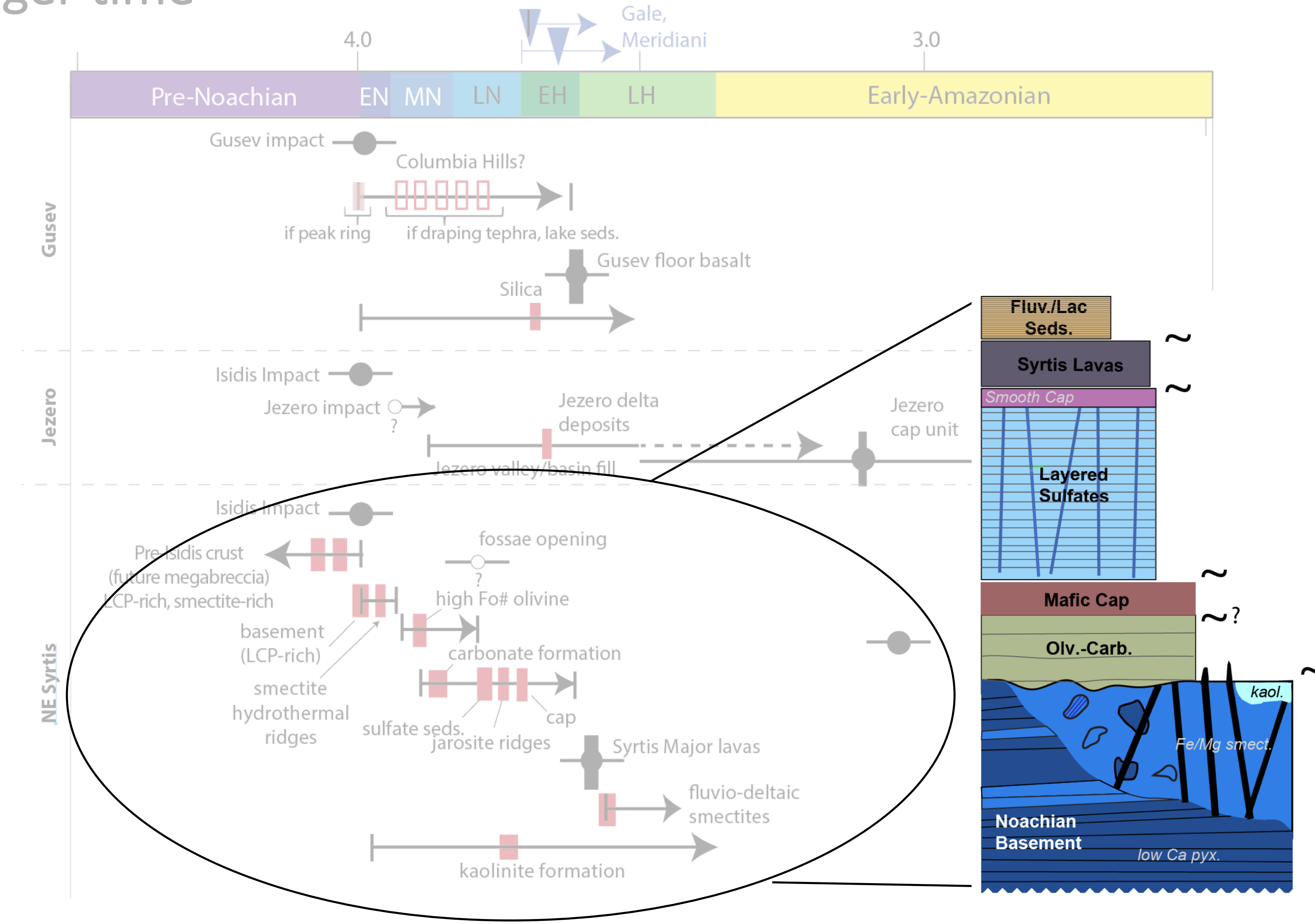
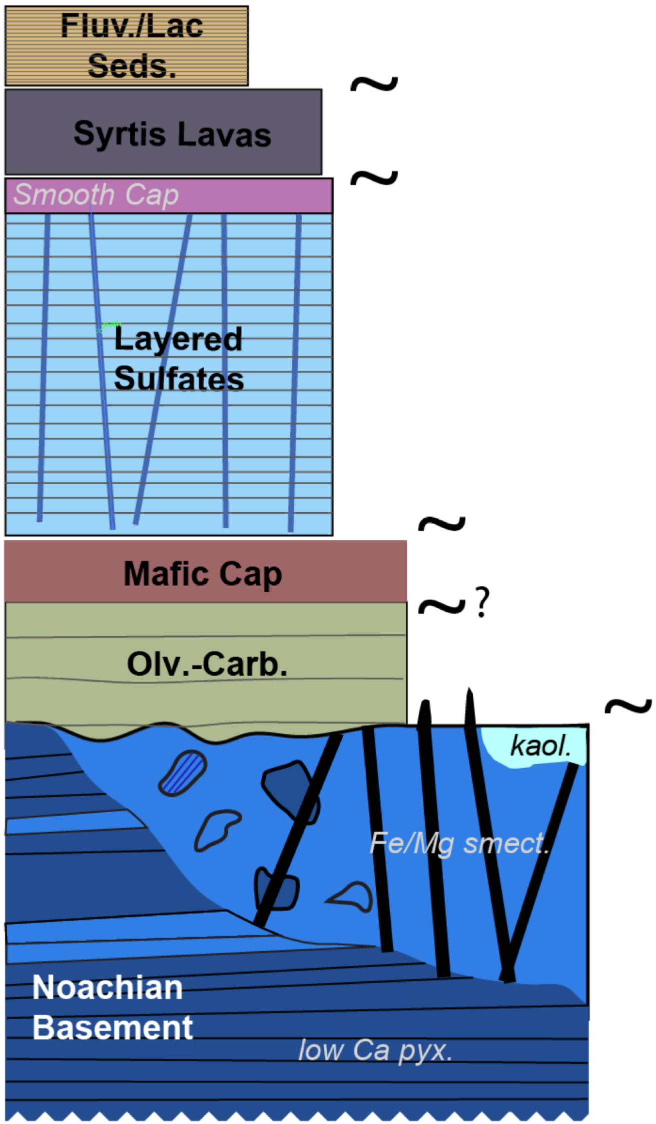


We are sampling the last stages of a Gale-like environment. Will we find more organics or biosignatures?

Midway and NE Syrtis offer a richer set of units sampling longer time



NE Syrtis and Midway Units that Allow Decadal-level Science in Understanding Mars Evolution



	iMOST (2018) Objectives
1	***Geological environment(s)*** Interpret the primary geologic processes and history that formed the martian geologic record, with an emphasis on the role of water.
	Sedimentary System, Hydrothermal, Deep groundwater, Subaerial
	Igneous terrane: Determine the petrogenesis of martian igneous rocks in time and space.
2	***Life:*** Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life. ***Organics, Ancient Biosignatures, Modern Biosignatures***
3	***Geochronology***: Determine the evolutionary timeline of Mars.
4	***Volatiles:*** 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	***Planetary Scale Geology***: Reconstruct the history of Mars as a planet, elucidating those processes that have affected the origin and modification of the crust, mantle and core.
6	***Environmental hazards*** : Understand and quantify the potential martian environmental hazards to future human exploration and the terrestrial biosphere.
7	***ISRU:*** Evaluate the type and distribution of *in situ* resources to support potential future Mars Exploration.

On Complexity

It is not a mission of exploration and discovery if we already know the answers

What is Decadal-level science?

BOX 6.3
Sample Return Is the Next Step

The analysis of carefully selected and well-documented samples from a well-characterized site will provide the highest science return on investment for understanding Mars in the context of solar system evolution and for addressing the question of whether Mars has ever been an abode of life.

Search for Life

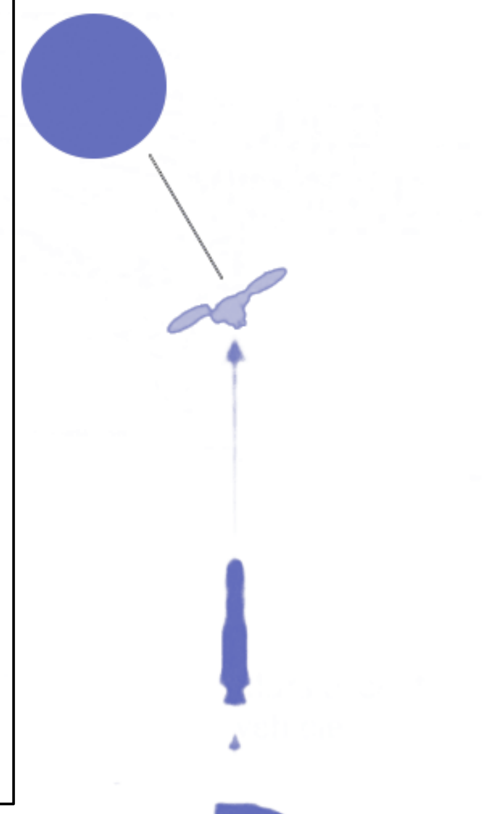
- Go where you have the most chances at findings life
- Look deep (as well as shallow)
- Seek biosignatures, but in situ ID is not necessary for return
- Midway and NE Syrtis investigate ALL iMOST target terrains

Understanding Mars as a system

- Go to the Noachian: Mars at its most active and habitable
- Go where you can test important hypotheses
- Go where you can sample the longest period of time
- Go for a diverse, in-context sample suite
- Midway and NE Syrtis investigate ALL iMOST target terrains

Conclusions and Recommendations

- Mars Sample Return is a substantial investment for the planetary science community, indeed the NASA Science community
- The Midway and NE Syrtis are the only finalist sites with a mission profile worthy of this investment
- At these Noachian sites, M2020 could do extraordinary in situ science and make a substantial progress toward addressing the most important outstanding questions about ancient Mars climate, habitability, and geology – achieve ALL iMOST objectives
- **During our Baseline mission (not relying on extensions), it is our responsibility to make a sample cache that is worthy of the investment to return**
- **→Land on Midway or NE Syrtis.**



modified from Nature.com graphic

EXTRAS

Key Decadal Drivers in Understanding Mars Evolution

Building new worlds

Planetary Habitats

Solar System Workings

TABLE S.1 Crosscutting Science Themes, Key Questions, and the Missions in the Recommended Plan That Address Them

Crosscutting Science Theme	Priority Questions	Missions
Building new worlds	1. What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated?	Comet Surface Sample Return, Trojan Tour and Rendezvous, Discovery missions
	2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?	Jupiter Europa Orbiter, Uranus Orbiter and Probe, Trojan Tour and Rendezvous, Io Observer, Saturn Probe, Enceladus Orbiter
	3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?	Mars Sample Return, Venus In Situ Explorer, Lunar Geophysical Network, Lunar South Pole-Aitken Basin Sample Return, Trojan Tour and Rendezvous, Comet Surface Sample Return, Venus Climate Mission, Discovery missions
Planetary habitats	4. What were the primordial sources of organic matter, and where does organic synthesis continue today?	Mars Sample Return, Jupiter Europa Orbiter, Uranus Orbiter and Probe, Trojan Tour and Rendezvous, Comet Surface Sample Return, Enceladus Orbiter, Discovery missions
	5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?	Mars Sample Return, Venus In Situ Explorer, Venus Climate Mission, Discovery missions
	6. Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?	Mars Sample Return, Jupiter Europa Orbiter, Enceladus Orbiter, Discovery missions
Workings of solar systems	7. How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?	Jupiter Europa Orbiter, Uranus Orbiter and Probe, Saturn Probe
	8. What solar system bodies endanger Earth's biosphere, and what mechanisms shield it?	Comet Surface Sample Return, Discovery missions
	9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?	Mars Sample Return, Jupiter Europa Orbiter, Uranus Orbiter and Probe, Venus In Situ Explorer, Saturn Probe, Venus Climate Mission, Discovery missions
	10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?	All recommended missions

Key Decadal Drivers in Understanding Mars Evolution

Building new worlds

Accretion, differentiation
Atmospheric evolution
Bombardment by projectiles

3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

Planetary Habitats

Organic matter sources

4. What were the primordial sources of organic matter, and where does organic synthesis continue today?

Habitable environments

5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?

Habitable environments

6. Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?

Solar System Workings

Controls on planetary climate

9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?

Accretionary material, impact rate, solar luminosity

10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?

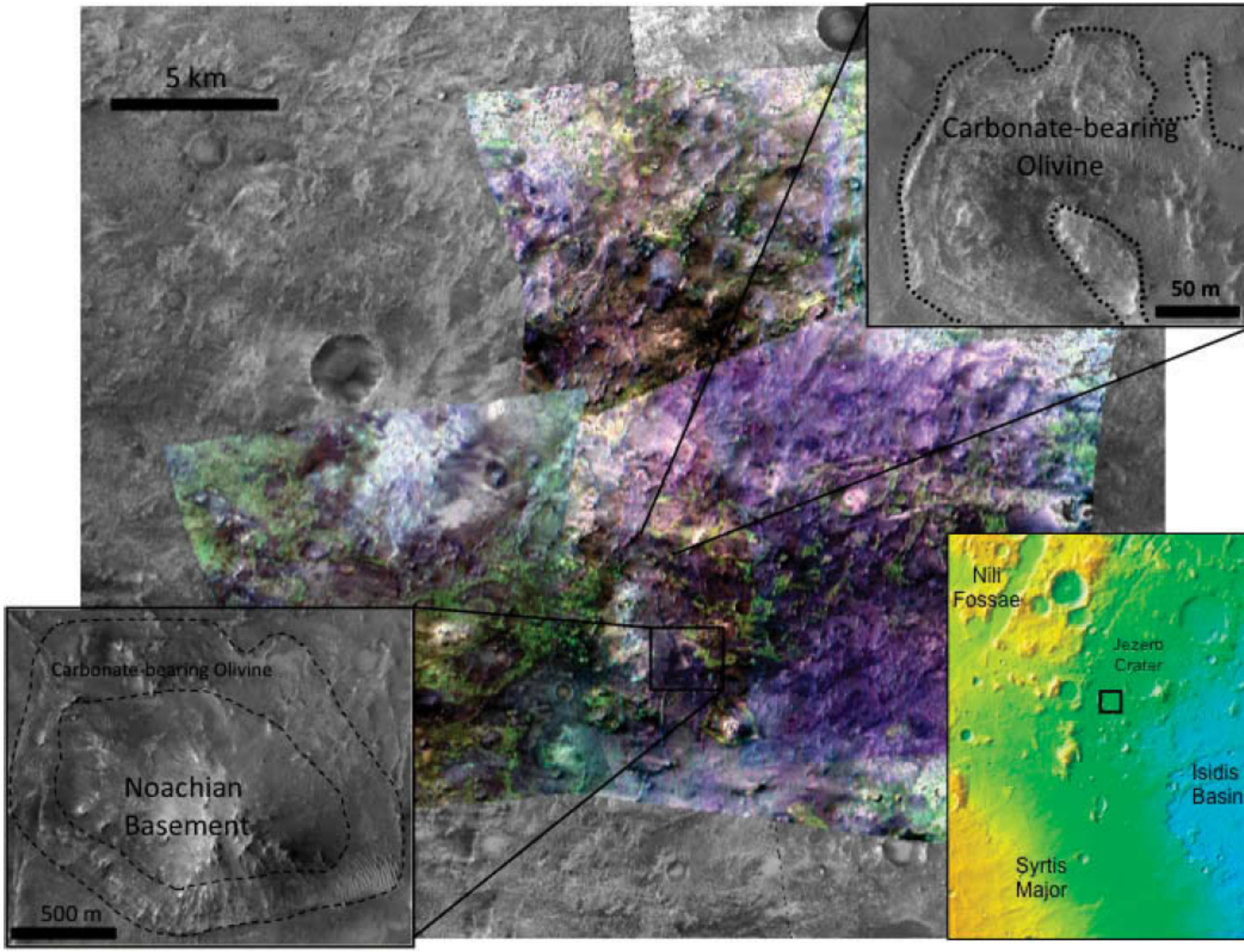


FIGURE 6.3 Diverse mineralogy, observed with Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data, formed by water-related processes and indicative of potentially habitable environments. SOURCE: B.L. Ehlmann and J.F. Mustard, Stratigraphy of the Nili Fossae and the Jezero Crater Watershed: A Reference Section for the Martian Clay Cycle, presentation at the First International Conference on Mars Sedimentology and Stratigraphy, April 19-21, 2010, El Paso, Texas, #6064, Lunar and Planetary Science Conference 2010. Lunar and Planetary Institute.

What is Decadal Level Science?

Not defined by mission technical specs but by science

chemistry and composition, and the geology of prospective landing sites.

- *Mars Astrobiology Explorer-Cacher (MAX-C)*—This mission is the first of the three components of the Mars Sample Return campaign. It is responsible for characterizing a landing site selected for high science potential, and for collecting, documenting, and packaging samples for return to Earth.
- *Uranus Orbiter and Probe*—This mission's spacecraft would deploy a small probe into the atmosphere

Mars Astrobiology Explorer-Cacher

The MAX-C, the sample-collection rover, would be landed using a duplicate of the Sky Crane EDL system. The baseline design is a MER-class (~350 kg), solar-powered rover with about 20 km of mobility over a 500-sol mission lifetime. It will carry approximately 35 kg of payload for sample collection, handling, and caching, and a MER-class (~25 kg) suite of mast- and arm-mounted remote sensing and contact instruments to select the samples. The key new development will be the sample-coring, sample-collection, and sample-caching system.

- Key Questions for Mars Exploration

  - What are the nature, ages, and origin of the diverse suite of geologic units and aqueous environments evident from orbital and landed data, and were any of them habitable?
  - How, when, and why did environments vary through Mars history, and did any of them host life or its precursors?
  - What are the inventory and dynamics of carbon compounds and trace gases in the atmosphere and surface, and what are the processes that govern their origin, evolution, and fate?
  - What is the present climate and how has it evolved on timescales of 10 million years, 100 million years, and 1 billion years?
  - What are the internal structure and dynamics, and how have these evolved over time?

habitable conditions and life.

Building on the work of MEPAG, the committee has established three high-priority science goals for the exploration of Mars in the coming decade:

- *Determine if life ever arose on Mars*—Does life exist, or did it exist, elsewhere in the universe? This is perhaps one of the most compelling questions in science, and Mars is the most promising and accessible place to begin the search. If answered affirmatively, it will be important to know where and for how long life evolved, and how the development of life relates to the planet's evolution.
- *Understand the processes and history of climate*—Climate and atmospheric studies remain a major objective of Mars exploration. They are key to understanding how the planet may have been suited for life and how

major parts of the surface have been shaped. In addition, studying the atmosphere of Mars and the evolution of its climate at various timescales is directly relevant to our understanding of the past, present, and future climate of Earth. Finally, characterizing the environment of Mars is also necessary for the safe implementation of future robotic and human spacecraft missions.
- *Determine the evolution of the surface and interior*—Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as to providing context for the history and processes of Earth. Geological and geophysical investigations will shed light on critical environmental aspects such as heat flow, loss of a global magnetic field, pathways of water-rock interaction, and sources and cycling of volatiles including water and carbon species (e.g., carbon dioxide and hydrocarbons). In contrast to Earth, Mars appears to have a rich and accessible geologic record of the igneous, sedimentary, and cratering processes that occurred during the early history of the solar system. Geophysical measurements of Mars's interior structure and heat flow, together with detailed mineralogic, elemental, and isotopic data from a diverse suite of martian geologic samples, are essential for determining the chemical and physical processes that have operated through time on this evolving, Earth-like planet.

Technical Implementation and Feasibility

A three-element, step-by-step sample return campaign would reduce scientific, technical, and cost risks. It would build on technologies developed over the past decade of Mars exploration, although major technical challenges remain that must be addressed in a technology development effort that would be an integral part of the sample return campaign.

The proposed strategy would conduct sample return as a campaign with three separate steps:

1. A caching rover, the Mars Astrobiology Explorer-Cacher (MAX-C), followed by—
2. A Mars Sample Return Lander (MSR-L) that would include a rover to fetch the sample cache and an ascent vehicle to loft the cache into orbit for—
3. Rendezvous and return by a Mars Sample Return Orbiter (MSR-O).

This campaign would be scientifically robust, with the flexibility to return to a previously visited site (e.g., if motivated by an MSL discovery), to go to a new site, or to fly a second MAX-C rover if the first mission was unsuccessful for any reason. It would also be technically and programmatically robust, with a modular approach and multiple caches left on the surface by MAX-C to recover from a failure of either the MSR-L or MSR-O elements without requiring a reflight of MAX-C.

What

• Quote

Some important questions concerning whether life is or was present on Mars and the characterization of carbon cycling and prebiotic chemistry in a geochemical context include the following:

- Can evidence of past (or present) life in the form of organic compounds, aqueous minerals, cellular morphologies, biosedimentary structures, or patterns of elemental and mineralogic abundance be found at sites that have been carefully selected for high habitability and preservation potential?
- Do habitable environments exist today that may be identified by atmospheric gases, exhumed subsurface materials, or geophysical observations of the subsurface? Does life exist today, as evidenced by biosignatures, atmospheric gases, or other indicators of extant metabolism?

Future Directions for Investigations and Measurements

To address the key questions concerning life listed above, there must be a broad range of mineralogic, elemental, isotopic, and textural measurements of a diverse suite of martian rocks from well-characterized sites that have high potential for habitability. Deposits formed by aqueous sedimentation, hydrothermal activity, or aqueous alteration are important targets in the search for life. These deposits typically contain assemblages of materials that indicate geological (and, possibly, biological) processes. Accordingly, a *sample suite* is defined as the set of samples required to determine the key processes that formed these samples and, in turn, required to assess any evidence of habitable environments or life. Many of the specific investigations and measurements overlap with those necessary to determine the geologic context and to understand the potential for habitability described earlier,

Important Questions

Some important questions concerning Mars's ancient climate and climate processes include the following:

- What was the nature of the early martian climate? Were the conditions suitable for liquid water episodic or stable on longer timescales? What processes enabled such conditions?
- How and why did the atmosphere evolve? Which processes did and still do control the escape and the outgassing of the atmosphere?

Future Directions for Investigations and Measurements

Major progress in understanding the ancient martian climate can come from determining the rates of escape and outgassing of key species from the martian atmosphere, their variability, and the processes at work. It will also be crucial to investigate the physical and chemical record constraining past climates, particularly regarding the polar layered deposits.[78] In order to follow up on scientific results and discoveries from the Phoenix and Mars Reconnaissance Orbiter missions, an in situ analysis of laterally or vertically resolved measurements of grain size, dust content, composition, thickness and extent of layers, elemental and isotopic ratios relevant to age (e.g., deuterium/hydrogen) and astrobiology (CHNOPS) should be performed.

Important Questions

Some important questions concerning the nature and evolution of the geologic processes that have created and modified the martian crust over time include the following:

- How, when, and why did environments vary through Mars's history, and were these environments habitable? What was the origin and nature of the diverse sedimentary units and inferred aqueous environments, what