Multiple Habitable Environments across the Noachian-Hesperian Environmental Transition: Phyllosilicates, Carbonate, Sulfates, and Multiple Igneous Units in Stratigraphy at the Isidis-Syrtis Major Contact

Compelling Mars and Astrobiology Land-on Science

- Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  - early crustal: creation or distribution by impact? Phyllosilicate formation
  - carbonate/serpentine: surface alteration or hydrothermal?
  - layered phyllosilicates (Al- over Fe/Mg)
  - sedimentary sulfate formation
- A record of aqueous low-T geochemistry preserved in-situ, in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting well-suited for the M2020 measurements and caching
- Key stratigraphies from Noachian and Hesperian eras
- Hydrothermal, pedogenic and sedimentary environments
- Multiple igneous units of distinct age
# How NE Syrtis Meets Mars-2020 Site Selection Criteria

<table>
<thead>
<tr>
<th>Obj. A</th>
<th>1. Geologic setting and history of the landing site can be characterized and understood w/ orbital and in-situ obs.</th>
<th>-clear timing constraints (EN to EH -multiple well-ordered strat. Units, delineated with orbital composition and morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obj. B</td>
<td>2a. Landing site w/ <strong>ancient habitable enviro.</strong></td>
<td>-carbonate formation by neutral alk waters (HT or weath.)+ Deep biosphere</td>
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<tr>
<td></td>
<td>2b. <strong>Rocks with high biosignature preservation potential</strong> are available and <strong>are accessible</strong> to rover instr. astriobio. investigation.</td>
<td>&quot;Phyllosilicate Deep Biosphere&quot; &quot;Sulfate Sediments&quot; &quot;Carbonate/Partially Serpentinized: Deep Biosphere&quot;</td>
</tr>
<tr>
<td>Obj. C</td>
<td>3a. Offers <strong>abundance, diversity, and quality of samples suitable for addressing key astrobio. questions if/when they are returned to Earth.</strong></td>
<td>-yes: Carbonate, mineralized fracture zones, sulfate deposits, phyllosilicate-bearing basement as window to deep biosphere</td>
</tr>
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<td></td>
<td>3b. Offers <strong>abundance, diversity, and quality of samples for addressing key planetary evolution questions</strong> if/when they are returned to Earth.</td>
<td>-planetary formation and evolution, basin forming processes, hydration and crustal alteration, two dateable surfaces in extended mission, Noachian volcanism and putonism.</td>
</tr>
</tbody>
</table>
Isidis Basin
Early/Mid Noachian
(~3.96 Ga, Werner, 2005)

Syrtis Major
Early Hesperian

Nilli Fossae graben

Jezero Crater

NE Syrtis Landing Ellipse

Isidis Basin
Early/Mid Noachian
(~3.96 Ga, Werner, 2005)
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Syrtis Major
Early Hesperian

Nilli Fossae graben

Jezero Crater
NE Syrtis Landing Ellipse

Value
High : 4375
Low : -5846
Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian.
Well Understood, Time-Ordered Stratigraphy


Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian
<table>
<thead>
<tr>
<th>Major Hypotheses to be Tested</th>
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<td><strong>Olivine-bearing regional unit</strong></td>
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<td>• Ultramafic <em>volcanic</em> emplaced post-Isidis</td>
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<td><strong>Olivine-Magnesite Mineral Assemblage</strong></td>
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<td>• Near-surface weathering</td>
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<td>• <strong>Serpentinizing hydrothermal systems</strong></td>
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<td>• Aqueous alteration in a metamorphic setting</td>
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<td>• Sedimentary/lacustrine deposits within ultramafic catchments</td>
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<td><strong>Megabreccia with phyllosilicate and unaltered igneous outcrops</strong></td>
</tr>
<tr>
<td>• Altered with phyllosilicate: Low-T subsurface vs buried sediments</td>
</tr>
<tr>
<td>• Unaltered (igneous)</td>
</tr>
<tr>
<td>• Remnants of Mars primary crust</td>
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<tr>
<td>• Noachian-aged low-Ca pyroxene lavas</td>
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<td><strong>Layered kaolinite-bearing capping stratigraphy:</strong></td>
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<td>• Extensive leaching during a period of vertically integrated water cycle</td>
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<td>• Acid leaching and snow melt</td>
</tr>
<tr>
<td><strong>Erosionally resistant ridges</strong></td>
</tr>
<tr>
<td>• Fracture zones mineralized with <em>hydrothermal precipitates</em></td>
</tr>
<tr>
<td>• Breccia Dikes</td>
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<tr>
<td><strong>Hesperian-aged Sulfate stratigraphy</strong></td>
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<tr>
<td>• Sedimentary deposition</td>
</tr>
<tr>
<td>• Alteration of basalt and Box-work structures with jarosite:</td>
</tr>
<tr>
<td>• Exiting vs. infiltrating acid waters</td>
</tr>
<tr>
<td><strong>Syrtis Major Hesperian volcanics</strong></td>
</tr>
<tr>
<td>• <strong>Calibration of crater chronology</strong>, testing the formation mechanism (chemistry and mineralogy), validating remote sensing</td>
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</table>
16 x 14 Ellipse on CTX DEM
Mapping Northeast Syrtis Major
Major Hypotheses to be Tested

Jezero Crater

Syrtis Major
Regional Stratigraphy provides the context for in-ellipse and go-to science

Morphgeologic mapping establishes the local stratigraphy tied to the regional stratigraphy

Ehlmann and Mustard GRL 2013
Noachian Crust: Megabreccia
Noachian Crust: No samples...yet*

- Megabreccia uplifted and exposed by the Isidis Basin Forming event
  - Tap into Noachian rocks from the era of phyllosilicate formation:
  - Access to samples relevant to the deep biosphere:
  - Ancient, crystalline igneous crust:
  - Sample low-Ca pyroxene rich and other crystalline igneous rocks to constrain early crustal processes (Elkins-Tanton et al., 2005; 2012; Baratoux et al., 2011; Grott et al., 2013)

- Sample materials from the period during which Mars likely had
  - Magnetic field (Acuna et al., 1999),
  - Thicker atmosphere with different isotopic composition (Jakosky & Jones, 1997),
  - Pre-/during-the late heavy bombardment

- Highly relevant to the question "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 impact play?"
Noachian Basement: In Ellipse Megabreccia

Hydrothermal (<100°C) surface
Hydrothermal (<100°C) subsurface
Widespread ridges in the Noachian crustal unit, 10s m wide, 100s m long

Morphology and Orientation of over 4000 Ridges suggest mineralized fracture zones

NE-SW orientation: Hydrothermal circulation in response to Isidis Impact?

Stratigraphically post-Isidis/pre-olivine/carbonate

Saper and Mustard (GRL, 2013)
Noachian Basement: In Ellipse Ridges
Mesa Package Stratigraphy

Topographic Profile from CTX DEM
Mesa Forming Package

- Regional unit with three members
  - Crater retaining upper unit
  - Middle boulder shedding and slope forming unit
  - Lower unit that is banded, olivine bearing with variable carbonate
- Stratigraphically rests on basement of megabreccia and phyllosilicate
- Connected to many long, linear features with raised ridge borders, interiors of olivine-carbonate bearing materials
- Hypotheses:
  - Volcanic (Hamilton and Christensen, 2005; Tornabene et al., 2008)
    - Differentiated thick lavas
    - Sequence of volcanic flows from evolving source
  - Differentiated impact melt (Mustard et al., 2007; 2009)
- Olivine-bearing unit is a time-stratigraphic dateable unit!
Spectroscopy/Mineralogy

- Olivine-rich basaltic composition (Mustard et al., 2007; Edwards and Ehlmann 2015)
- Partially carbonated (Ehlmann and Mustard, 2012)
- Broad 1-1.6 µm absorption
- Paired 2.3 and 2.5 µm band indicative of carbonate
- 1.9 µm band of variable strength
- No 1.4 µm band
- Variable presence of a 2.38-2.39 band
  - Mixing with Fe-Mg phyllosilicate (Ehlmann et al., 2008, 2009)
  - Mixing with Talc (Viviano et al., 2013)
Spectroscopy/Mineralogy

- Capping and Middle units show weak mafic igneous absorptions near 1 and 2 µm
- Consistent with pyroxene and olivine, as modeled by Edwards and Ehlmann 2015
- Capping and Middle units distinguished by morphology and texture
Carbonation of olivine-rich rocks

Hypotheses

1) Water-rock interaction in the shallow subsurface at slightly elevated temperatures altered olivine to Mg-carbonate

2) Olivine-rich material, heated by impact or volcanic processes, emplaced on top of a water-bearing phyllosilicate rich unit initiated hydrothermal alteration along the contact

3) Olivine-rich rocks were weathered to carbonate at surface (cold) temperatures in a manner similar to olivine weathering of meteorites in Antarctica

4) Carbonate precipitated from shallow ephemeral lakes

5) Extended period of heat and water with burial leading to olivine-serpentine-talc-chlorite alteration pathway with carbonate from carbonation of serpentine (Brown et al., 2010; Viviano et al., 2013)

Unit of high value for environmental and astrobiological significance
Carbonation of Olivine

\[ Mg_2SiO_4 + 2H_2O + 2CO_2 \rightarrow 2MgCO_3 + H_4SiO_4 \]

- Multiple reaction pathways with different intermediate products (e.g. talc, serpentine) depending on diverse environmental constraints
- The direct pathway, observed in Oman, is energetically favorable and consistent with the geologic observations
- Carbonation of olivine is enhanced by multicomponent basalt (Sissman et al., 2014)
- Significant liberation of SiO₂: what is its fate?
- Assemblages, texture and context critical input to hypothesis testing

Power et al. (2013) DOI: 10.2113/gselements.9.2.115
Mesa Package Stratigraphy

Topographic Profile from CTX DEM
Fe/Mg smectite cap

(Analog: soil formation under intermittently wet conditions, Hawaii, Italy)

Kaolinite-smectite alteration occurs where precursor rock is not olivine-rich (pyx, Fe/Mg smectite)
Bonus, Out of Ellipse Science

- Significant Sulfate Deposits
- Syrtis Major Lavas
- Layered Sedimentary Units

Syrtis Major lavas

layered sulfates
beneath dusty mantle

HiRISE Stereo DEMs
PSP_009217_1975 - ESP_027625_1975
View to the northwest
2x vertical exaggeration

Olivine carbonate
Fe/Mg smectites
Layered sulfates preserved beneath Syrtis Major flow margin
5. Differential erosion

Layered sulfates are preserved only where protected

Within mineralized boxwork fractures
Layered sulfate chronology

1. Deposition as flat-lying sediments
2. Burial by lava (± other sediments)
3. Diagenesis and volume-loss fracturing
4. Fluid mineralization along fractures
5. Differential erosion
Stratigraphy of Nili Fossae/NE Syrtis record multiple aqueous environments from the Middle Noachian to Early Hesperian.
Conclusions

• Target-rich in ellipse science; go-to science traverses Noachian to Hesperian
• Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  – early crustal: creation or distribution by impact
  – carbonate/serpentine: surface alteration or hydrothermal?
  – layered phyllosilicates (Al over Fe/Mg): from leaching with surface hydrology?
  – (sedimentary?) acid sulfate formation
• A record of aqueous geochemistry preserved in-situ, in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting well-suited for the M2020 instrument suite
• Key stratigraphies, dateable from Noachian to Hesperian eras: does this capture Mars global environmental change?
Compelling Mars and Astrobiology Science

- Bedrock strata in-situ representing four distinct environments of aqueous alteration where reactants and products are together
  - early crustal: creation or distribution by impact? Phyllosilicate formation
  - carbonate/serpentine: surface alteration or hydrothermal?
  - layered phyllosilicates (Al over Fe/Mg)
  - sedimentary sulfate formation

- A record of aqueous low-T geochemistry preserved in mineral-bearing strata, distinct in age, primary mineralogy, and geologic setting

- Well-suited for the M2020 measurements and caching

- Key stratigraphies from Noachian and Hesperian eras

- Hydrothermal, pedogenic and sedimentary environments

- Multiple igneous units of distinct age
## Mars 2020 Rubric

### Mars 2020 Mission and Decadal Priority Science Factors

<table>
<thead>
<tr>
<th>Environmental Setting for Biosignature Preservation and Taphonomy of Organics</th>
<th>Type 1A &amp; 1B Samples: Aqueous Geochemical Environments indicated by Mineral Assemblages</th>
<th>Type 2 Samples: Igneous</th>
<th>Context: Martian History Sampled, Timing Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltaic or Lacustrine (perennial)</td>
<td>Crustal phyllosilicates</td>
<td>Igneous unit (e.g., lava flow, pyroclastic, intrusive)</td>
<td>Pre- or Early-Neobatholithic Megabreccia</td>
</tr>
<tr>
<td>Lacustrine (evaporitic)</td>
<td>Sedimentary clays</td>
<td>2nd Igneous unit</td>
<td>Oldest stratigraphic constraint</td>
</tr>
<tr>
<td>Hydrothermal (110°C) surface</td>
<td>Al clays in stratigraphy</td>
<td>Youngest stratigraphic constraint</td>
<td>Stratigraphy of units well-defined</td>
</tr>
<tr>
<td>Hydrothermal (110°C) subsurface</td>
<td>Carbonate units</td>
<td>Dateable surface, volcanic (unmodified crater SFD)</td>
<td></td>
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<tr>
<td>Pedogenic</td>
<td>Sulfate sediments</td>
<td></td>
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<tr>
<td>Fluvial/Alluvial</td>
<td>Acid sulfate units</td>
<td></td>
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<tr>
<td>No diagenetic overprinting</td>
<td>Silica deposits</td>
<td></td>
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<tr>
<td>Recent exposure</td>
<td>Ferric Ox/-Peroxous clays</td>
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### Landing Site Factor

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<tr>
<th>NE SYRTIS</th>
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- **Saper and Mustard, 2013**
- **Mangold et al., 2008; Fassett et al., 2009; Skok et al., 2013**
- **Mustard, 2007; 2009, Ehlmann 2009; 2011, Mangold et al., 2007; Viviano 2013, Ehlmann and Mustard, 2011**
- **Mustard, 2007; 2009, Ehlmann 2009; 2011, Mangold et al., 2007; Viviano 2013, Ehlmann and Mustard, 2011; Michalski et al., 2010 +++**
- **Baratoux et al., 2007, 2011; Skok et al., 2010; Heisinger and Head, 2003; Clenet et al., 2013; +++**
- **Mustard et al., 2007; 2009**
Backup And Extras

4 Unprioritized ROI’s
Landing Site and Engineering Constraints

- Target-rich in ellipse science; go-to traverses Noachian to Hesperian
- Key hypotheses addressed in the ellipse with M2020 measurements and caching

<table>
<thead>
<tr>
<th>Center Coordinates</th>
<th>17.84° N 77.15° W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>-2000 m WRT MOLA geoid</td>
</tr>
<tr>
<td>Prime Science and/or Sampling Targets</td>
<td></td>
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<tr>
<td></td>
<td>Olivine-carbonate assemblage</td>
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<td></td>
<td>Isidis (?) megabreccia with phyllosilicate and unaltered igneous outcrops</td>
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<td>Layered kaolinite-bearing capping stratigraphy</td>
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<td>Mineralized fracture zones</td>
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<td>Hesperian-aged Sulfate stratigraphy</td>
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<td></td>
<td>Hesperian Syrtis Major volcanics (lowest priority)</td>
</tr>
<tr>
<td>Distance of Science and/or sampling targets from Ellipse Center</td>
<td></td>
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<tr>
<td></td>
<td>In Ellipse targets are typically 3-5 km from the ellipse center (olivine-carbonate outcrops, megabreccia, mineralized fracture zones, layered stratigraphies)</td>
</tr>
<tr>
<td></td>
<td>Hesperian targets (sulfate stratigraphy and Syrtis volcanics) are outside the ellipse</td>
</tr>
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## Major Hypotheses to be Tested

<table>
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<th>Category</th>
<th>Hypotheses</th>
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| Olivine-bearing regional unit                                 | - Ultramafic volcanic emplaced post-Isidis  
|                                                              | - Ultramafic impact melt from Isidis that tapped the mantle               |
| Olivine-Magnesite Mineral Assemblage                          | - Near-surface weathering                                                  |
|                                                              | - Serpentinizing hydrothermal systems                                       |
|                                                              | - Aqueous alteration in a metamorphic setting                              |
|                                                              | - Sedimentary/lacustrine deposits within ultramafic catchments              |
| kaolinite-bearing capping stratigraphy:                       | - Extensive leaching during a period of vertically integrated water cycle  |
| Erosionally resistant ridges                                  | - Fracture zones mineralized with hydrothermal sediments                   |
|                                                              | - Volcanic dikes                                                           |
|                                                              | - Breccia dikes                                                           |
| Hesperian-aged Sulfate stratigraphy                           | - Deposition as flat lying sediments                                       |
|                                                              | - Extensive dewatering and mineralization of fractures                     |
| Hesperian Syrtis Major volcanics                              | - Calibration of crater chronology, testing the formation mechanism        |
|                                                              | (chemistry and mineralogy), validating remote sensing                     |
| Megabreccia with phyllosilicate and unaltered igneous outcrops | - Phyllosilicate in megabreccia: Low-T, low water/rock ratio alteration in  |
|                                                              |   the shallow crust                                                        |
|                                                              | - Unaltered igneous outcrops                                               |
|                                                              |   - Remnants of Mars primary crust                                         |
|                                                              |   - Noachian-aged low-Ca pyroxene lavas                                   |
### Examples of the Strength of MSL Instrument To Address the Hypotheses

| Olivine-bearing regional unit | Ultramafic volcanic emplaced post-Isidis  
|                              | Ultramafic impact melt from Isidis that tapped the mantle  
|                              | Mastcam-Z  Context geology  
|                              | Supercam: Reconnaissance and close-in major element chemistry LIBS VNIR mineral spectroscopy of ferrous igneous mineralogy to derive olivine Fe/Mg ratios  
|                              | Raman to determine context and close up mineralogy  
|                              | PIXEL: Detailed elemental chemistry among mineral phases to resolve textures  
|                              | SHERLOC: Discriminate detailed mineralogic associations  

| Olivine-Magnesite Mineral Assemblage | Supercam: Context and close-up aqueous mineralogy with VNIR Spectroscopy and RAMAN  
|                                      | PIXEL Detailed mineralogy among minerals to determine assemblages  
|                                      | SHERLOC Discriminate detailed mineralogic associations  

Regional Stratigraphy provides the context for in-ellipse and go-to science
Regions of Interest

- Target rich landing ellipse provides innumerable targets of interest, and we show 4 here

- Easily accomplish 90% of landing site goals in these 3 ROIs
Numbered regions of interest corresponding with subsequent slides.
Region of Interest

#1

- Kaolinite-bearing outcrop
- Smooth plains
- Fe/Mg phyllosilicate basement
- Rounded megabreccia
- Crustal unit
- Crater-retaining cap unit
- Olivine-carbonate mesa basal unit
- Olivine-carbonate-bearing large linear feature
- 200 m

Region of Interest #1
Region of Interest #2

- Crater-retaining cap unit
- Linear features and fractures
- Rounded megabreccia
- Olivine-carbonate mesa basal unit
- Crustal knob
- Raised ridge

200 m scale
Region of Interest

#4
Region of Interest

#4

- Crustal unit
- Raised ridge
- Boulder-shedding slopes without capping unit
- Olivine-carbonate mesa basal unit
- Brecciated filaments
- Megabreccia
- Northern extent of kaolinite-bearing unit

200 m
Region of Interest

#8

200 m
Region of Interest

#6

- **Crustal units**
- **Recessive linear ridge into crustal units with light-toned internal blocks**
- **Light-toned basement breccia blocks**
- **Fracturing (some with light-toned edges)**
- **Banded olivine-carbonate mesa basal unit**
- **Younger crater**
- **Crater-retaining cap unit**

Scale: 200 m
Mapping Northeast Syrtis Major

Legend:
- Ellipse
- Contacts
- Interpreted Contacts

Unit Name:
- Aeolian Cover
- Crater - Young
- Smooth Plains
- Feature-bearing Smooth Slope
- Syrtis Major Volcanics
- Dark-toned Extensive Basal Unit
- Extensive Basal Unit
- Knobby Plains
- Knobby Coherent Unit
- Long Linear Feature
- Smooth-Sloped Mound
- Capping Mesa Unit - Remnants
- Capping Mesa Unit
- Embedded Capping Mesa Unit
- Raised Boxwork Ridges
- Raised Linear Ridges
- Crater - Eroded
- Crustal Unit
- Large Crustal Mound
- Undifferentiated Crustal Mélange
- HiRISE coverage

4 km