100s of Myr of Astrobiology at
Northeast Syrtis Major Mesas

Time-Capsules of Mars from the Pre-Noachian to Hesperian
4 Aqueous Environments, 3 Igneous Lithologies in Stratigraphy to
Explore and Sample

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with many helpful conversations over the years with Jack Mustard, Christopher Edwards, Elena Amador, Daven Quinn, Mike Bramble, Ralph Harvey, Tim Goudge, Sandra Wiseman, Paul Niles, Nicolas Mangold, Deanne Rogers, Tim Glotch, Francois Poulet, Adrian Brown, Christina Viviano-Beck, Scott Murchie, Abigail Fraeman, Renyu Hu, Yuk Yung

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By D. Berry for National Geographic
Northeast Syrtis Major mesas are spatially concentrated time capsules that record the majority of geological processes active on Mars during the Noachian and Hesperian and are special because of the large carbonate deposit.

**Characterize geologic history of astrobiologically relevant site/units**
- **3 distinct, time-ordered formations** (morphic cap, carbonate, basement); one with 3+ subunits (megabreccia basement, massive basement, Al-phyllosilicate weathering horizon) are mappable from orbit for easy rover direction.
- **~250 Myr early Noachian to Hesperian historical record** is the earliest accessible and well-understood in the context of Mars history, bounded by the Isidis impact event and Syrtis Major volcanism (with still older megabreccia).

**Assess habitability/past life in units with high biosignature preservation potential**
- **Regionally extensive carbonates** represent either near-subsurface mineralization of host rock or travertine-like mineral springs precipitation – either has high biosignature preservation potential.
- The Noachian clay basement and breccia blocks within preserve rocks from the time Mars had a magnetic field and thicker atmosphere. Cross-crossing veins point to available water in a continuously habitable environment – the NE Syrtis paleo-aquifer is a good place to search for mineralized life.

**Cache scientifically compelling samples**
- **4 aqueous environments** (early clays, early carbonates, weathering horizons, go-to sulfate sediments) have distinct astrobio. potential, record of atm. evolution, volatile sequestration for traditional, clumped isotopes.
- **4 age-date pins** for Martian chronology (1) Isidis-formed melt within Noachian basement, (2) regional olivine-rich unit, (3) dark-toned mafic cap rock, (4) Syrtis lava front (go-to).
- **3 lithologies** record Igneous evolutionary history from Pre-Noachian to Early Hesperian, with low-Ca pyroxene, olivine enriched (komatiite-type hot lava or mantle xenolith), high-Ca pyroxene lavas.
Northeastern Syrtis Major Mesas

1. Investigating Multiple Aqueous, Habitable Environments for Biosignatures:
   1. Largest exposure of carbonate-bearing rock on Mars, formed by precipitation from neutral/alkaline liquid water. Here, in place.
   2. Deep aquifers with Fe/Mg-clay mineralization
   3. Weathering zones with Al-clay mineralization
   4. (Go-to) Sulfate-cemented sediments (300+ m thick)

2. Key for Understanding Planetary Evolution
   - **Sources and Sinks of the Martian Atmosphere:** CO₂ sequestration mechanism, isotopic signature; also D/H signature through time
   - **Origin of Water-Bearing Clays, Implications for Early Climate:** Whether thick sequences of Noachian Clays form at the subsurface or surface
   - **Alkaline-Acid Transition (go-to):** Why clays and carbonates early, then sulfates?
   - **Changes in Igneous Processes:** Transition from low-Ca pyroxene to high-Ca pyroxene, hypothesized to result from mantle evolution and the largest, highest Fo# olivines on the planet (see Mustard talk just prior)

Thus, fulfills all the objectives for Mars-2020 in situ exploration and sample return
Why It Is Important to Explore an Ancient Stratigraphy (vs. a frozen geomorphic feature)

- The strata are go deeper into Mars time in the stratigraphies
- The deposits span a much longer time period of Mars history
- A greater diversity of astrobiologically-relevant and igneous environments can be explored and sampled at a single site
  - rather than a collection of grains from a key stratigraphy integrated into a shale, we actually get to examine the petrology of the original strata to figure out its environment of formation
  - tradeoff: more hypotheses to examine and less certainty to exact interpretation based on orbit-spatial (petrology needed)
- Biosignature Strategy: go to long-lived habitats to look for life, go to the interfaces (redox and permeability), find the organics entombed within minerals or chemical/isotopic potential biosignature, collect, return to Earth and confirm (see Day #1 Rock-Hosted Life ppt)
Northeastern Syrtis Major Mesas – 3rd Mars 2020 Landing Site Workshop - 7

Ehlmann et al., 2016, JGR
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To the NE Syrtis Site...
Noachian Terrains

Jezero

NE Syrtis Major Lava Flow Margins

10 km
Syrtis lavas have an Irregular flow margin due to pre-existing topography (now eroded) and possibly lava-ice interactions [Ivanov & Head, 2002, JGR; Skok, this wkshp]
Lavas exploit pre-existing fluvial valleys/channels and are sutured by fluvial valleys/channels pointing to surface processes available over a long period of time, at least episodically [Mangold et al., 2007; 2008; Skok, this wkshp]
Syrtis Major lavas
Syrtis Major lavas

Sulfate-sediments with jarosite-filled boxwork fractures (more later)
Noachian Terrains

Jezero

Syrtis Major

the discovery section (awesome but too steep for landing)
Ehlmann & Mustard, 2012, GRL
Ehlmann & Mustard, 2012, GRL
Distinctive Lithostratigraphic Sequences

- **Nili Basement Formation**: regional in extent. Subunits within are massive, layered, ridged, or megabrecciated. Different subunits have variable Fe/Mg clay, Al-clay, and low Ca-pyx content.
- **Isidis Olivine Formation** is restricted to east of Nili Fossae, variably bears the Mg-carbonate
- **Cap Formation**: Syrtis Major lavas at the south in the go-to area; a Syrtis ash (or lava) unit, apparently contemporaneous and of nearly identical composition, caps the in-ellipse units
Noachian Terrains

Jezero

NE Syrtis Major

Major Lava Flows Margins
Extreme Lack of Dust and Obvious Spectral Diversity/Unit Mapping from Orbit. We can best use our Mastcam-Z and SuperCam VNIR+SWIR for long range outcrop scouting at a place like the mesas of NE Syrtis.
Fe/Mg clay-enriched basement | Al clay-enriched basement | LCP-enriched basement | Mg carbonate/olivine unit
Northeastern Syrtis Major Mesas – 3rd Mars 2020 Landing Site Workshop - 25

100 m

Fe(II)

H₂O

Mg-CO₃

Radiative Transfer Abundance Model results from elsewhere to the north [Edwards & Ehlmann, 2015, Geology]
The Olivine-Carbonate Unit: 
Nature of the Habitable Environment,
Biosignature Search Strategy
Possible Mg-carbonate formation mechanisms

(Möller, 1989 – terrestrial occurrences of economic magnesite)

- Diagenesis of lake/marine beds?
- Precipitate in playas fed by ultramafic catchments?
- Weathering of olivine and serpentine rich bodies?
- Hydrothermal fluids?
- Serpentinization?

For Mg-carbonates on Mars,

(1) Olivine-rich rock and (2) its interaction with water seem to be essential
**Possible Mg-carbonate formation mechanisms**

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Maybe? Some (weak) morph evidence because layered, TI consistent with sediment. But no clear basins (but see Merid.)

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Insights from near NE Syrtis:
Serpentine in the Isidis Olivine (Carbonate) Formation

False color CRISM HRL0000B8C2

south of NE Syrtis ellipse
Ehlmann et al., 2010, GRL;
Ehlmann & Mustard, 2012; GRL

Nili Fossae Carbonate Plains -- 2nd Mars2020 Landing Site Workshop - 30
Interfacing and Fractures at Multiple Scales

serpentine-carbonate-olivine unit
A possible analog

Mg-carbonate

olivine, low Ca pyroxene, serpentine

Samail ophiolite, Oman
A possible analog

Samail ophiolite, Oman

Ca-carbonate

Spring initiates from groundwaters

biomass
Zones of Low-Temperature (15-50°C) Serpenitinization and Tracing the Process through Carbonate Chemistry

*process described further in Barnes & O’Neil, 1969*
*Kelemen & Matter, 2008; Streit et al., 2012 describe Oman deposits*
Fundamental Processes, Carbonates: Key to Past Climate/Habitability

- Understanding atmospheric evolution requires understanding the mechanism, timing, amount and isotopic signature of carbon sequestration
  - NF Carbonates: 0.25-12 mbar
- **In situ exploration**: establish the formation enviro, constrain timing
- **Sample return**: sample the isotopic record, determine precise timing

Hu et al., 2015 “The uncertainty in surface pressure is dominated by the uncertainties in the photochemical and sputtering escape rates, as well as the geological settings of early carbonate formation.”
Biosignature Model:

- Seeking interfaces:
  - Mineralization along fractures within carbonate
  - *Serpentine-carbonate contracts*
  - Zones of groundwater discharge

Recall demonstrated biomarkers in deep serpentine-carbonate assemblages from Lost City crust.

Work underway for the Oman example shown, e.g., Summons group (MIT) and also Templeton (CU-Boulder) and Shock (ASU).
Fe/Mg clay-enriched basement | Al clay-enriched basement | LCP-enriched basement | Mg carbonate/olivine unit
Northeastern Syrtis Major Mesas – 3rd Mars 2020 Landing Site Workshop - 40

10s of pixel local spectra

- H$_2$O
- Fe,Mg-OH (weak)
- metal-OH (weak)
- Al-OH
- carbonate
- low-Ca pyx
The Basement Unit:
Nature of the Habitable Environment,
Biosignature Search Strategy
The Basement Unit: Nature of the Habitable Environment, Biosignature Search Strategy

Pre-/Early Noachian Isidis megabreccia
LCP-enriched massive units
Fe/Mg clay enriched massive units
Fe/Mg clay mineralized fractures
Al clays on Fe/Mg clays

1. Water flow through a deep aquifer

2. Weathering or acid spring waters
[for more see Ehlmann et al., 2009, JGR; Ehlmann & Dundar, LPSC 2015]
What do groundwater basaltic aquifers look like?
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Hraunfossar, Iceland (photo by B. Ehlmann)

Groundwaters emanate from groundwater springs and form sizeable river!
Al clays in soil profiles or zones of fluid flow

Hvalfjorduer, Iceland (photo by B. Ehlmann)

10% hematite, 80% Al-smectite
If waters are acid, Al-clay zones of leaching and redox
Fundamental Processes, “Deep Clay Minerals”: Key to Past Climate/Habitability

- Understanding Noachian climate requires understanding the mechanism, timing, amount and isotopic signature of Fe/Mg phyllosilicates found in deep strata of much of the Noachian

- *In situ exploration*: establish the formation mechanism, constrain timing

- *Sample return*: sample the isotopic record, determine precise timing

Bibring et al., 2015 “If phyllosilicates had formed in the subsurface, the Mars environment might have always been tenuous, cold, and dry, except for transient episodes. If instead phyllosilicates formed at or close to the surface, this would require the Mars early atmosphere to be dense.”
Biosignature Model:

- Seeking interfaces:
  - Mineralization along vesicles, fractures w/in basement
  - Redox interfaces in weathering profiles

Recall demonstrated extant life and demonstrated paleobiosignatures in basalt cores, entombed in clay minerals and Fe/Mn-oxides

Also applicable to impacted, glassy materials
Sedimentary Sulfates (go-to):
Nature of the Habitable Environment,
Biosignature Search Strategy
Isidis Sulfates

Syrtis Major Lavas

Proposed 2020 landing site (May 2020)

Altered Noachian basement and ol-carbonate

Noachian highlands

Sulfates

Isidis
Isidis Sulfates Syrtis Major Lavas Proposed 2020 landing site (May 2020)

Altered Noachian basement and ol-carbonate

Noachian highlands

Isidis

Ehlmann & Mustard, 2012, GRL
Layered sulfates beneath capping lava

Layered sulfates up to 400 m thick beneath Syrtis Major lavas

Unconformable with overriding lavas

Shallow dips in bedding

Small-scale local dip changes show interaction with basement topography [Quinn & Ehlmann, in prep.]
Boxwork polygons: filled volume-loss fractures

Boxwork polygons with lack of preferred orientation and non-vertical dips consistent with volume-loss fracturing, later mineralization by acid-sulfate fluids [Quinn & Ehlmann, in prep.]

Ehlmann & Mustard, 2012, GRL
History of layered sulfates

1. Late Noachian
   - Deposition of sediments *gently draping basement*

2. Early Hesperian
   - Diagenesis and volume-loss fracturing

3. Early Hesperian
   - Erosion to unconformity surface

4. Early Hesperian
   - Burial by Syrtis Major lava flows

5. Early Hesperian
   - Filling of fractures and acid-sulfate alteration *likely associated with lava flow*

6. Amazonian
   - Differential erosion to present

[Quinn & Ehlmann, in prep.]
Fundamental Processes: Mars’ Alkaline-Acid Transition & Biosignature Model

- Understanding Mars history requires understanding why sulfates are more prevalent later
- *In situ exploration*: establish the nature of the units and causes of geochemical change
- *Sample return*: sample the isotopic record, determine precise timing

**Biosignature model:**
- Seeking organics entombed in polyhydrated sulfate sediments
- *Redox interfaces in Fe-redox reactions*
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CTX DEM: 2x vertical exaggeration

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NE Syrtis: Serpentine/Carbonate
Testing the Ocean Hypothesis – PUT EARLY

• Was there an ocean?
• If yes, how the heck does it fit into the global narrative of water on Mars? – major mystery

• How to use the rover to test?
  – Was Jezero a shallow marine basin? How to test with lake?
  – In contrast, can test whether fractured, banded NE Syrtis carbonates
NF Carbonate Plains

Geologic History & Stratigraphy
1. Basement Formation (clays) disrupted by Isidis impact (EN)
2. Isidis Olivine Formation emplaced atop basement (EN/MN)
3. Carbonate Unit Forms (MN/LN)

PROS
- Land On Primary Science*: two ROIs evenly distributed in ellipse for easy access
- Largest carbonate deposit formed by neutral to alkaline waters: key for Martian habitability and atmosph. Evolution
- Clear timing constraints: Early Noachian to Early Hesperian
- Immediate petrology to determine origin of Mars carbonate; measure in situ carbonate precipitates for organics
- Immediate petrology of one of Mars’ key igneous units (olv.rich)
- Multiple igneous units (olivine fm., ash unit in cap fm.)
- Go to regional stratigraphy with Fe/Mg clays and Al clays; use petrology to determine origins
- Datable igneous units for CFD calibration
- Sample Early N. to Early Hesp. isotopic record of enviro change

CONS
- Isotopic, mineralogical, chemical, morphological biosignatures can be present in multiple enviro settings; however, organics preservation potential of carbonate will not be

*IMPORTANT (based on bar conversations): New ellipse needs assessment. Traversability report of the old ellipse should not preclude a vote for this site if you support the science.
Talc-Carbonate from Contact Metamorphism?

Brown et al., 2010, EPSL; Viviano et al., 2013, JGR

- Hypothesis: Intraunit hydrothermal system (10’s meteres circulation)
- Possibly in some locations
- In general, very sharp and concordant morphologic and spectral change between the Isidis Olivine (Carbonate) Formation and Basement Formation suggests an unconformity with a significant hiatus
- Talc is nonunique spectral ID, though permitted
Northeastern Syrtis Major Mesas

- Well-examined with mature data analyses (MGS, Odyssey, Mars Express, MRO…). Much scientific literature characterizing the formations at Nili Fossae-Syrtis Major
  - Download the 30+ papers on the region at ftp://ftp.gps.caltech.edu/pub/ehlmann/mars2020
  - Competing origin theories require *in situ* petrology measurements to decipher
  - Agreement is widespread that these units are significant for understanding geologic processes during Mars’ most habitable era (Noachian) and its