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

Bethany Ehlmann
(California Institute of Technology)

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

3rd Mars 2020 Landing Site Workshop
February 8-10, 2017

By D. Berry for National Geographic

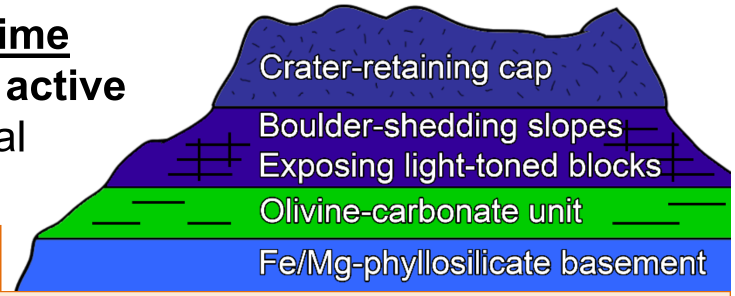
By D. Berry for National Geographic

Northeast Syrtis ROI Science

submitted Dec 2016 to the Mars-2020 project by Mustard/Bramble/Ehlmann

Jet Propulsion Laboratory
California Institute of Technology

Northeast Syrtis Major mesas are <u>spatially concentrated time capsules</u> 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** (mafic cap, carbonate, basement); one w/ 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

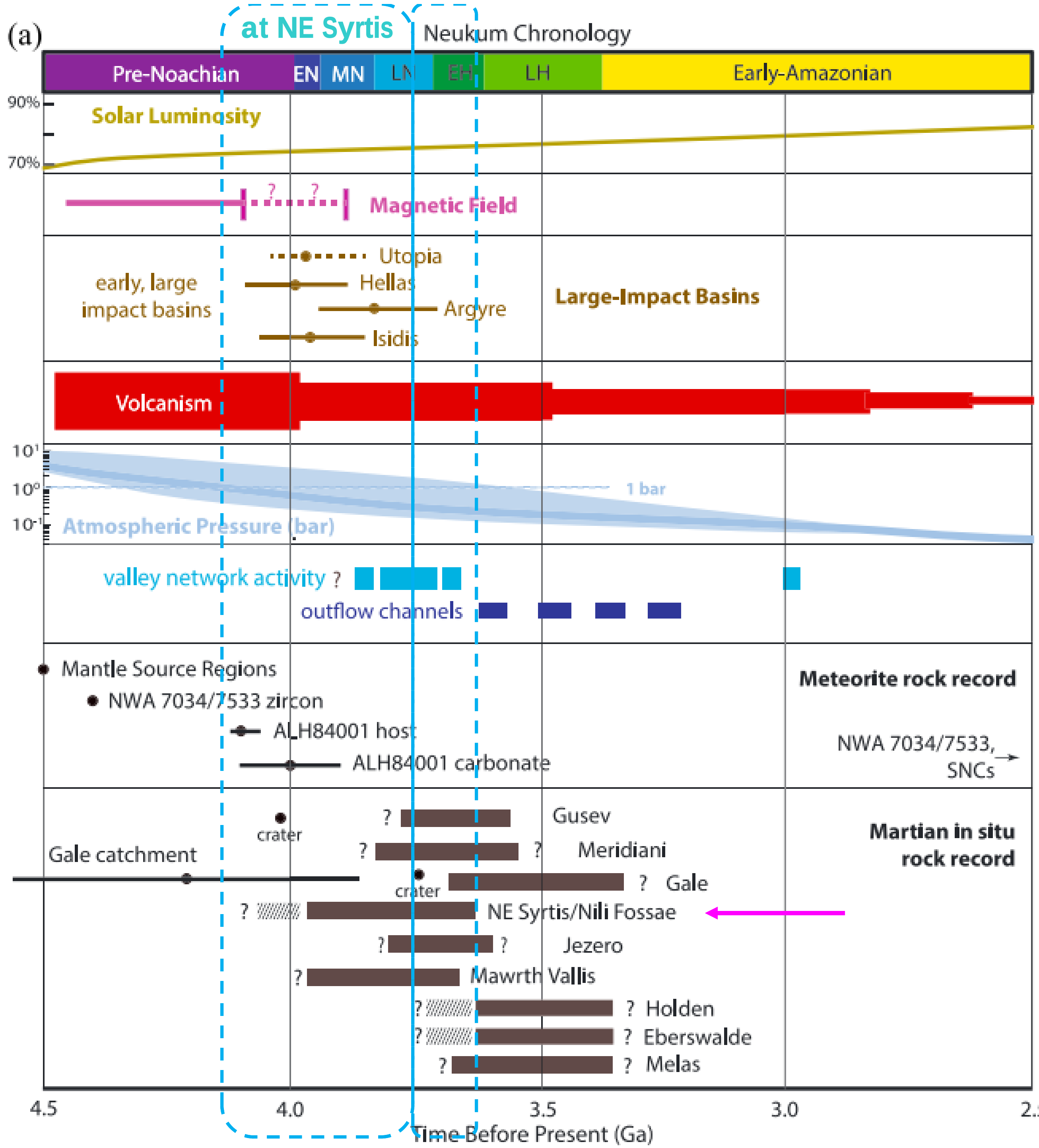
1. **Investigating Multiple Aqueous, Habitable Environments for Biosignatures**:
    1. Largest exposure of carbonate-bearing rock on Mars, formed by precipitation from neutral/alkaline liquid water. Here, in place.
    2. Deep aquifers with Fe/Mg-clay mineralization
    3. Weathering zones with Al-clay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

- **Sources and Sinks of the Martian Atmosphere**: CO_2 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)

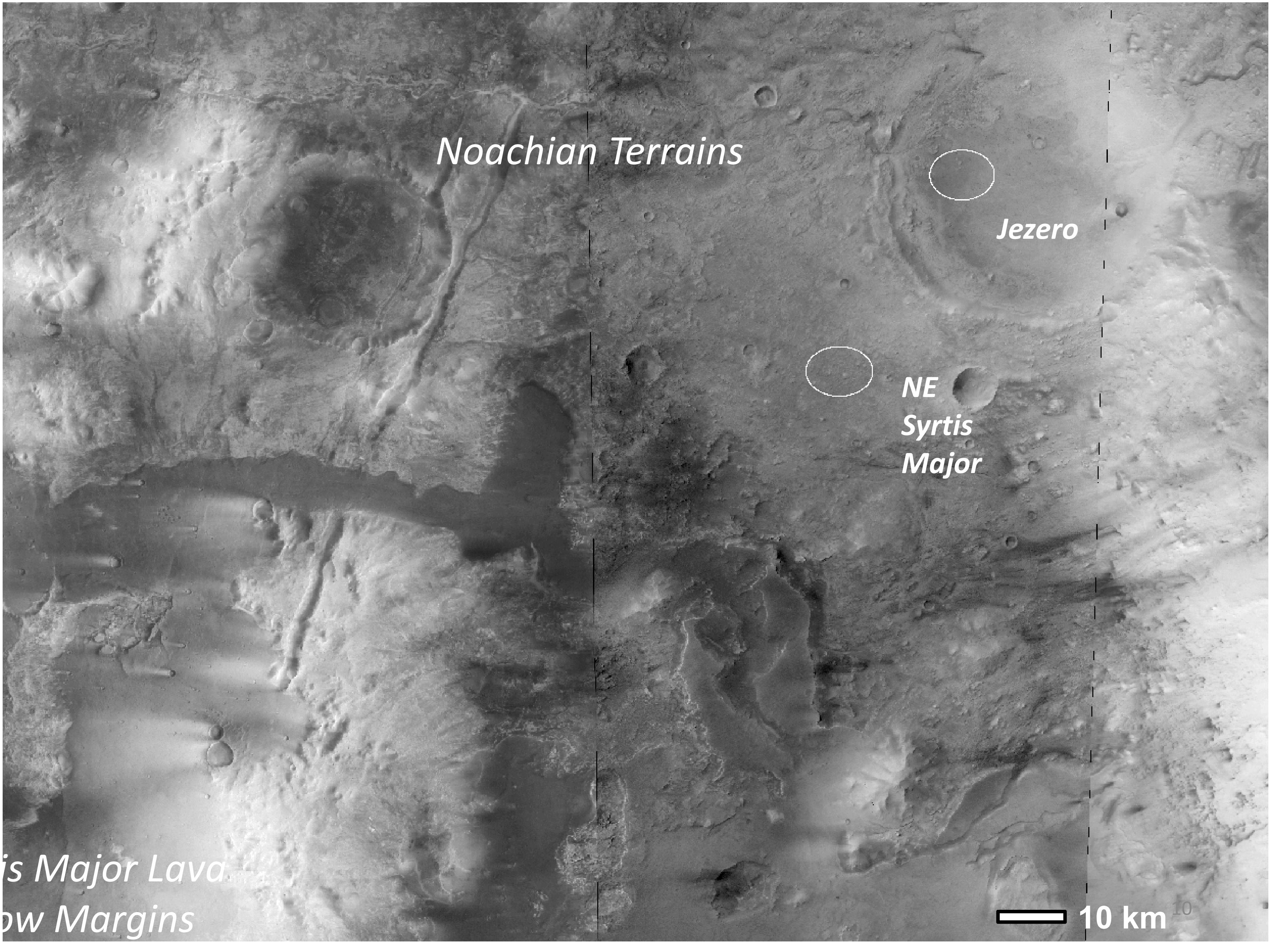


Ehlmann et al, 2016, JGR

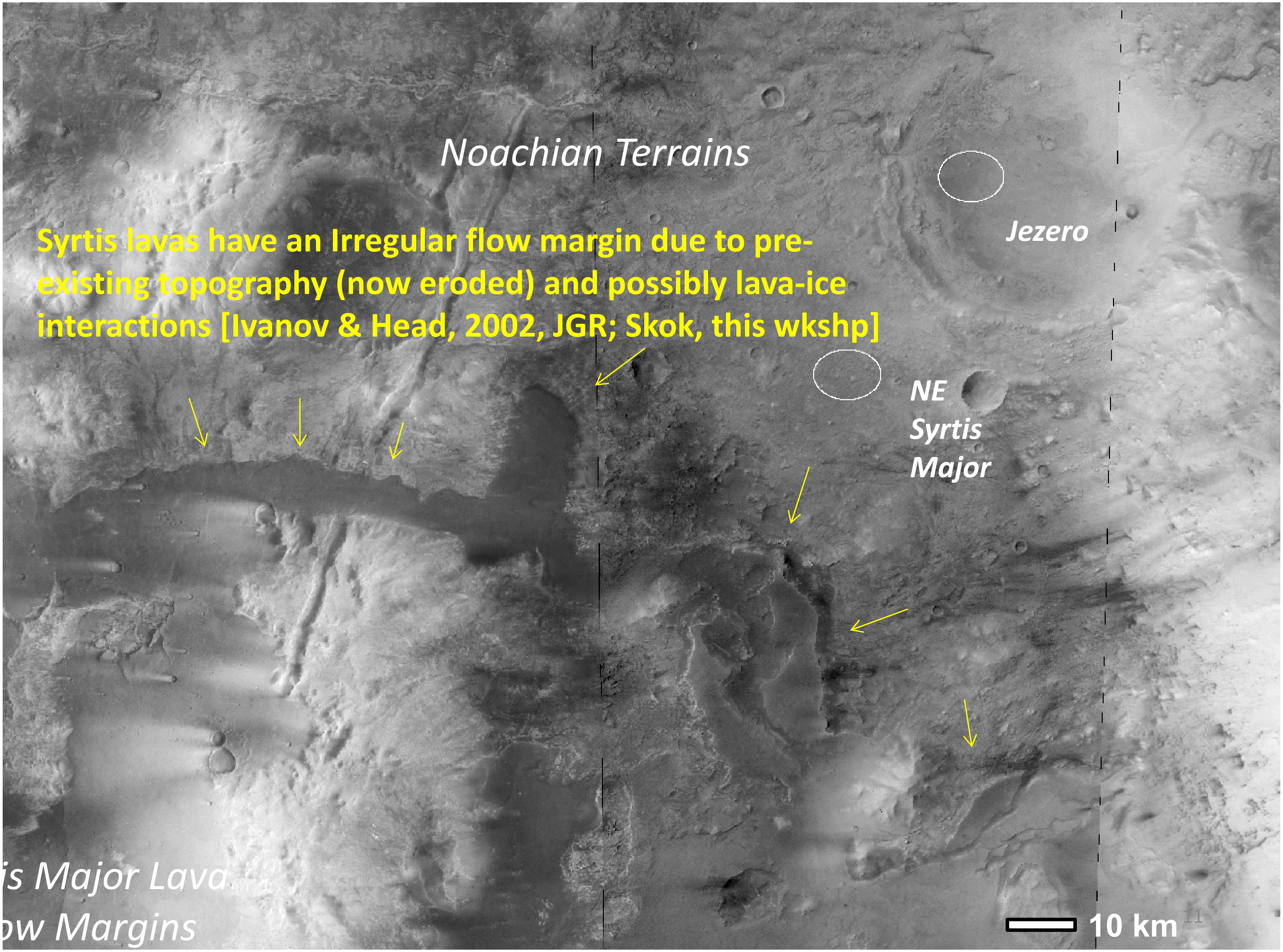
Why It Is Important to Explore an Ancient Stratigraphy (vs. a frozen geomorphic feature)

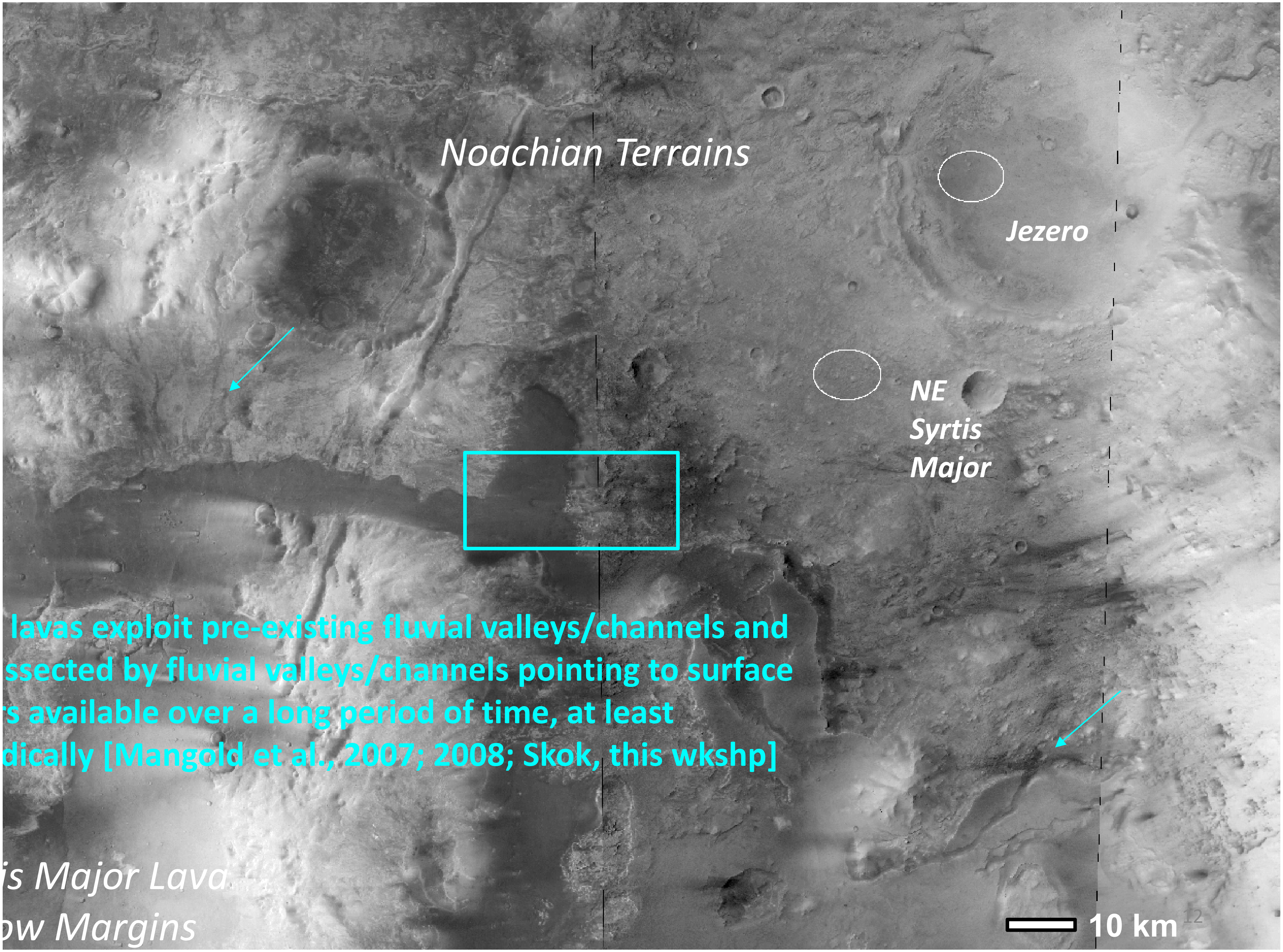
- The strata are go deeper into Mars time in the stratigraphies
- The deposits span a much longer time period of Mars history
- A greater diversity of astrobiologically-relevant and igneous environments can be explored and sampled at a single site
  - rather than a collection of grains from a key stratigraphy 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)

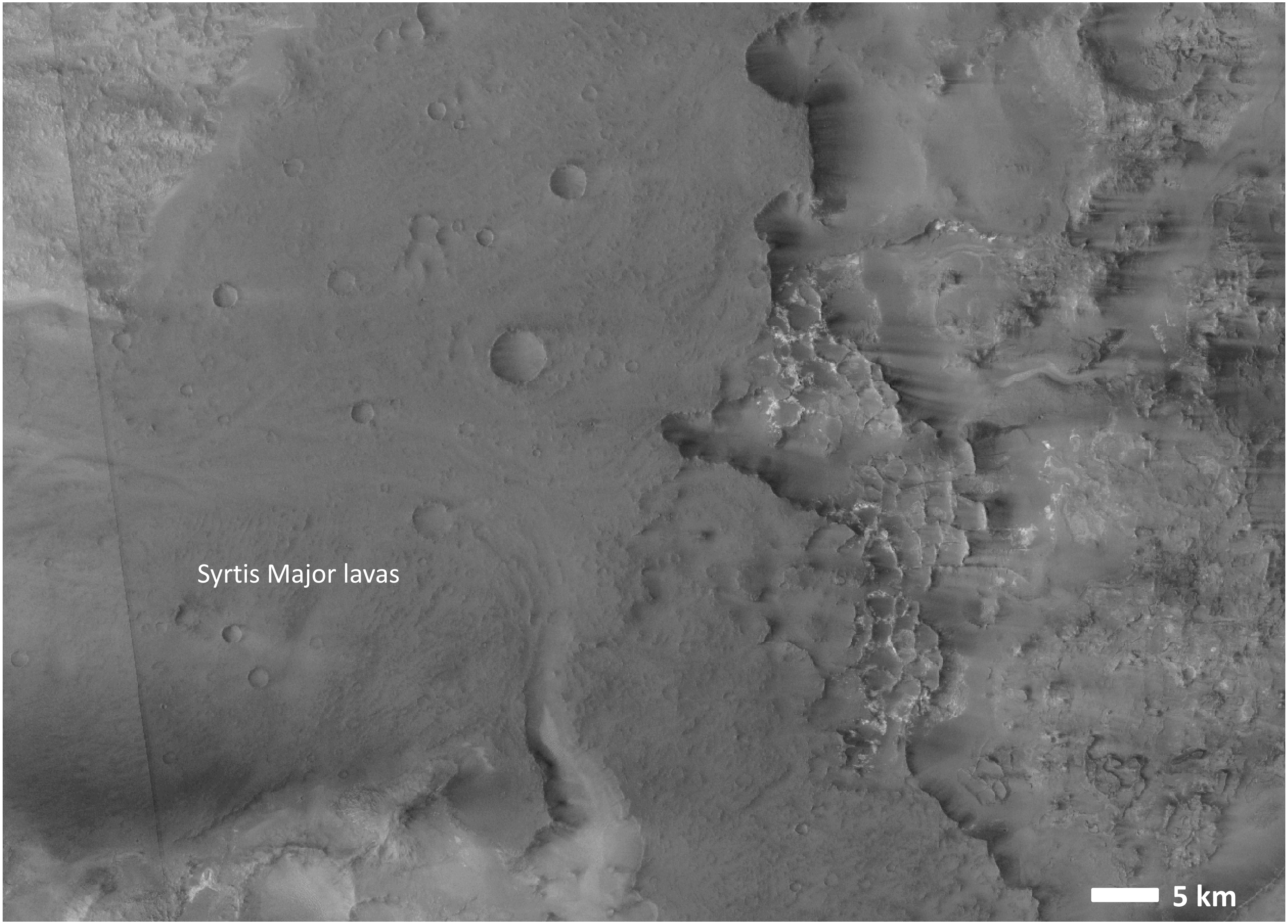
To the NE Syrtis Site…



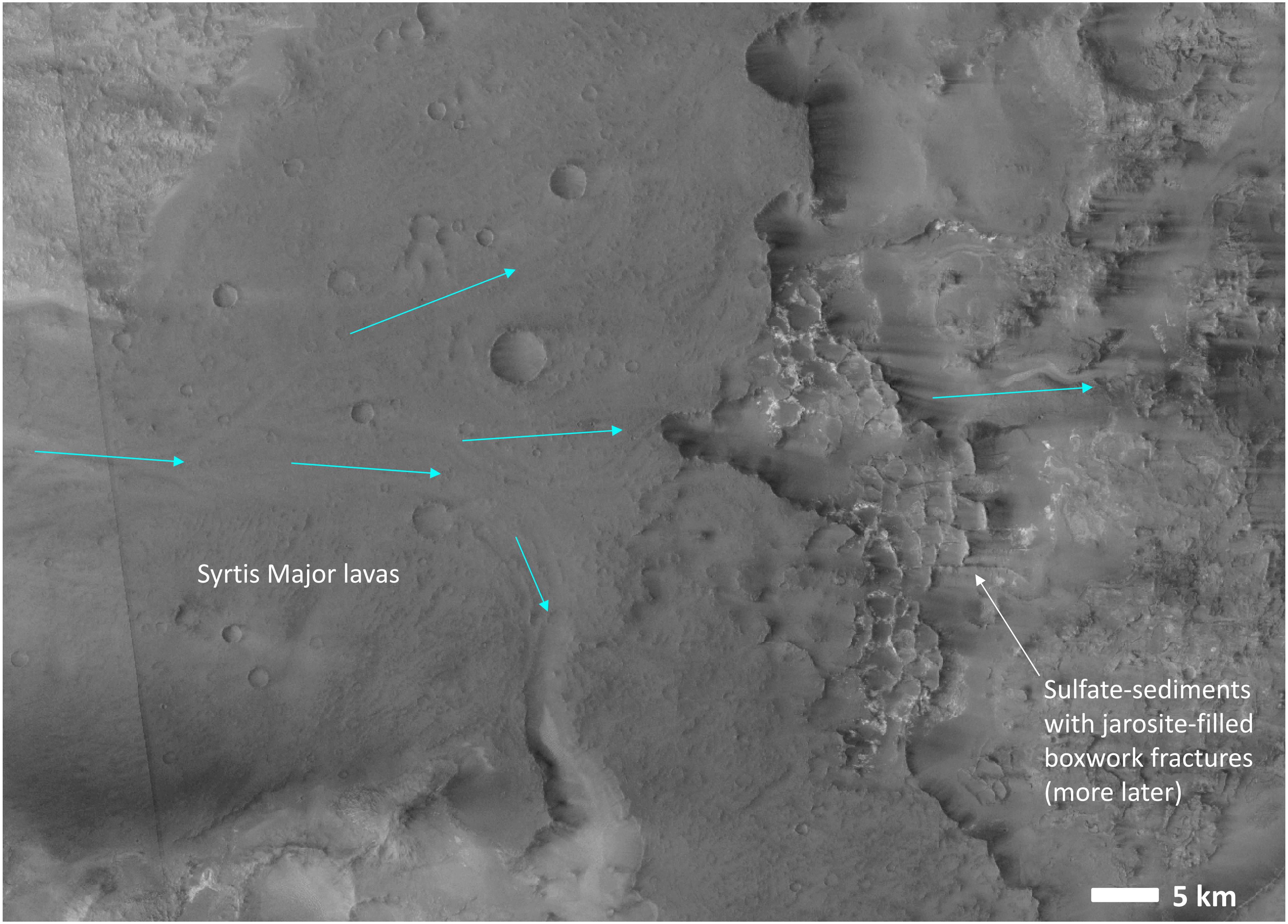
Noachian Terrains
Jezero
NE
Syrtis
Major
is Major Lava
ow Margins
10 km


Noachian Terrains
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]
Jezero
NE Syrtis Major
is Major Lava
ow Margins
10 km

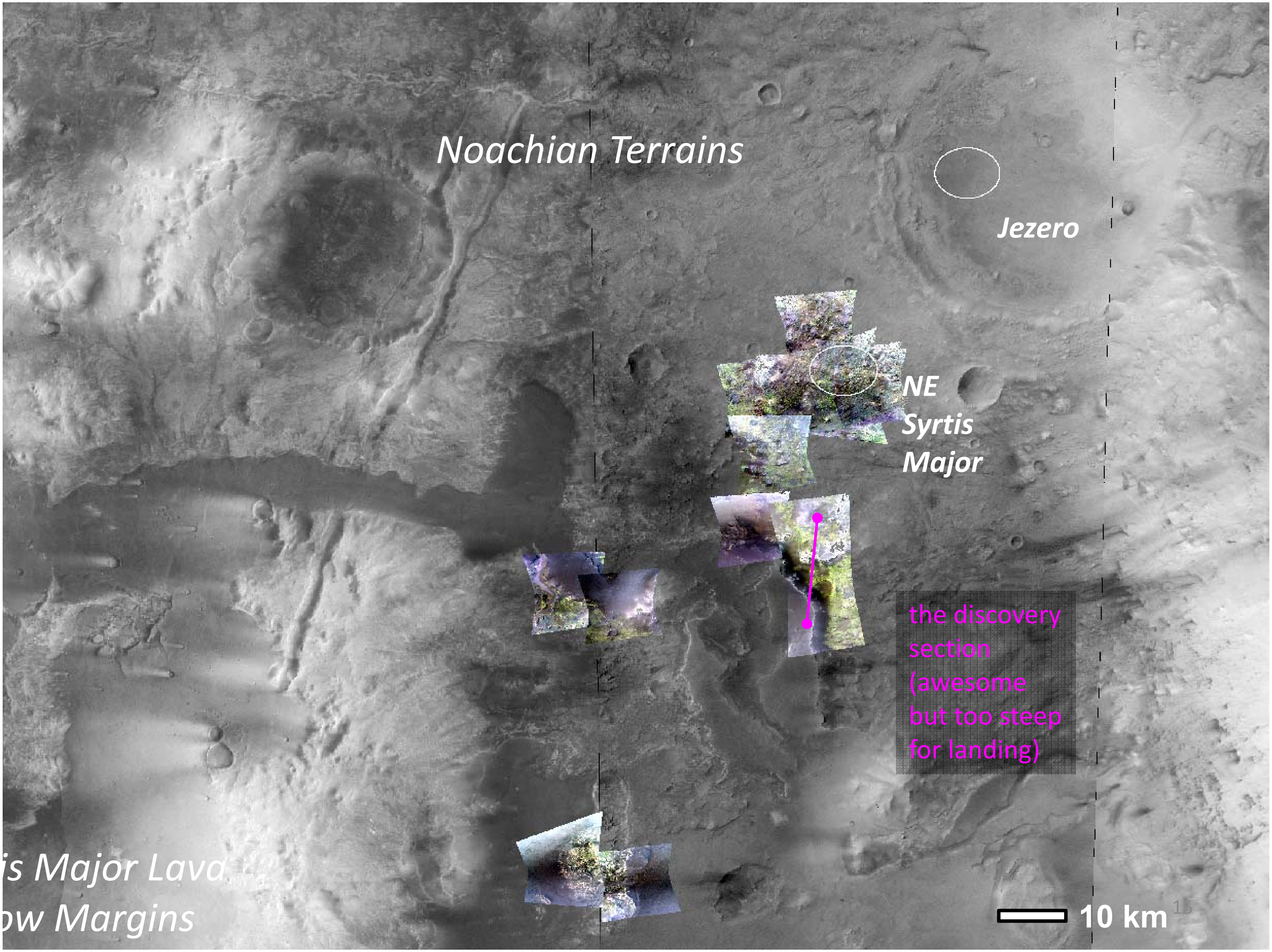

Noachian Terrains
Jezero
NE
Syrtis
Major
lavas exploit pre-existing fluvial valleys/channels and
ssected by fluvial valleys/channels pointing to surface
s available over a long period of time, at least
dically [Mangold et al., 2007; 2008; Skok, this wkshp]
is Major Lava
ow Margins
10 km

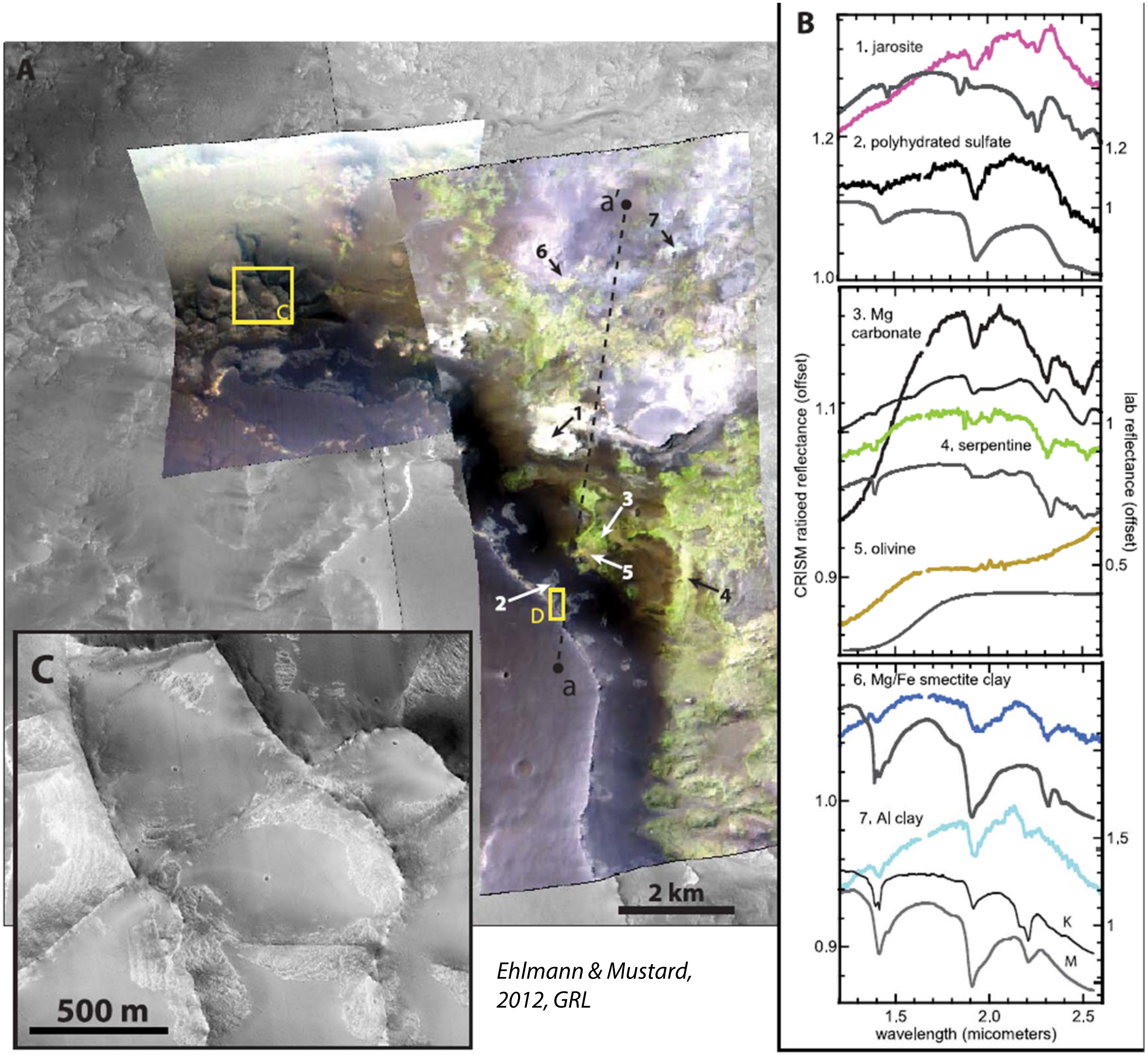


Syrtis Major lavas
5 km

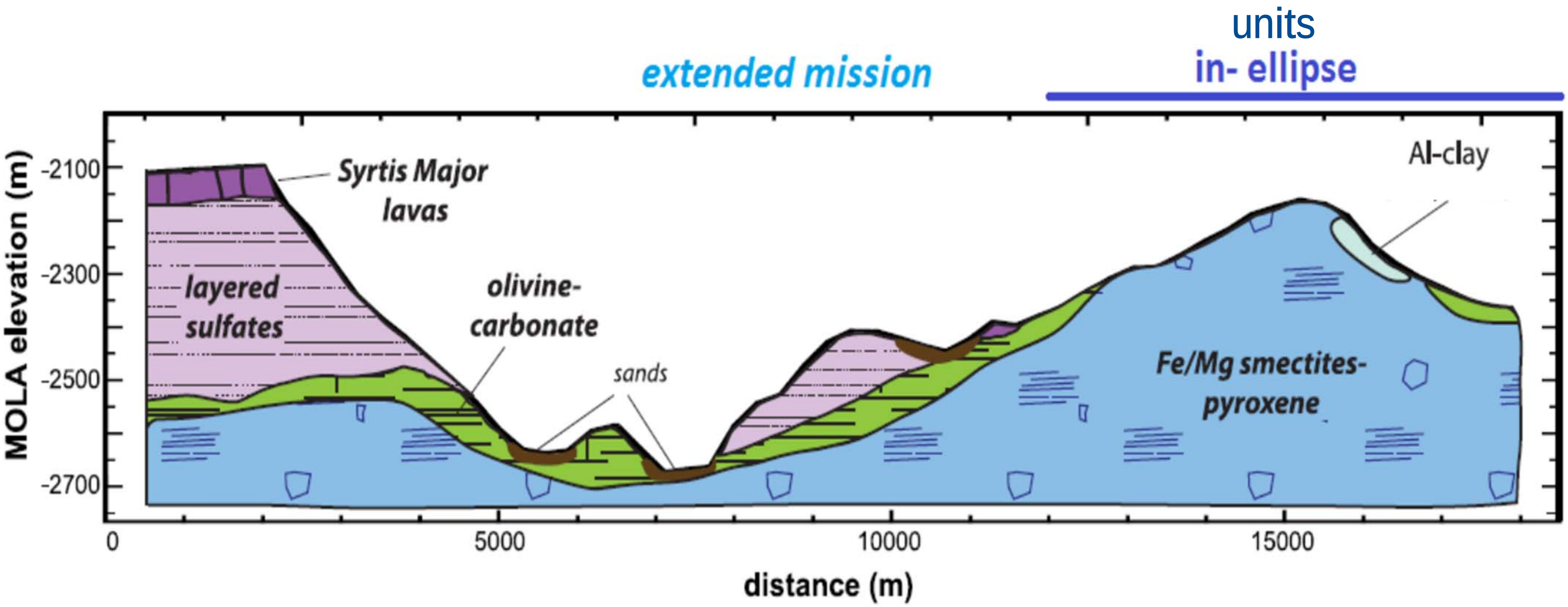


Syrtis Major lavas
Sulfate-sediments with jarosite-filled boxwork fractures (more later)
5 km


Noachian Terrains
Jezero
NE
Syrtis
Major
the discovery
section
(awesome
but too steep
for landing)
is Major Lava
ow Margins
10 km



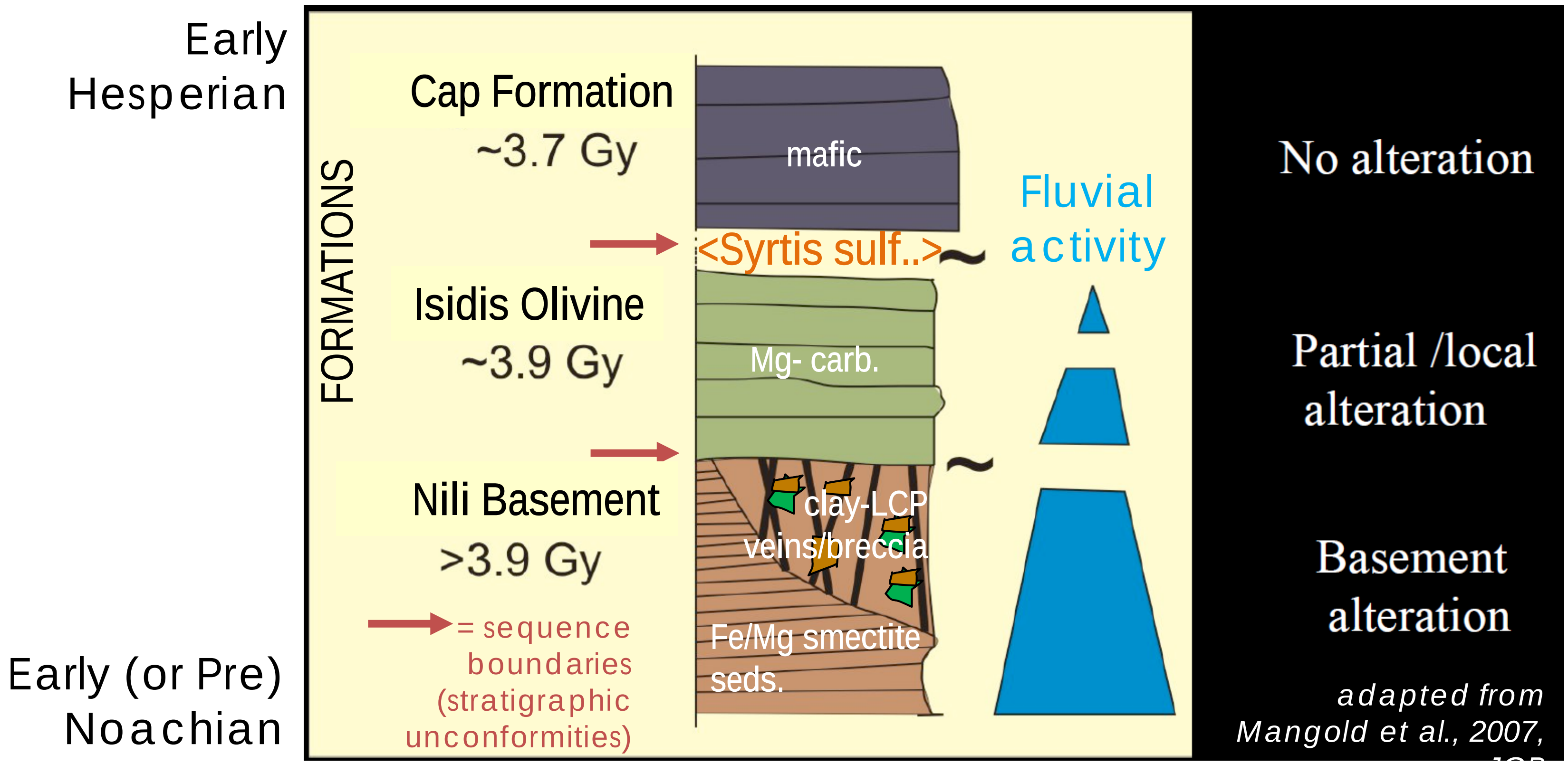
Ehlmann & Mustard, 2012, GRL



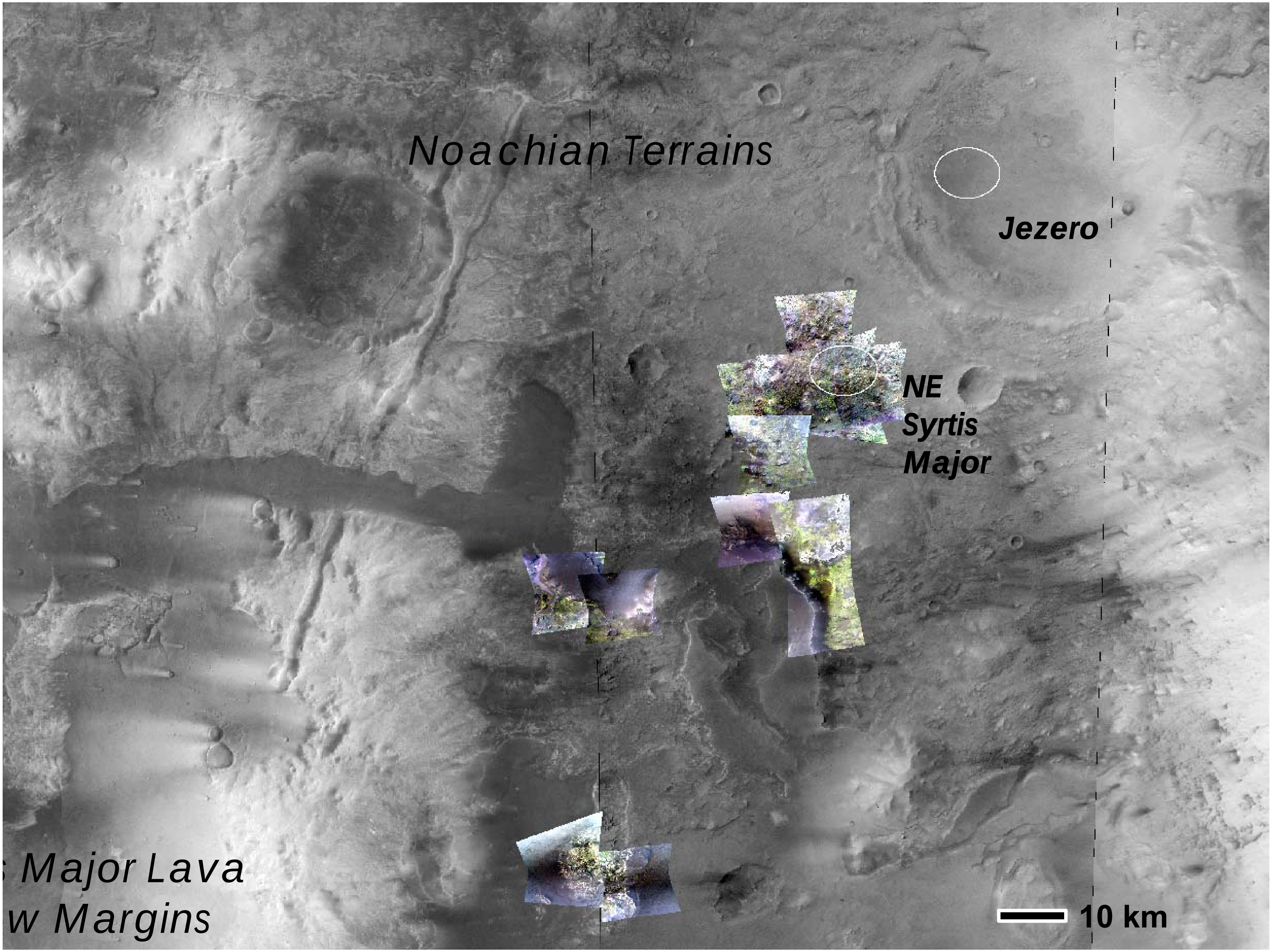
Ehlmann & Mustard, 2012, GRL

Distinctive Lithostratigraphic Sequences

E. Nili Fossae Group



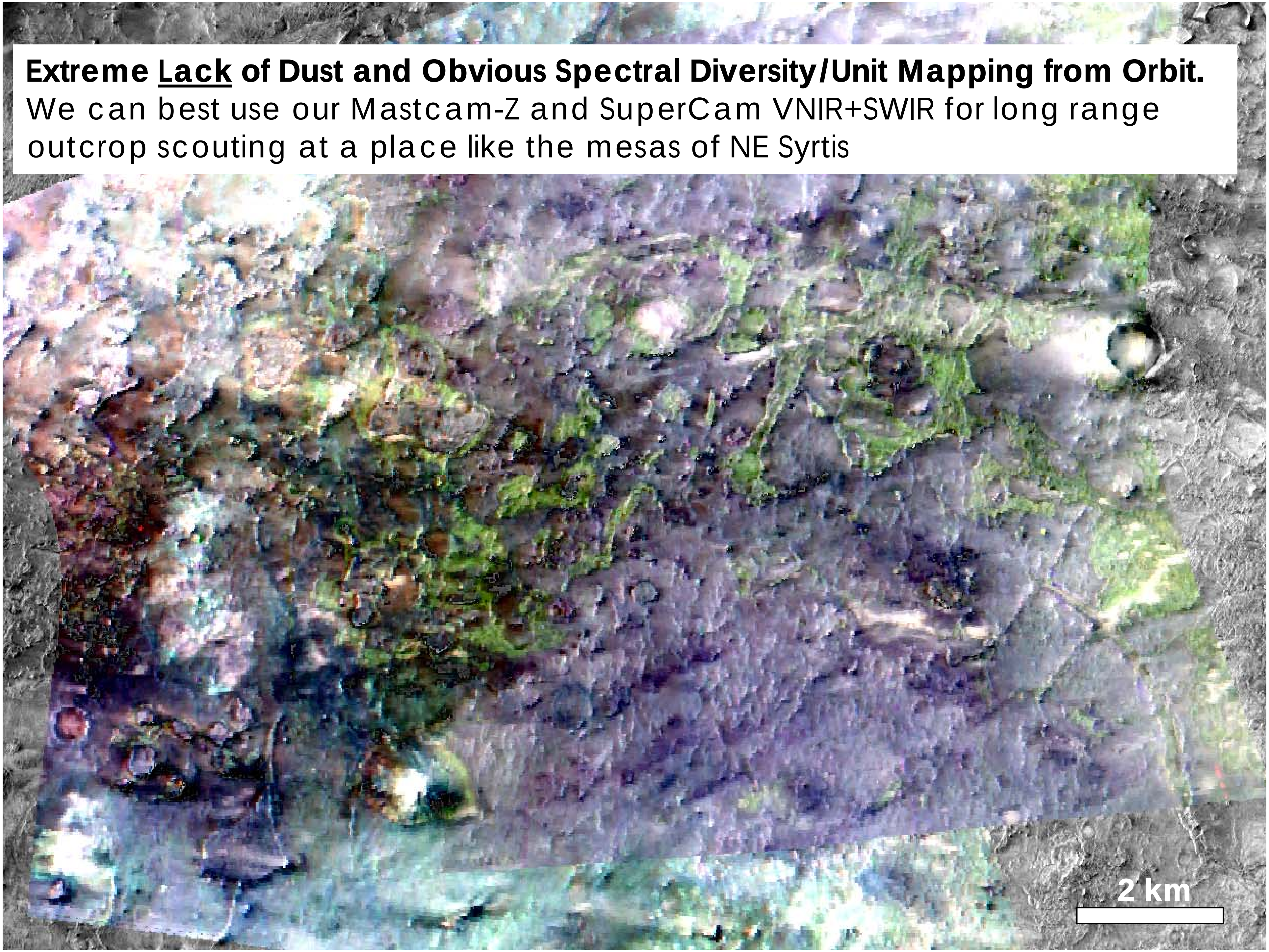
- **Nili Basement Formation**: regional in extent. Subunits within are massive, layered, ridged, or megabrecciated. Different subunits have variable Fe/Mg clay, Al-clay, and low Ca-pyx content.
- **Isidis Olivine Formation** is restricted to east of Nili Fossae, variably bears the Mg-carbonate
- **Cap 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

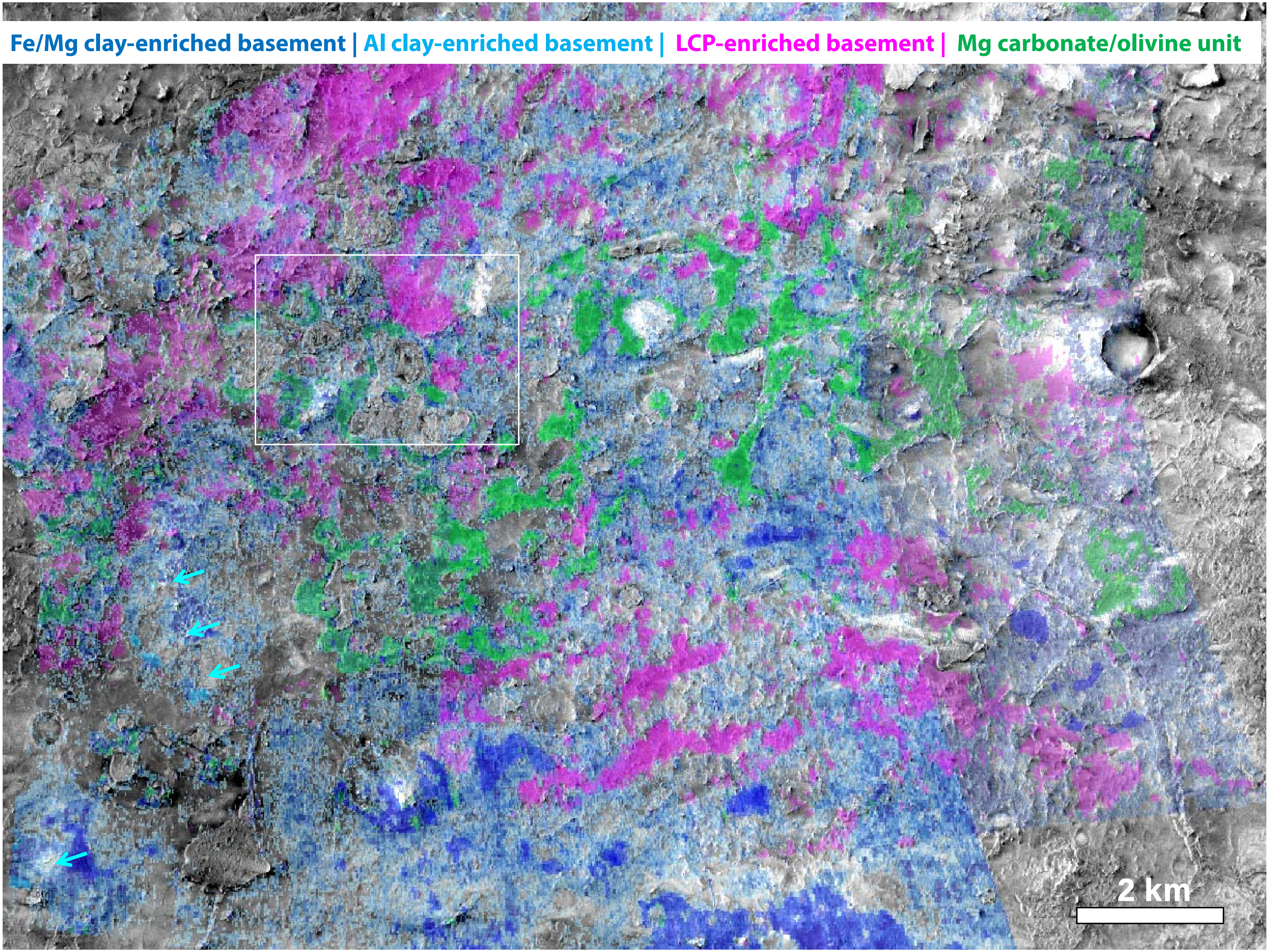


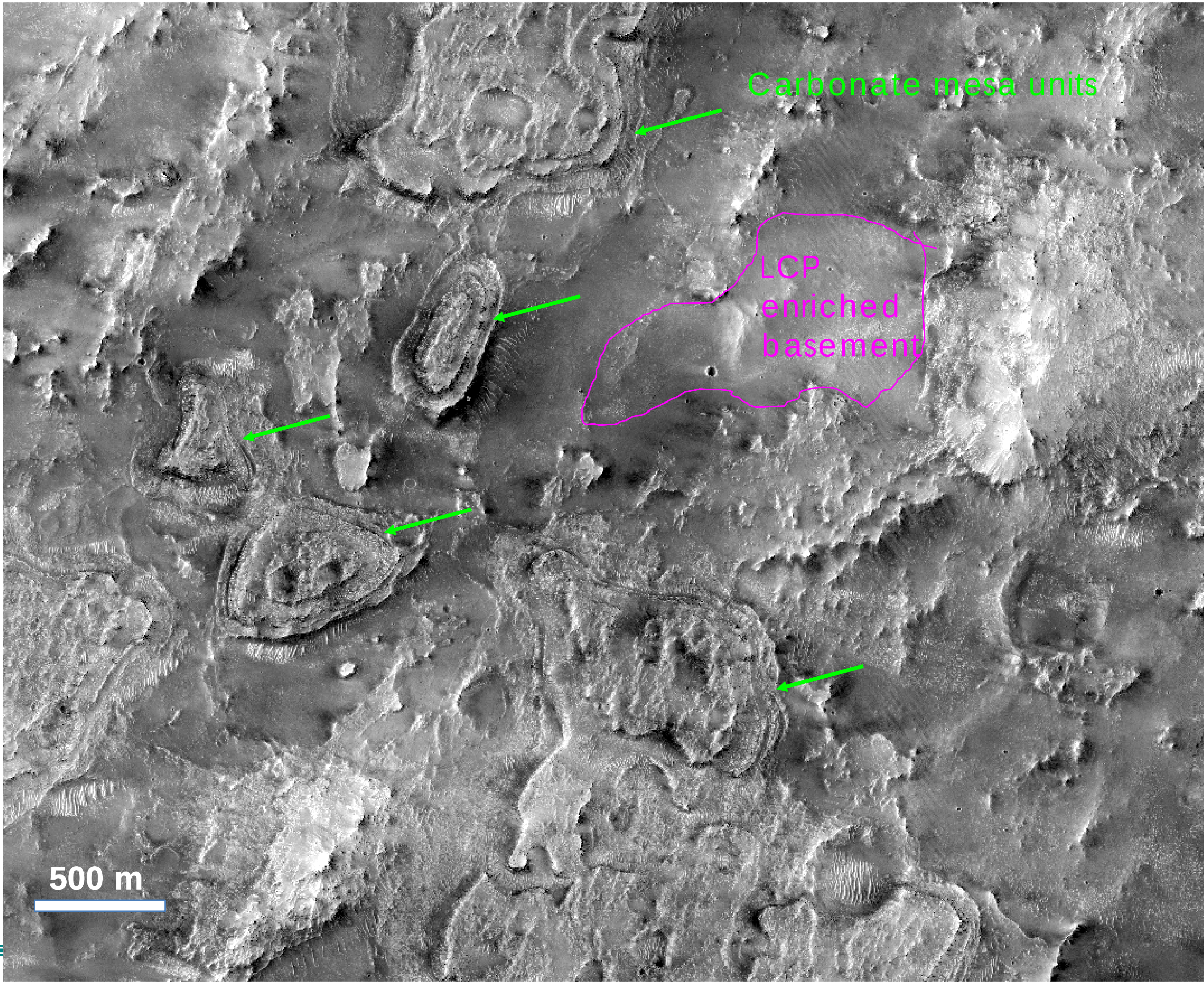
Noachian Terrains
Jezero
NE
Syrtis
Major
s Major Lava
w Margins
10 km

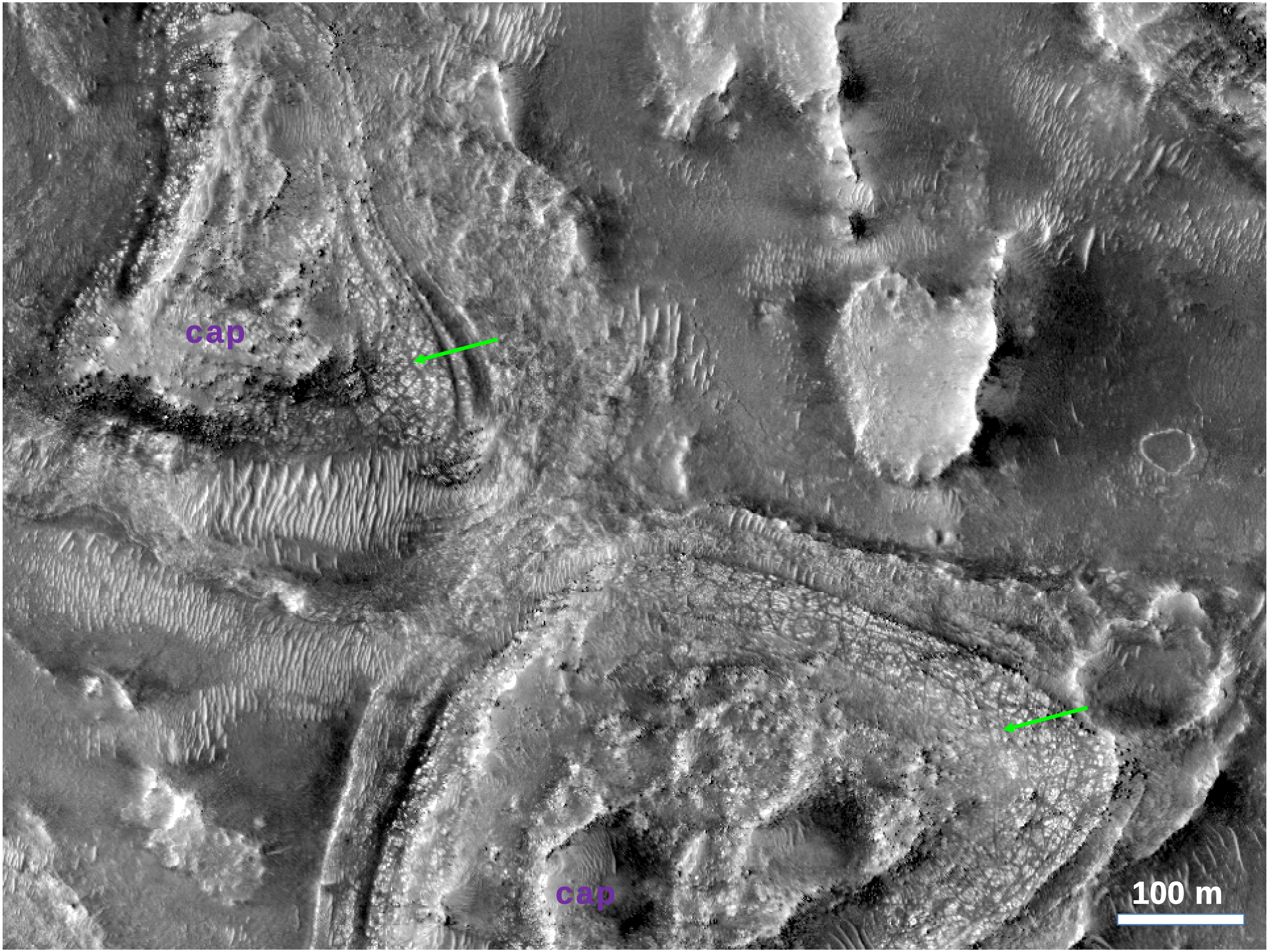

CRISM False Color IR
R: 2.4 μm, G: 1.8 μm, B: 1.0 μm
2 km

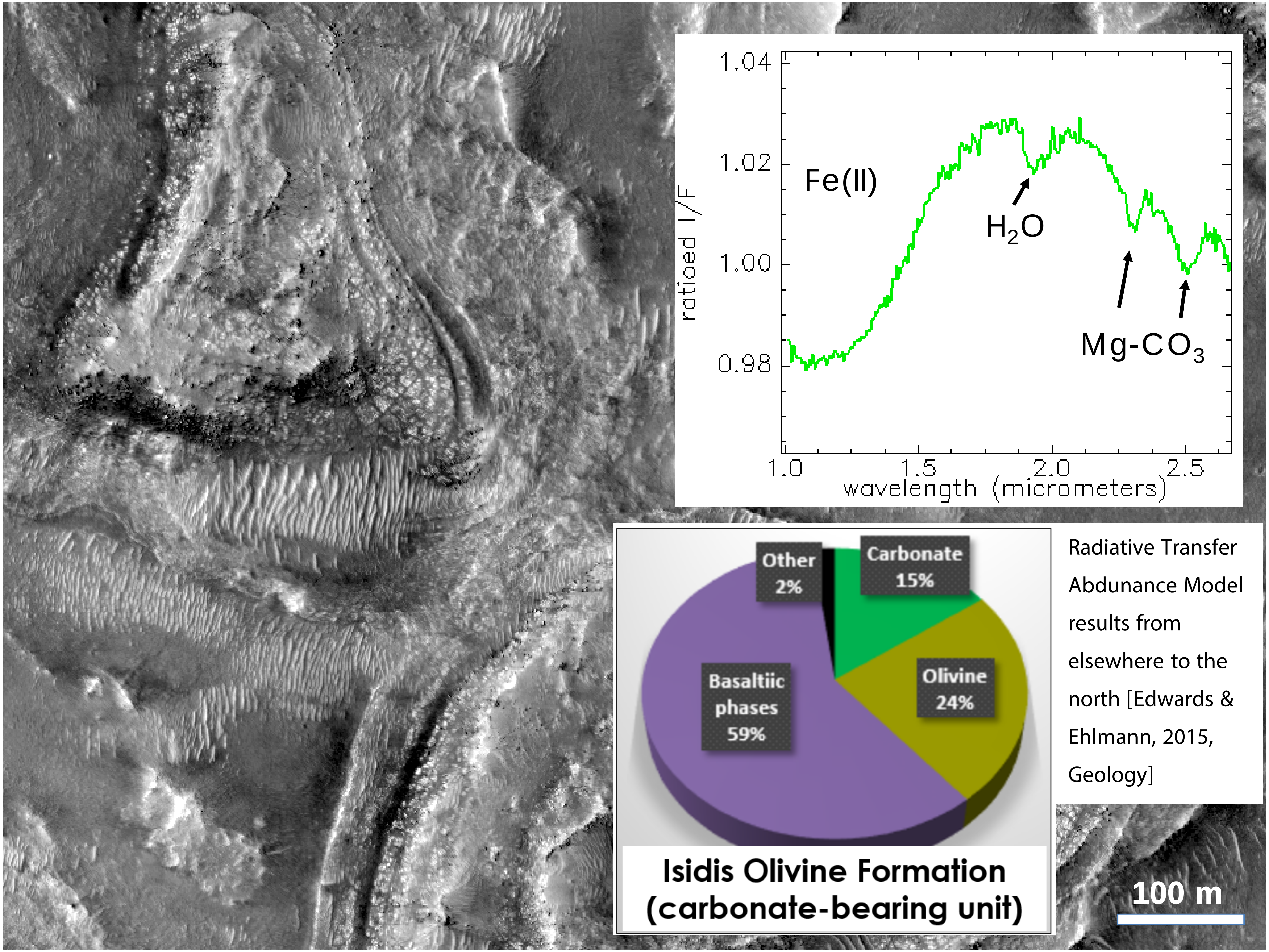
Extreme Lack of Dust and Obvious Spectral Diversity/Unit Mapping from Orbit.
We can best use our Mastcam-Z and SuperCam VNIR+SWIR for long range outcrop scouting at a place like the mesas of NE Syrtis




Fe/Mg clay-enriched basement | Al clay-enriched basement | LCP-enriched basement | Mg carbonate/olivine unit
2 km


Carbonate mesa units
LCP
enriched
basement
500 m


cap
cap
100 m


1.04
1.02
1.00
0.98
ratioed I/F
Fe(II)
H_2O
$Mg\text{-}CO_3$
1.0
1.5
2.0
2.5
wavelength (micrometers)
Other 2%
Carbonate 15%
Olivine 24%
Basaltiic phases 59%
Isidis Olivine Formation
(carbonate-bearing unit)
Radiative Transfer Abdunance Model results from elsewhere to the north [Edwards & Ehlmann, 2015, Geology]
100 m

The Olivine-Carbonate Unit: Nature of the Habitable Environment, Biosignature Search Strategy

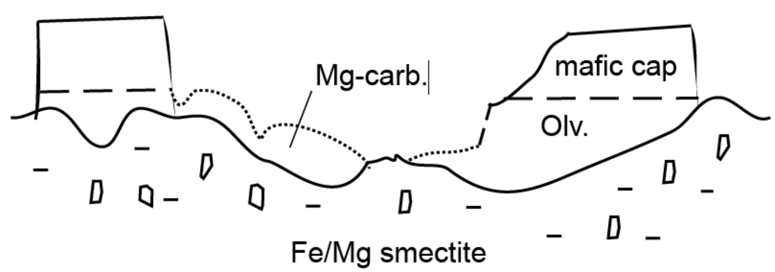
Possible Mg-carbonate formation mechanisms

(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?

SURFACE

SUBSURFACE



For Mg-carbonates on Mars,

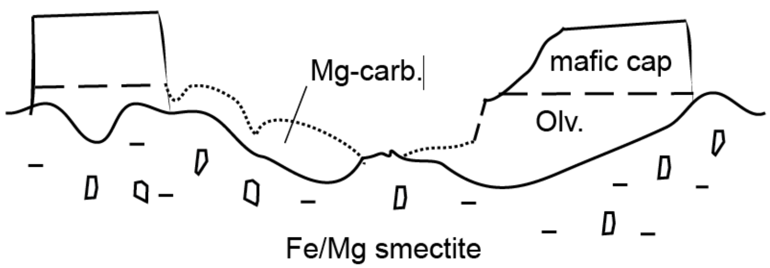
(1) Olivine-rich rock and (2) its interaction with water seem to be essential

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?

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



For Mg-carbonates on Mars,

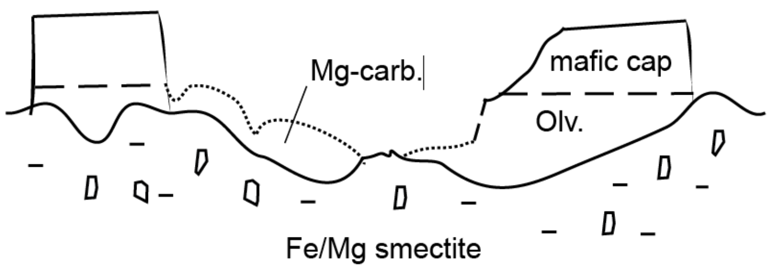
(1) Olivine-rich rock and (2) its interaction with water seem to be essential

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?

more likely

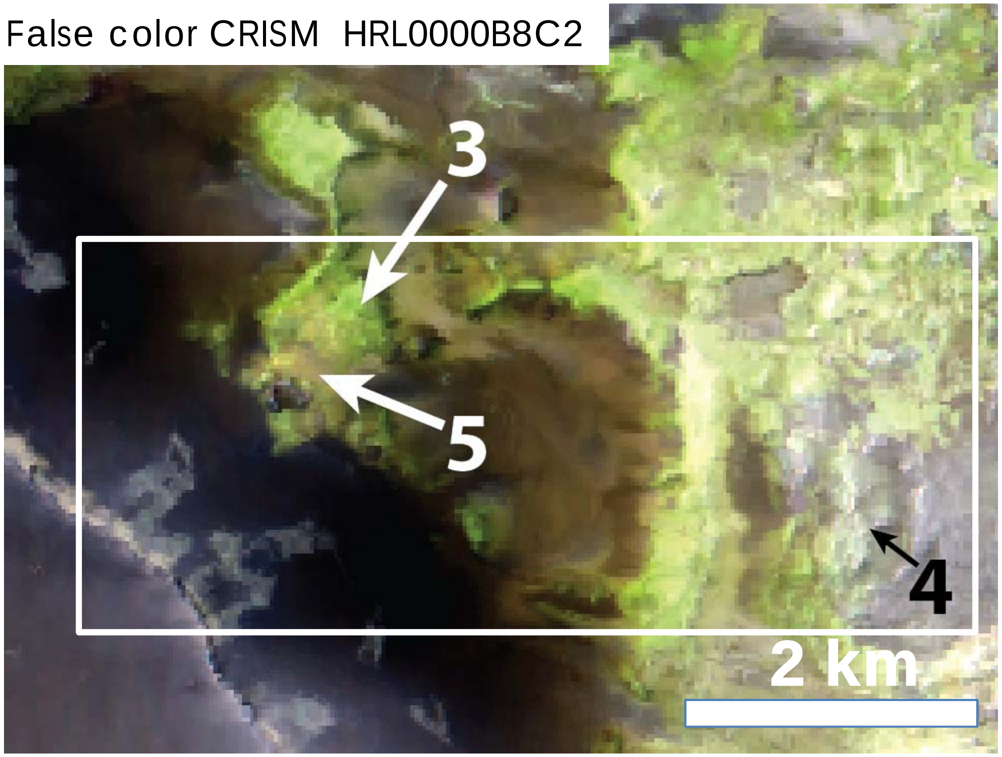


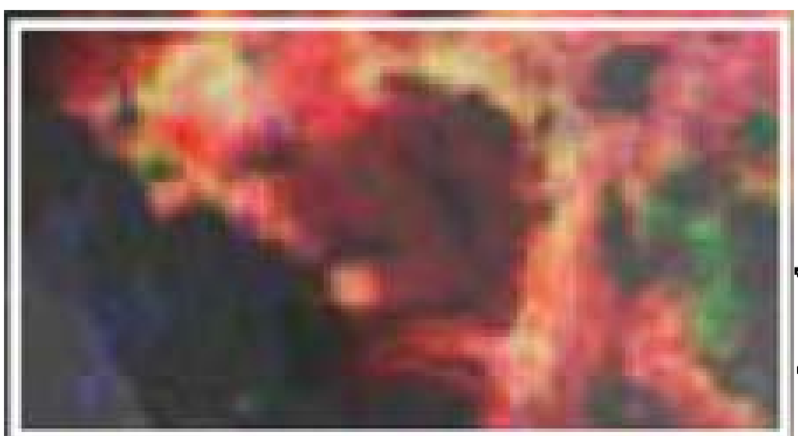
For Mg-carbonates on Mars,

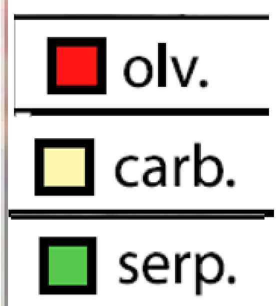
(1) Olivine-rich rock and (2) its interaction with water seem to be essential

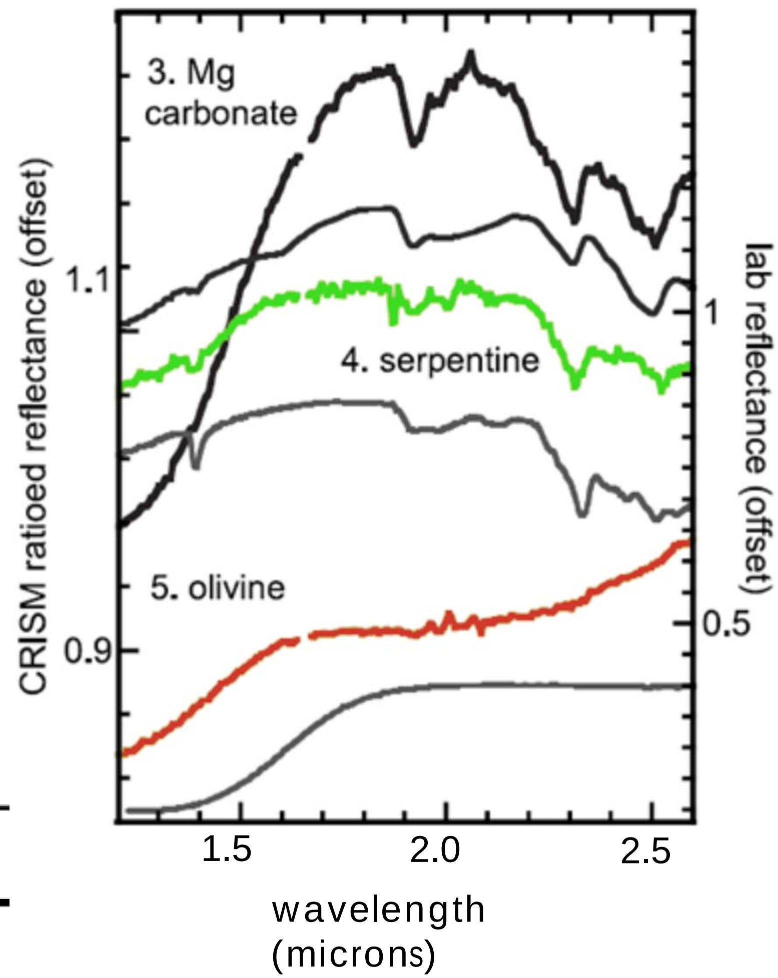
Insights from near NE Syrtis:
Serpentine in the Isidis Olivine (Carbonate) Formation

False color CRISM HRL0000B8C2





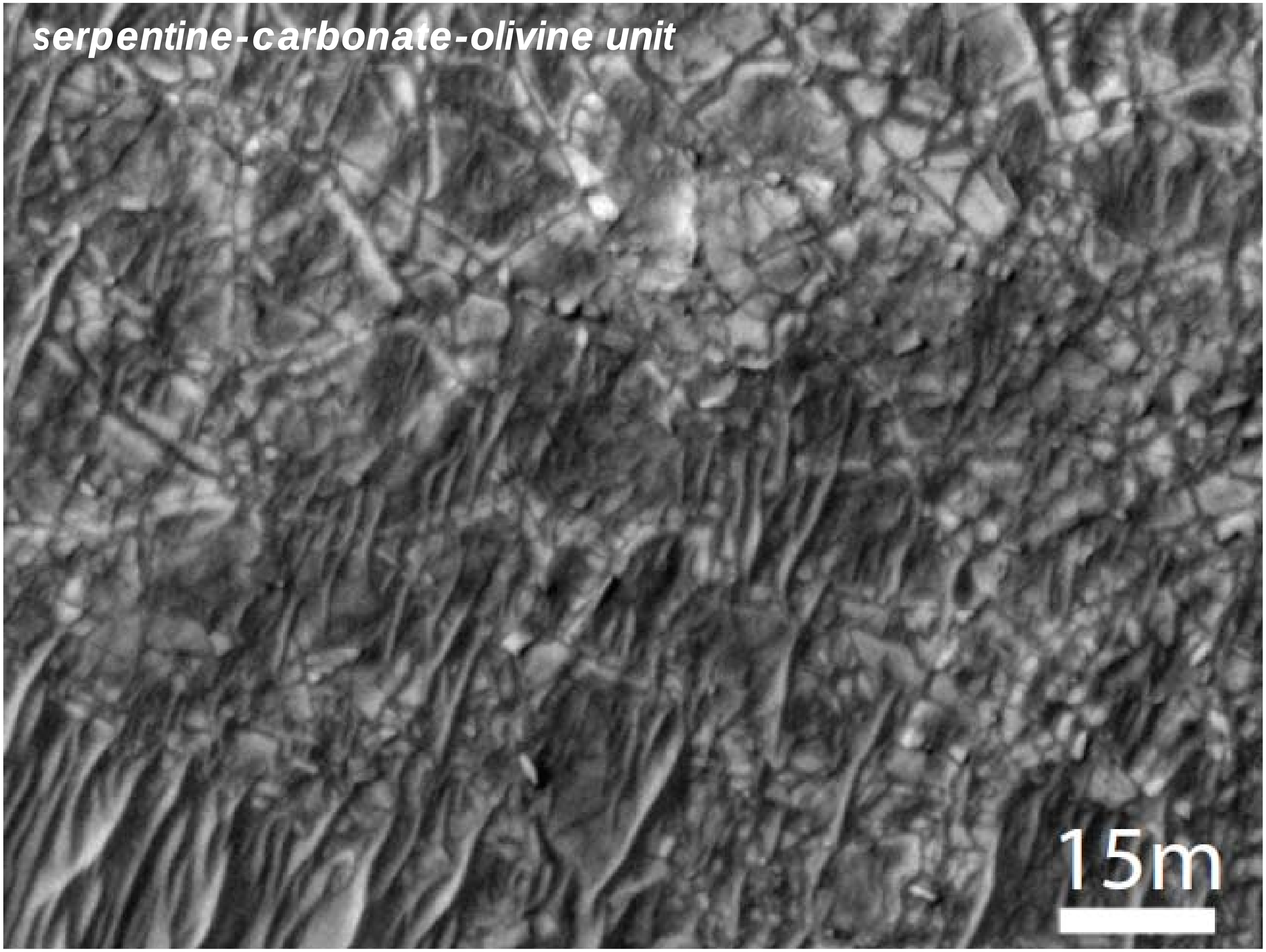


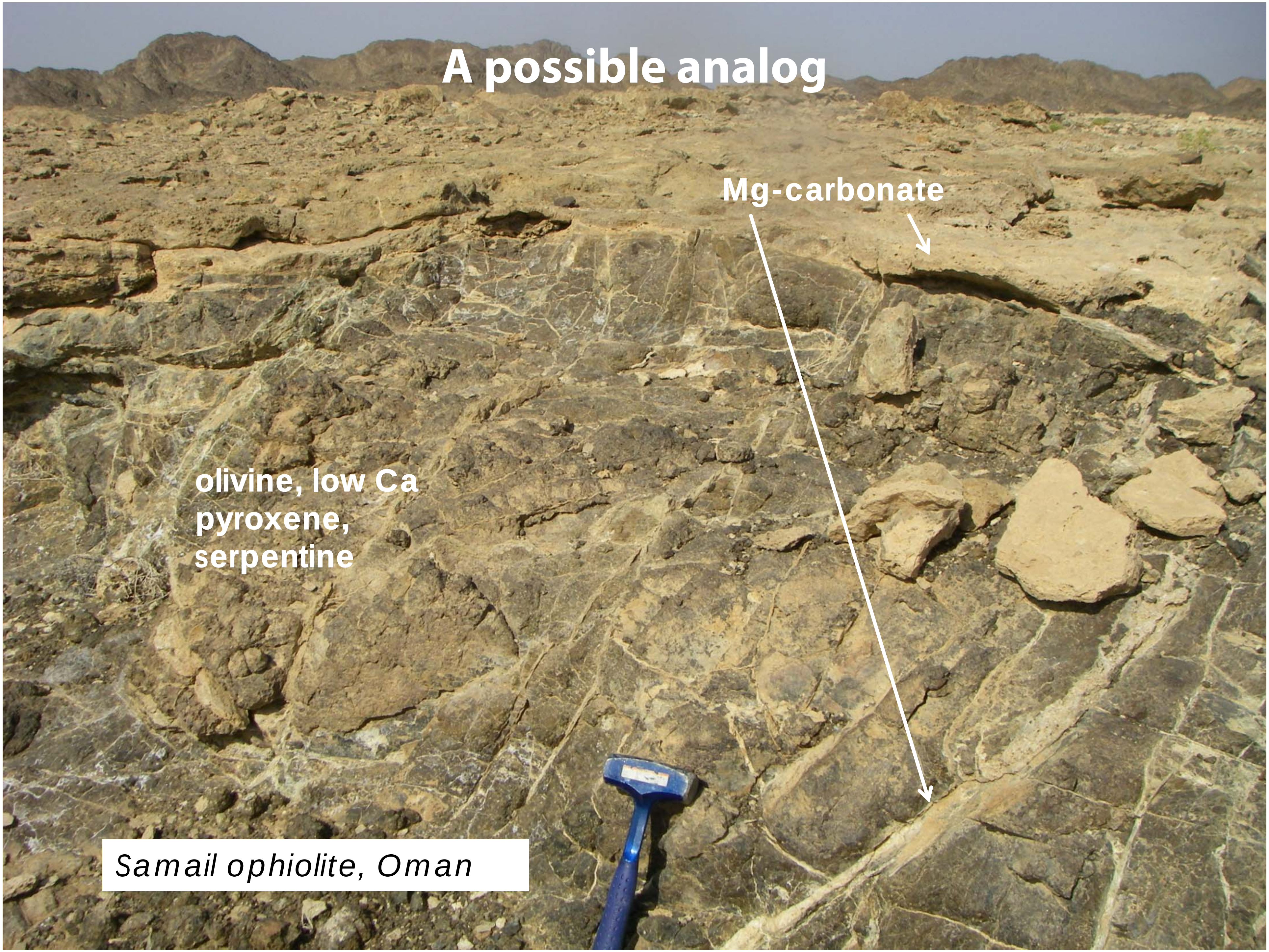


<u>south of NE Syrtis ellipse</u>

Ehlmann et al., 2010, GRL;
Ehlmann & Mustard, 2012; GRL

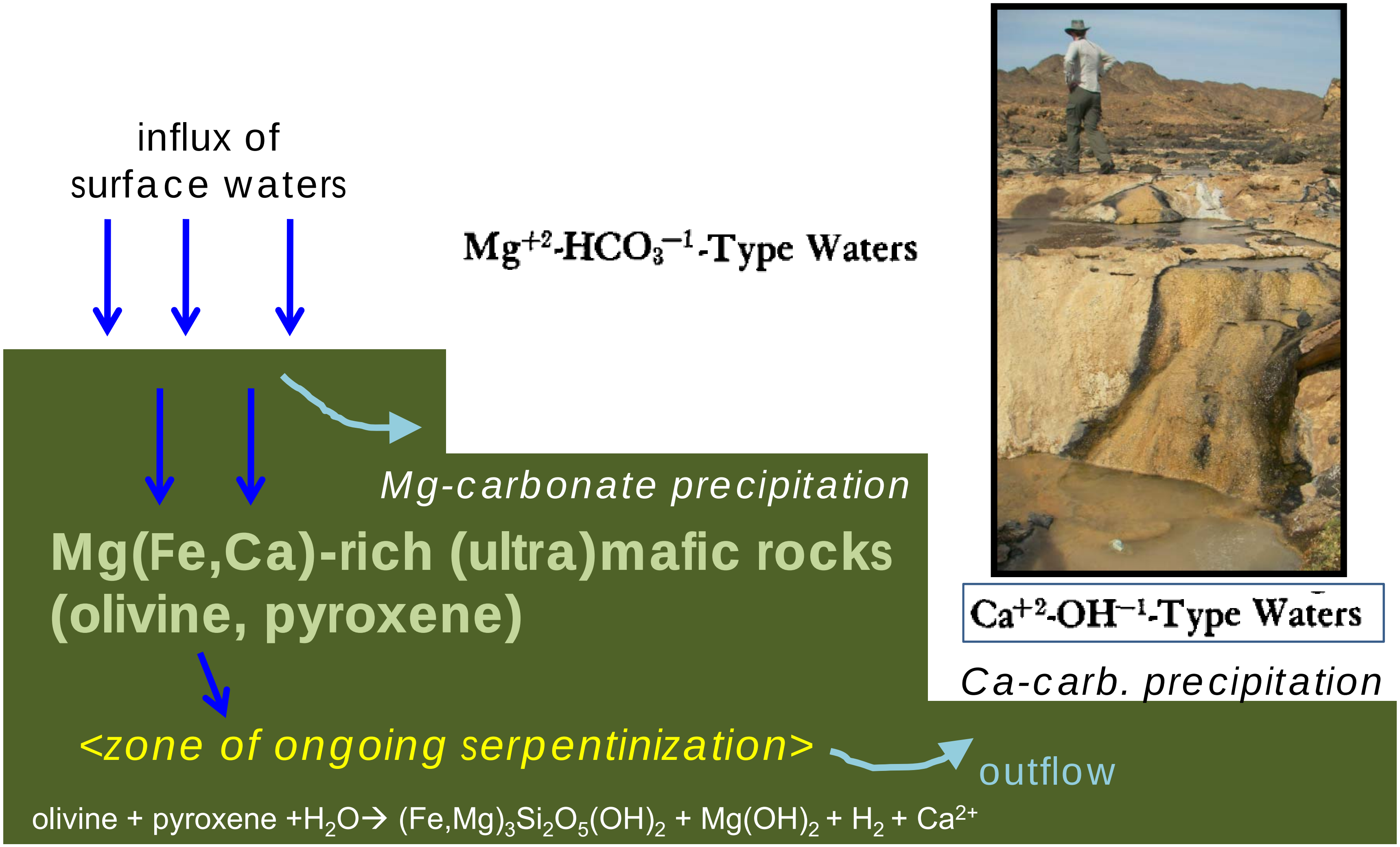
Interfacing and Fractures at Multiple Scales




A possible analog
Mg-carbonate
olivine, low Ca pyroxene, serpentine
Samail ophiolite, Oman


A possible analog
Spring initiates from groundwaters
Ca-carbonate
biomass
eadwall
Samail ophiolite, Oman

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



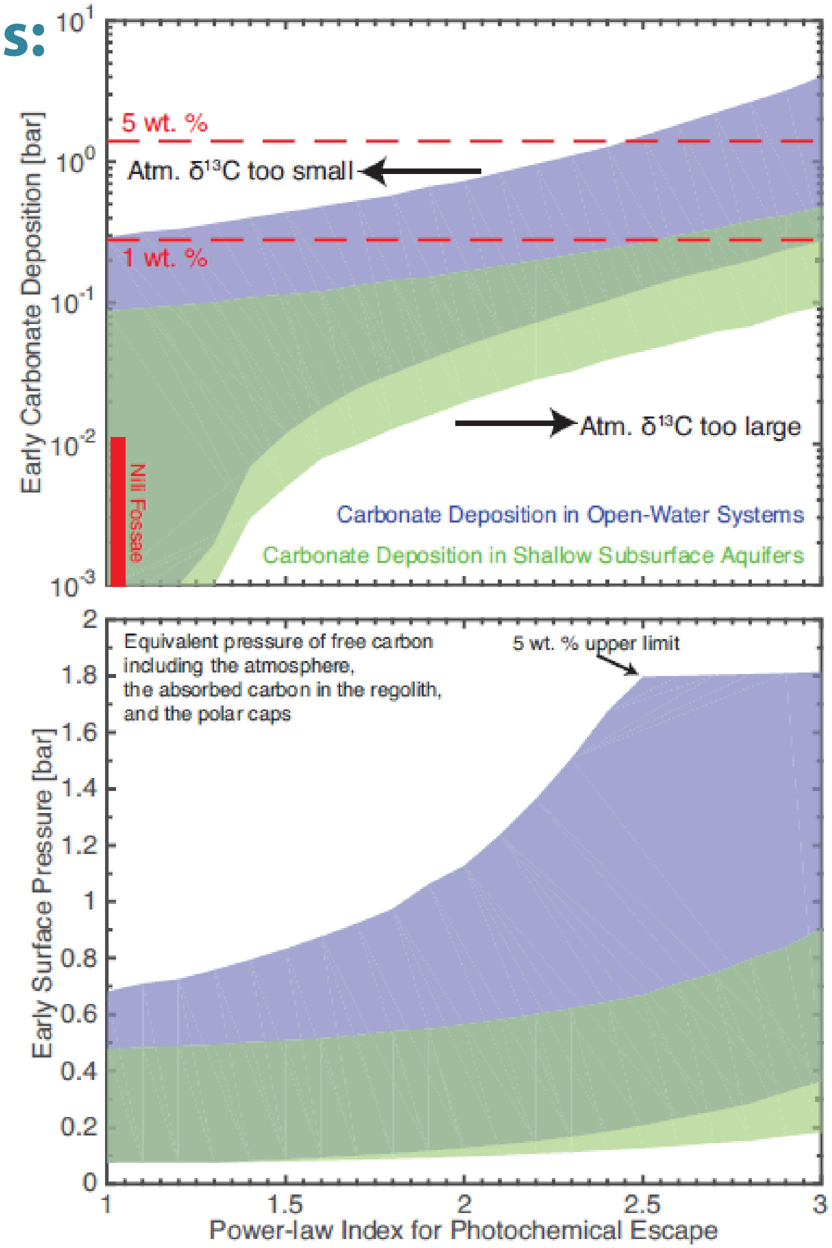
process described further in *Barnes & O'Neil, 1969*

Kelemen & Matter, 2008; Streit et al., 2012 describe Oman deposits

Fundamental Processes, Carbonates: Key to Past Climate/Habitability

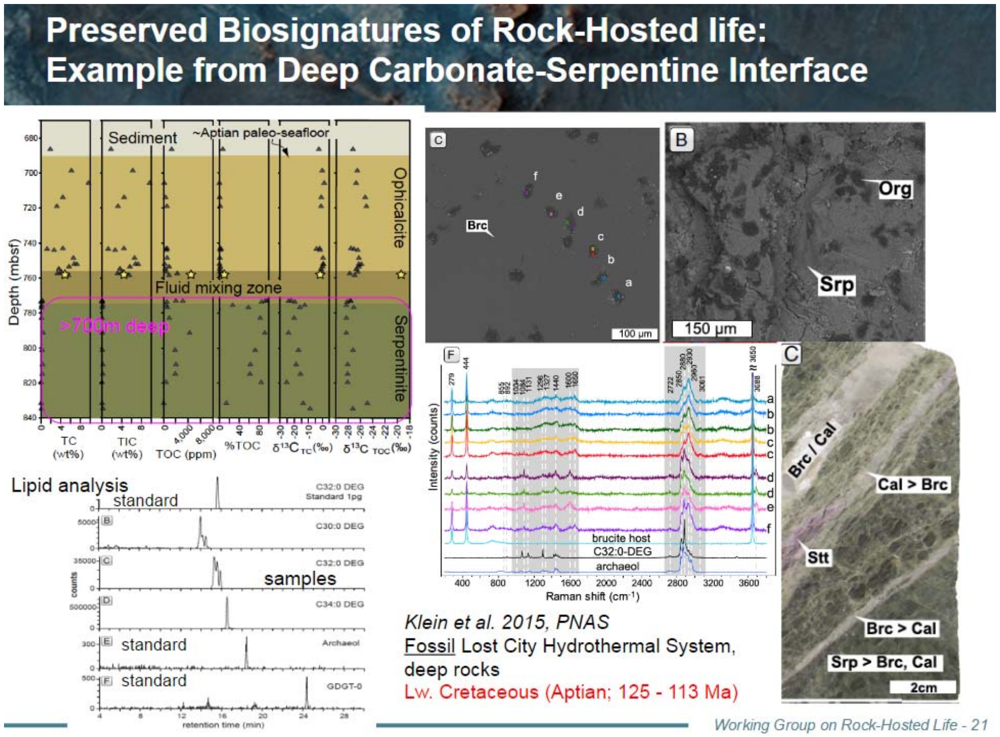
- Understanding atmospheric evolution requires understanding the mechanism, timing, amount and isotopic signature of carbon sequestration
  - NF Carbonates: 0.25-12 mbar
- ***In situ exploration*: establish the formation enviro, constrain timing**
- ***Sample return*: sample the isotopic record, determine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

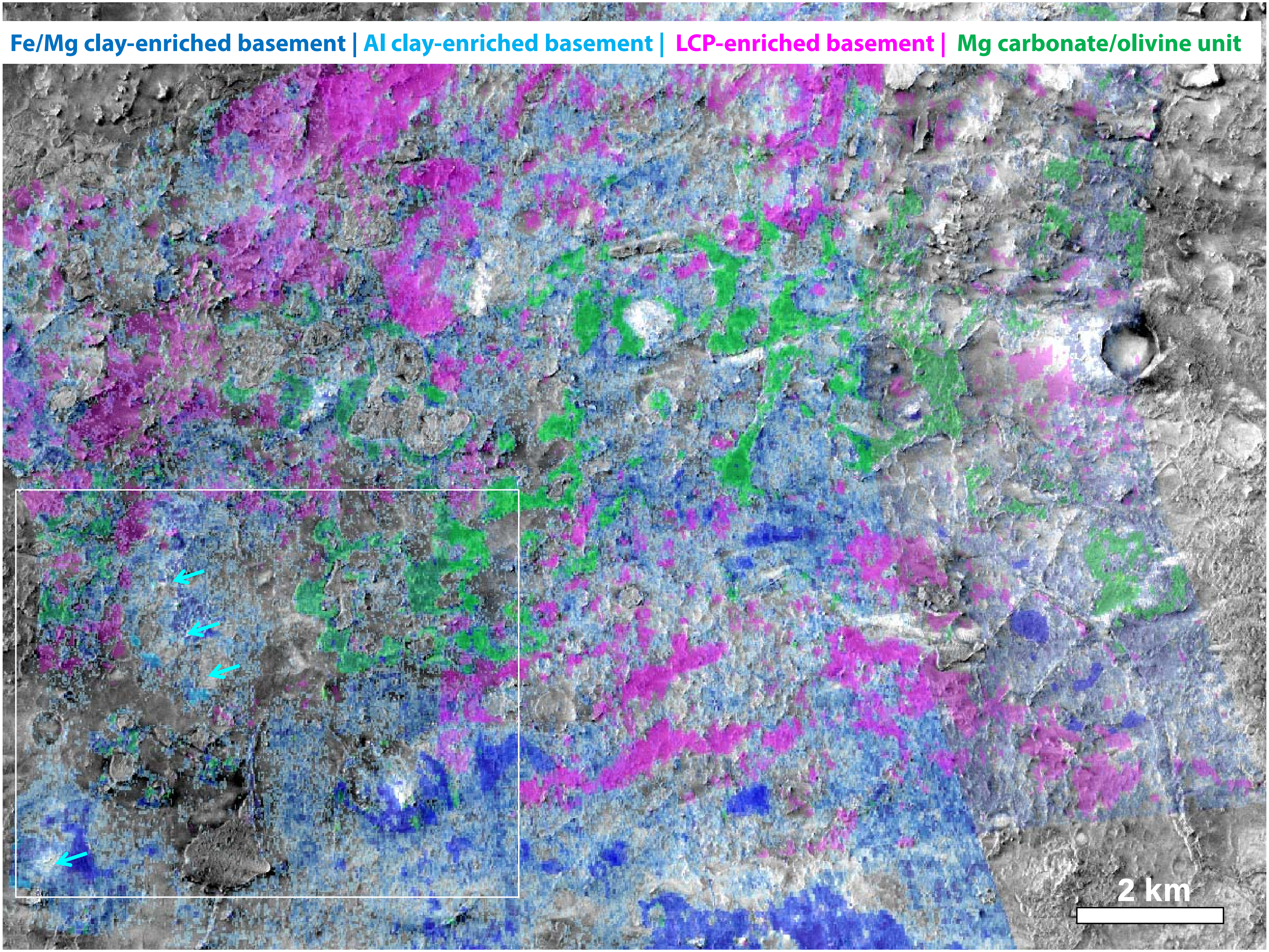


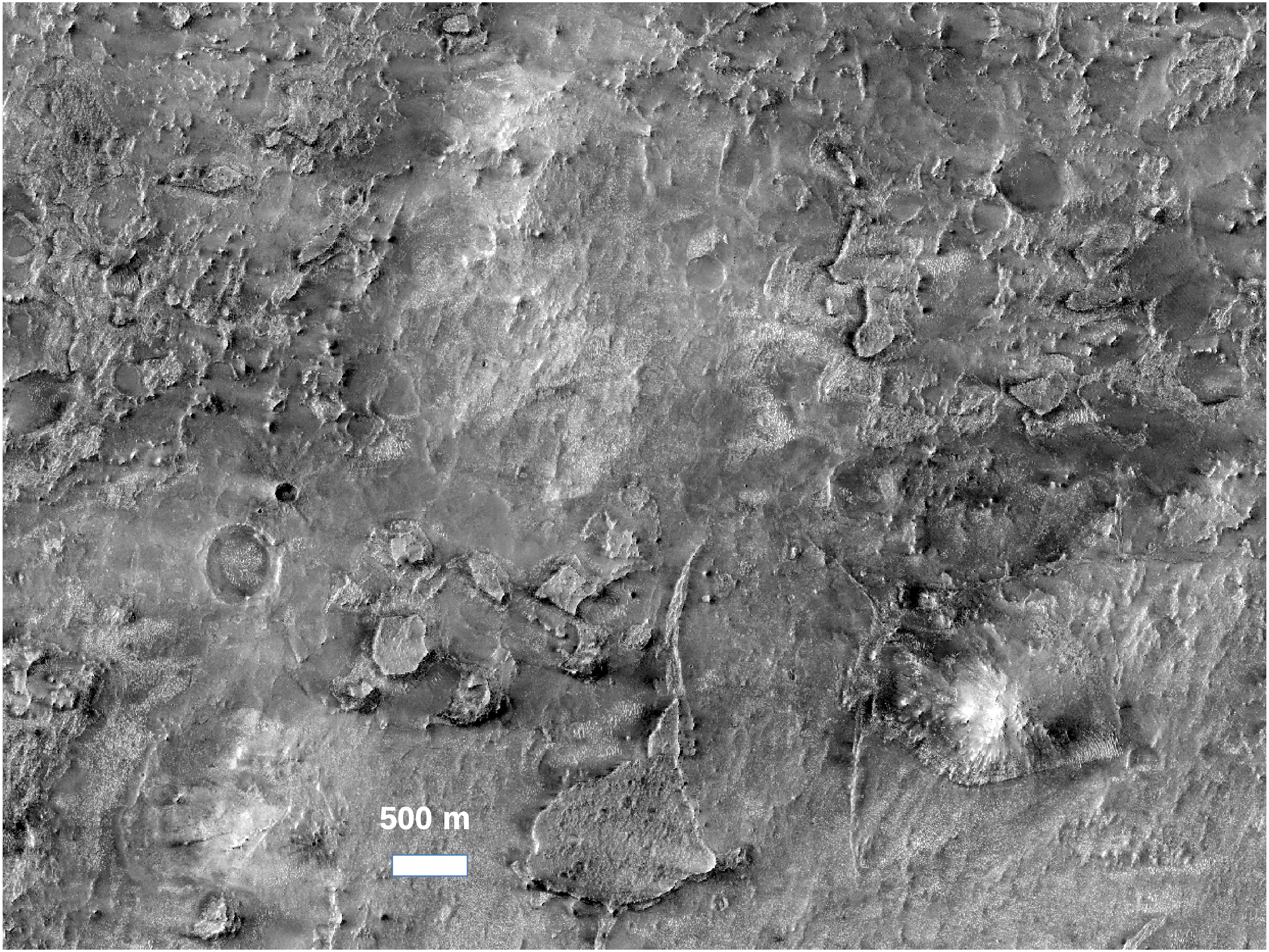
Recall demonstrated biomarkers in deep serpentine-carbonate assemblages from Lost City crust

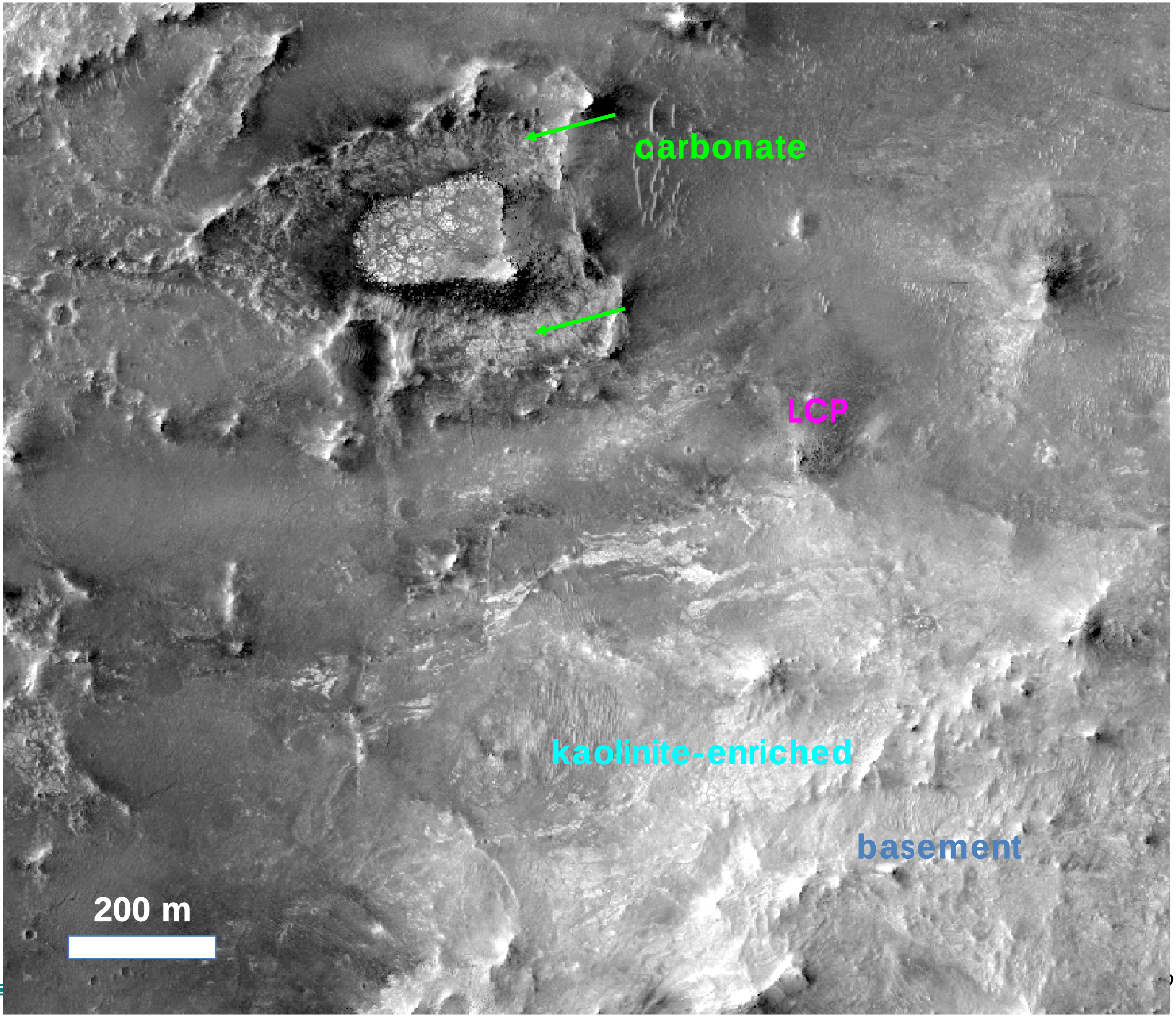
Work underway for the Oman example shown, e.g., Summons group (MIT) and also Templeton (CU-Boulder) and Shock (ASU)

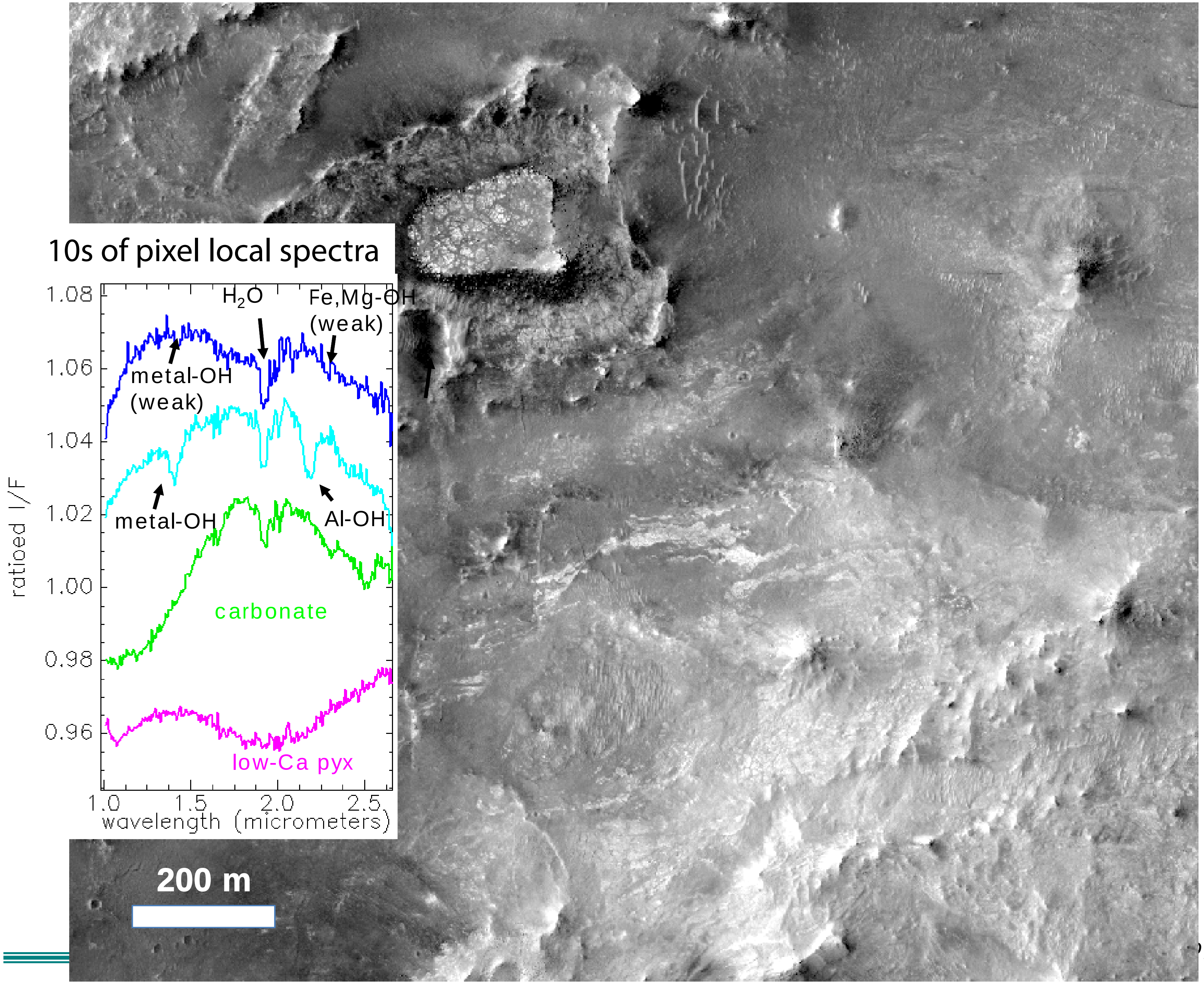
Astrobiology Science Conference 2015 (2015) **7536.pdf**

BIOMARKER INSIGHTS INTO MICROBIAL ACTIVITY IN THE SERPENTINITE-HOSTED ECOSYSTEM OF THE SAMAIL OPHIOLITE, OMAN. S. A. Newman[1] and S. A. Lincoln[1,2], E. L. Shock[3], P. B. Kelemen[4], R. E. Summons, [1]Massachusetts Institute of Technology, Earth, Atmospheric and Planetary Sciences, Cambridge, Massachusetts 02139, [2]Department of Geosciences, Penn State University, State College, PA 16801, [3]Department of Chemistry and Biochemistry, Arizona State University, Tempe, Arizona 85287–1604, [4]Lamont-Doherty Earth Observatory, Columbia University, 58 Geochemistry Building, Palisades, New York 10964


Fe/Mg clay-enriched basement | Al clay-enriched basement | LCP-enriched basement | Mg carbonate/olivine unit
2 km


500 m


carbonate
LCP
kaolinite-enriched
basement
200 m


10s of pixel local spectra
ratioed I/F
wavelength (micrometers)
1.08
1.06
1.04
1.02
1.00
0.98
0.96
1.0
1.5
2.0
2.5
H2O
Fe,Mg-OH
(weak)
metal-OH
(weak)
metal-OH
Al-OH
carbonate
low-Ca pyx
200 m

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

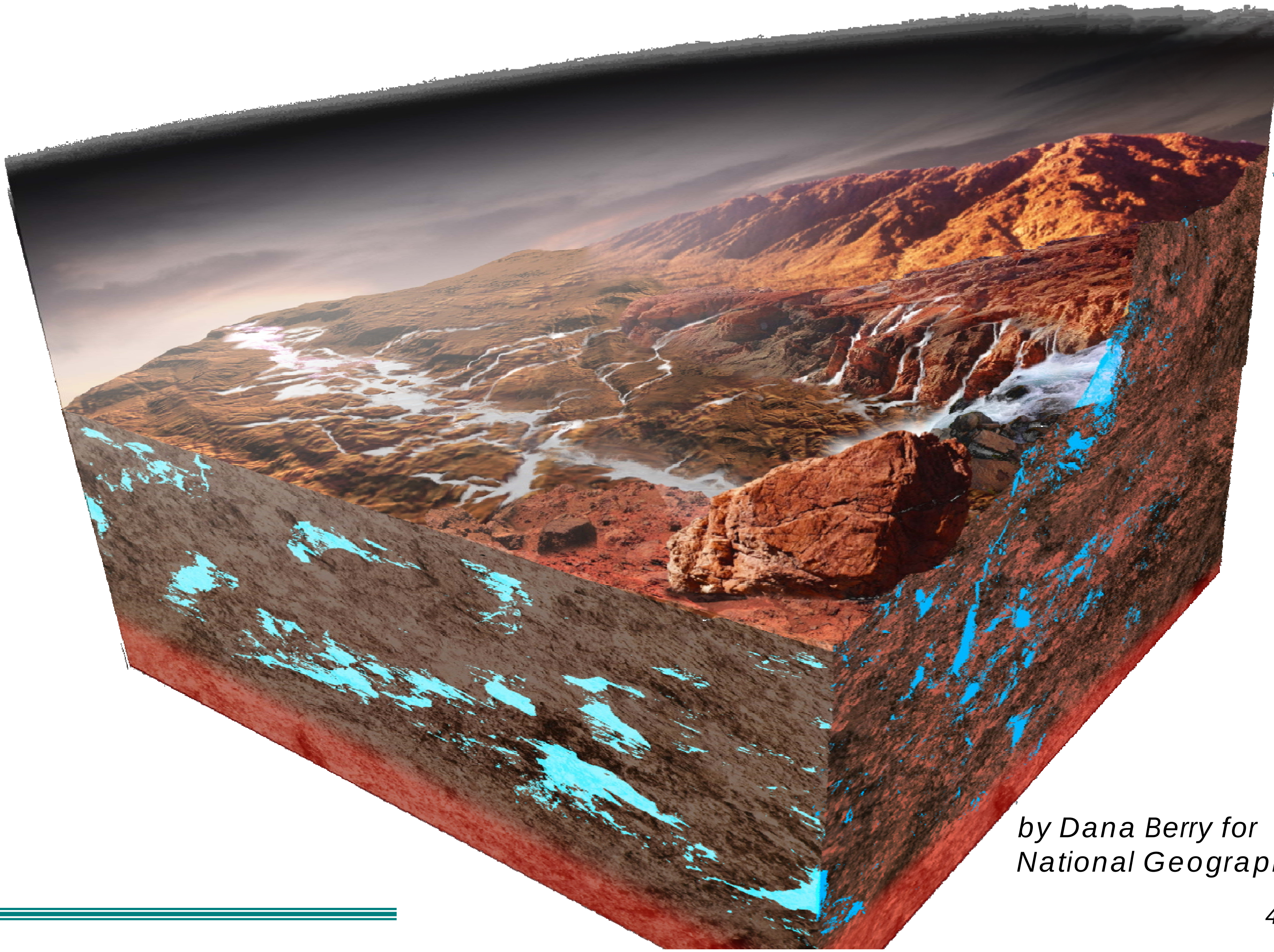
LCP-enriched massive units
Fe/Mg clay enriched massive units
Fe/Mg clay mineralized fractures

} **1. Water flow through a deep aquifer**

Al clays on Fe/Mg clays } **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?

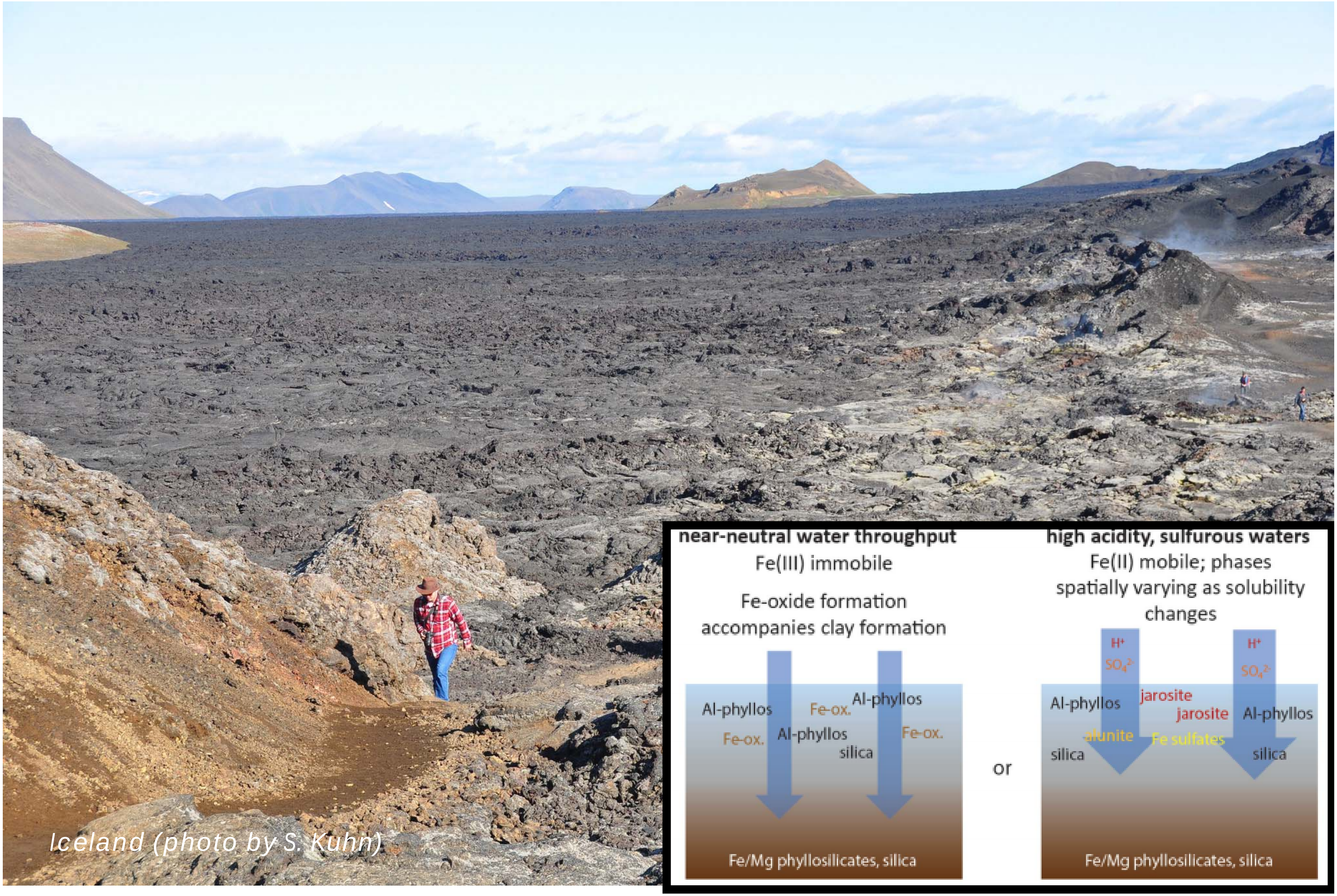


by Dana Berry for National Geographic

What do groundwater basaltic aquifers look like?

Al clays in soil profiles or zones of fluid flow

If waters are acid, Al-clay zones of leaching and redox

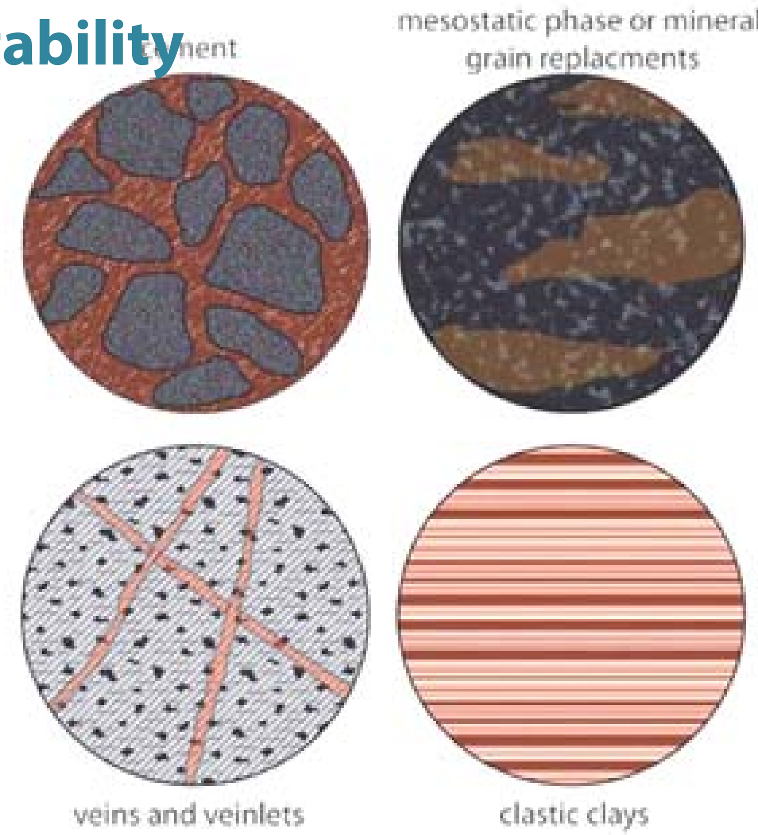


Iceland (photo by S. Kuhn)

Fundamental Processes, "Deep Clay Minerals": Key to Past Climate/Habitability

Advances require the sub-mm

- 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**



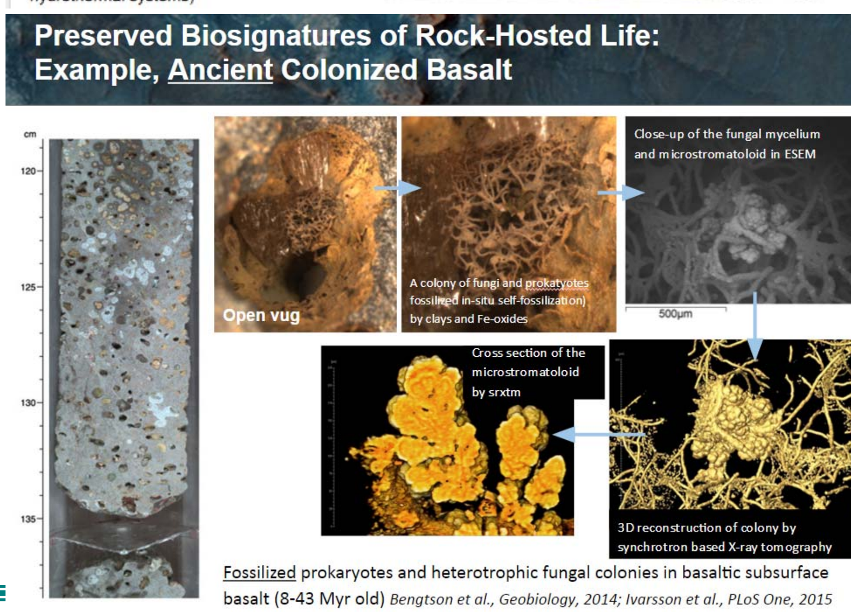
[Michalski et al., 2010]

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."

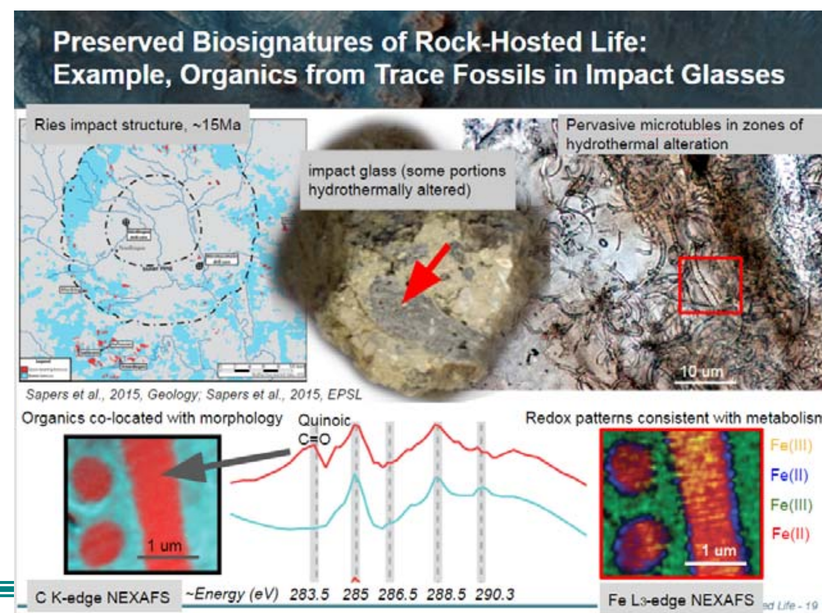
Biosignature Model:

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

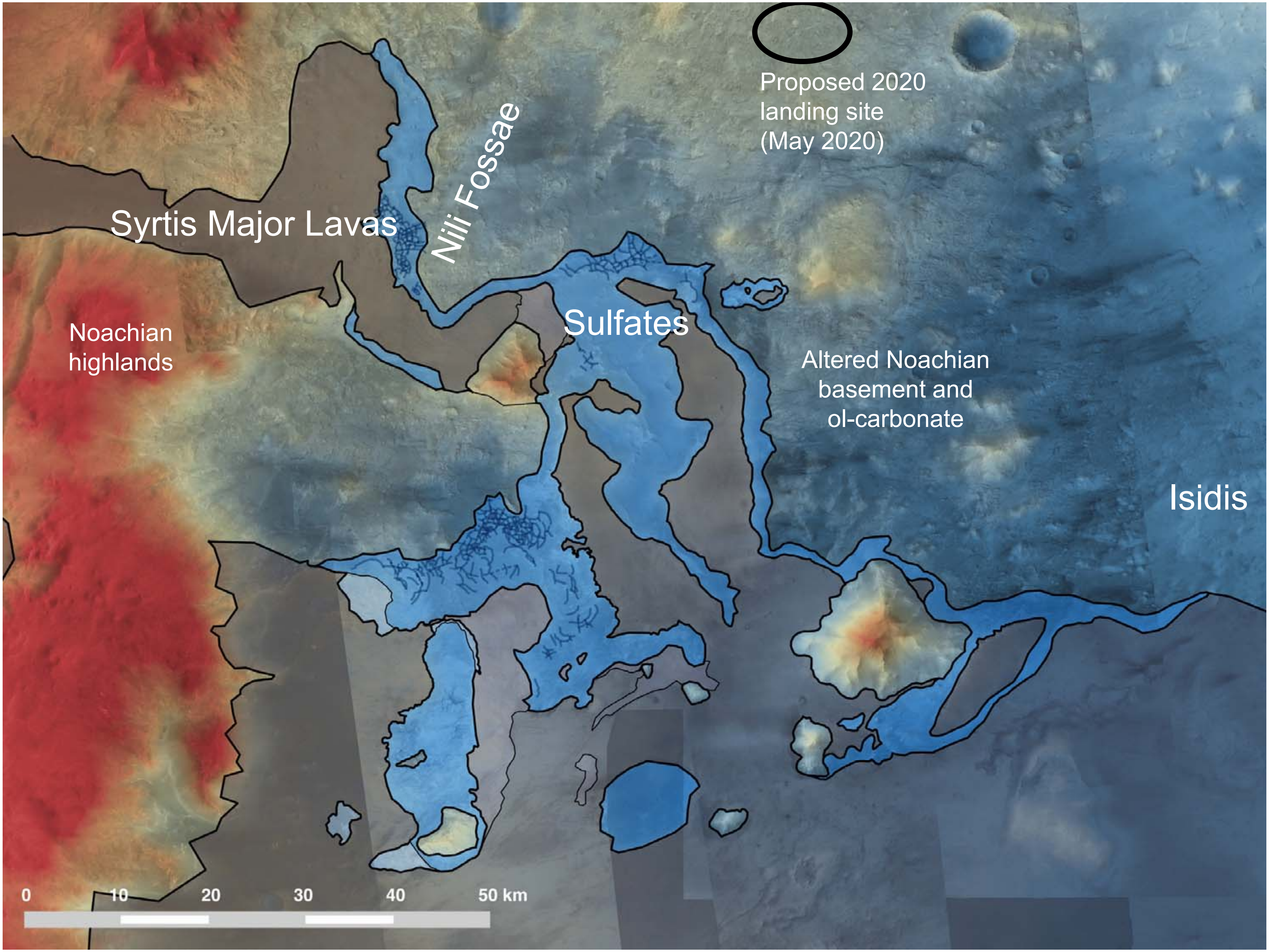
Recall demonstrated extant life and demonstrated paleobiosignatures in basalt cores, entombed in clay minerals and Fe/Mn-oxides



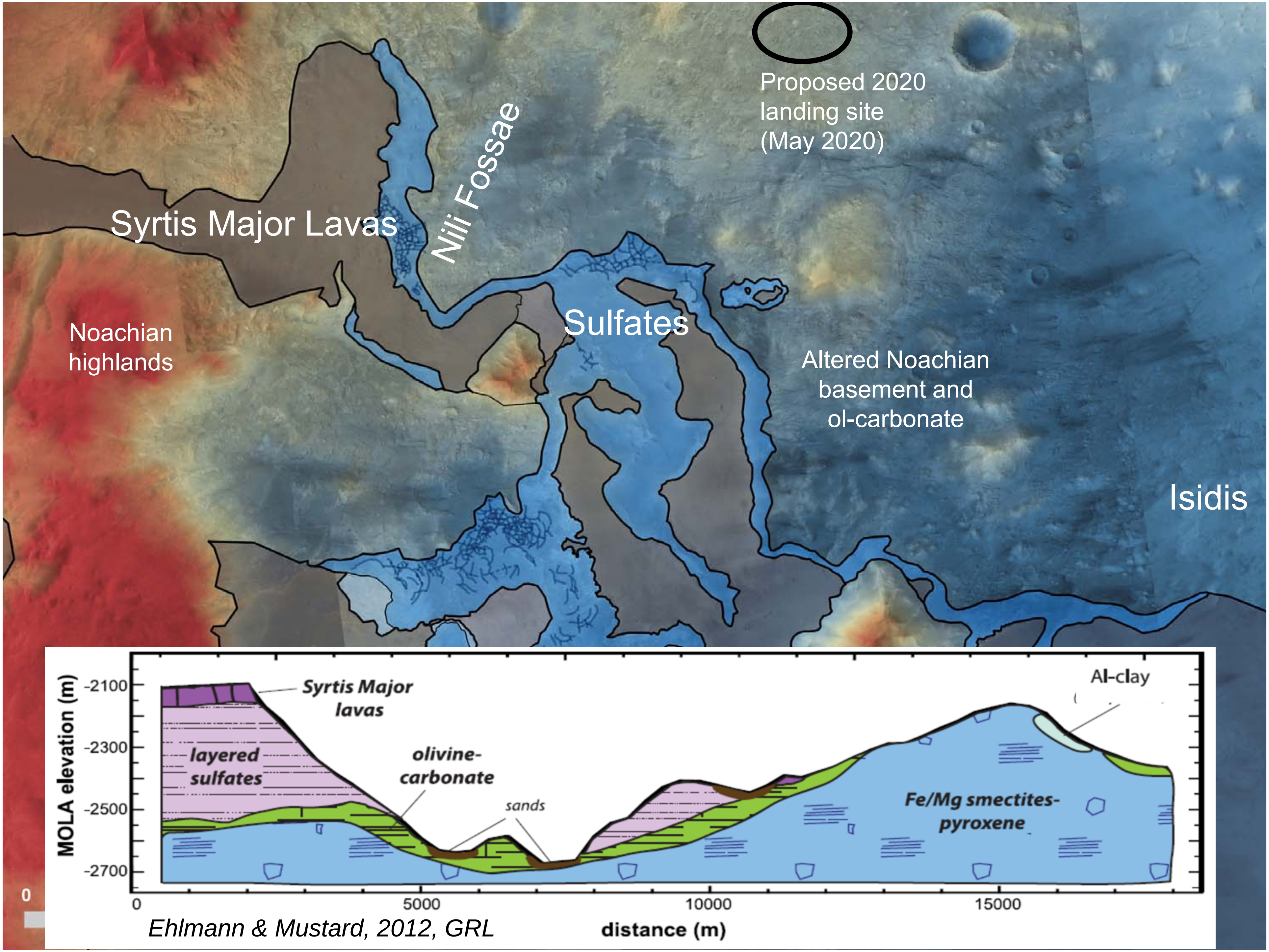
Also applicable to impacted, glassy materials



Sedimentary Sulfates (go-to): Nature of the Habitable Environment, Biosignature Search Strategy

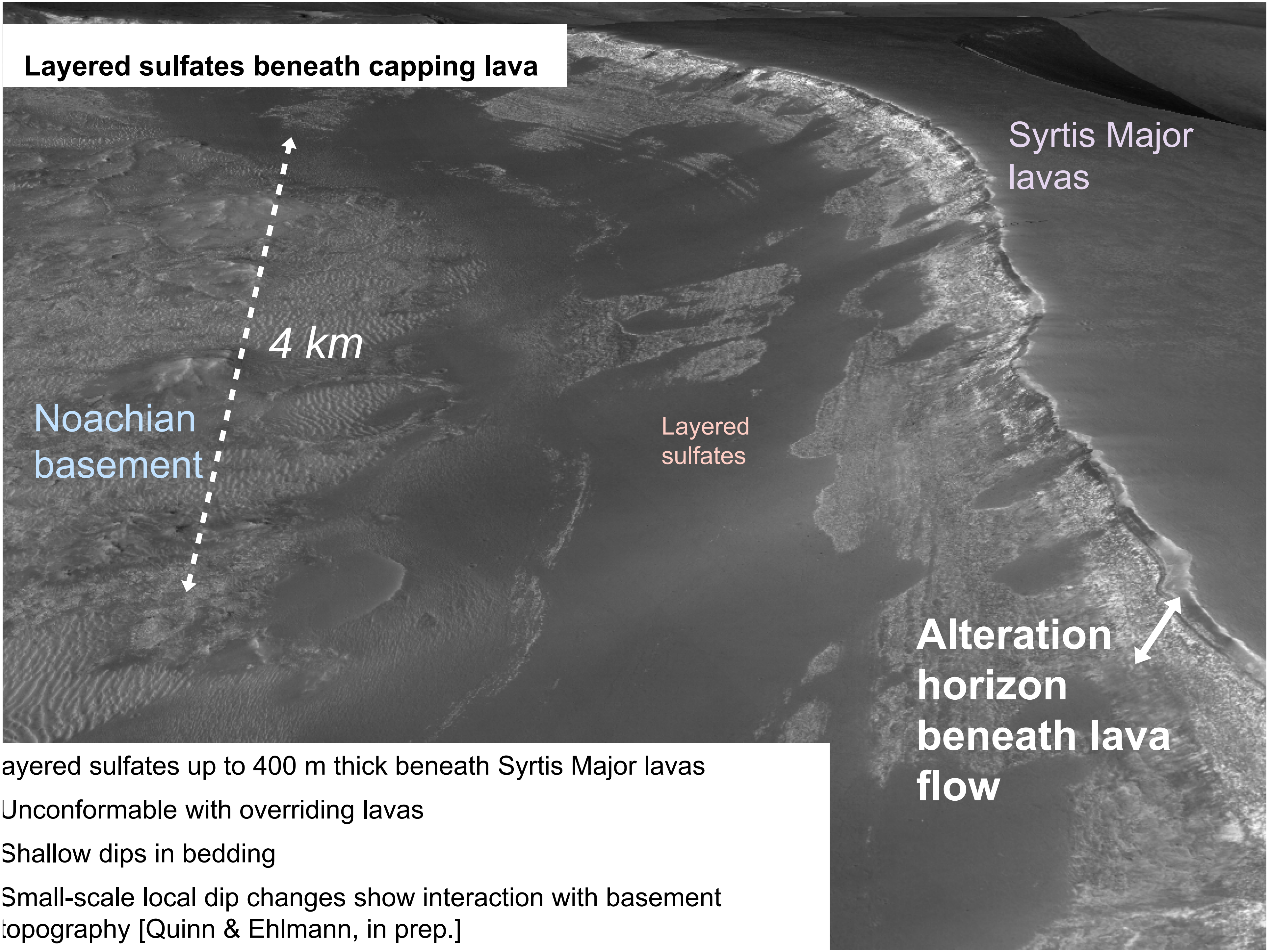


Proposed 2020
landing site
(May 2020)
Nili Fossae
Syrtis Major Lavas
Sulfates
Noachian
highlands
Altered Noachian
basement and
ol-carbonate
Isidis
0
10
20
30
40
50 km



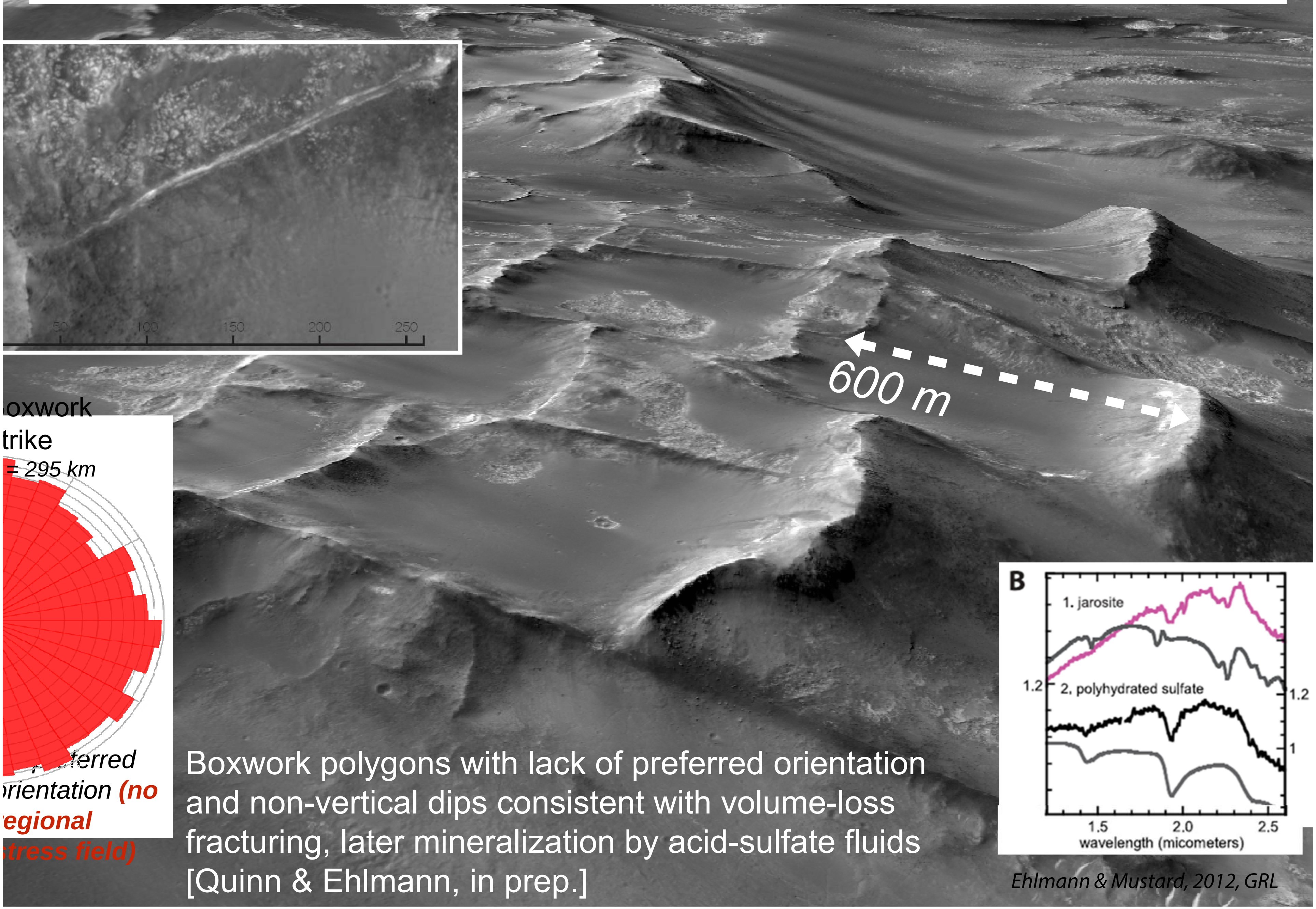
Ehlmann & Mustard, 2012, GRL

Layered sulfates beneath capping lava



- ayered 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.]

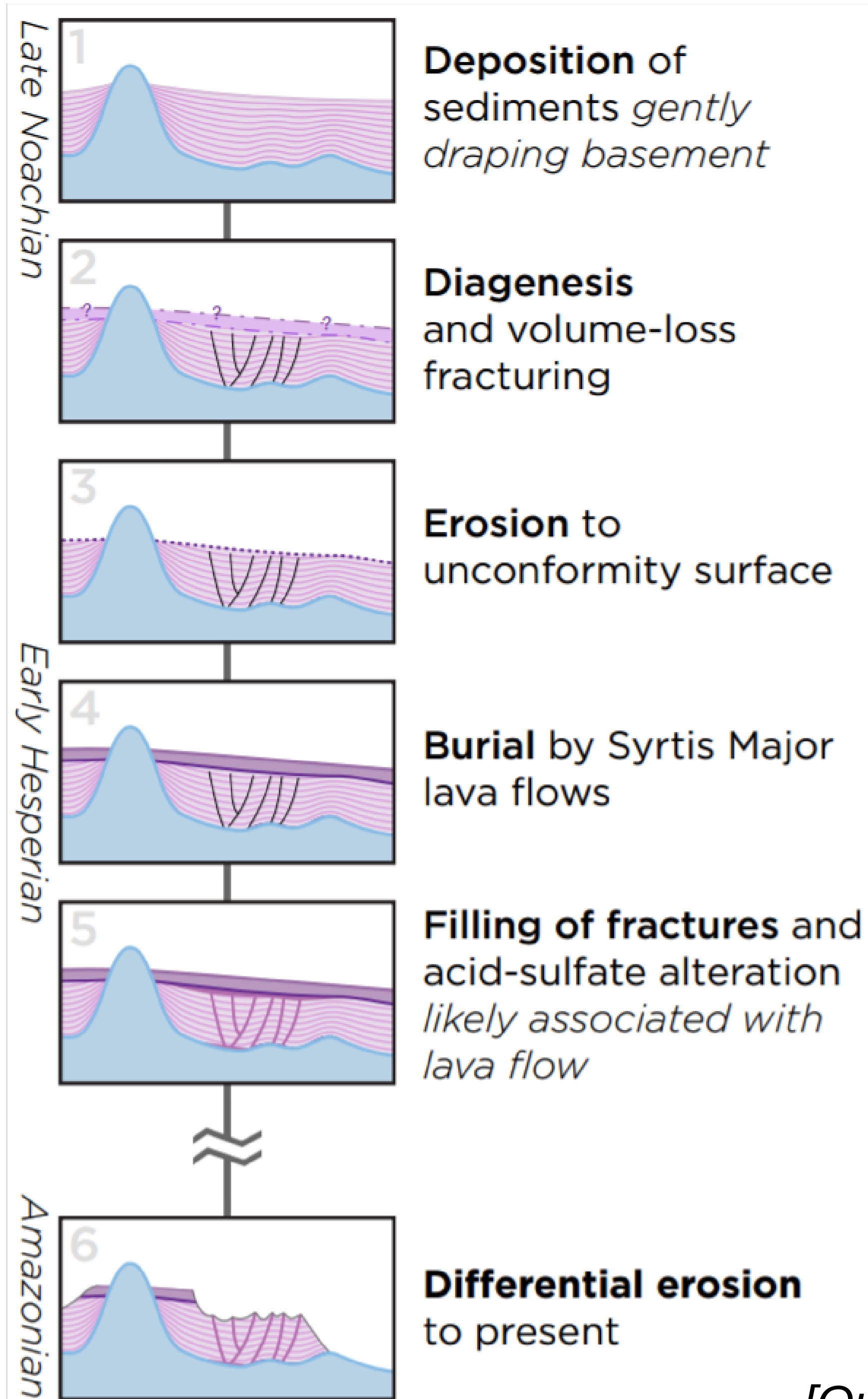
Boxwork polygons: filled volume-loss fractures



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

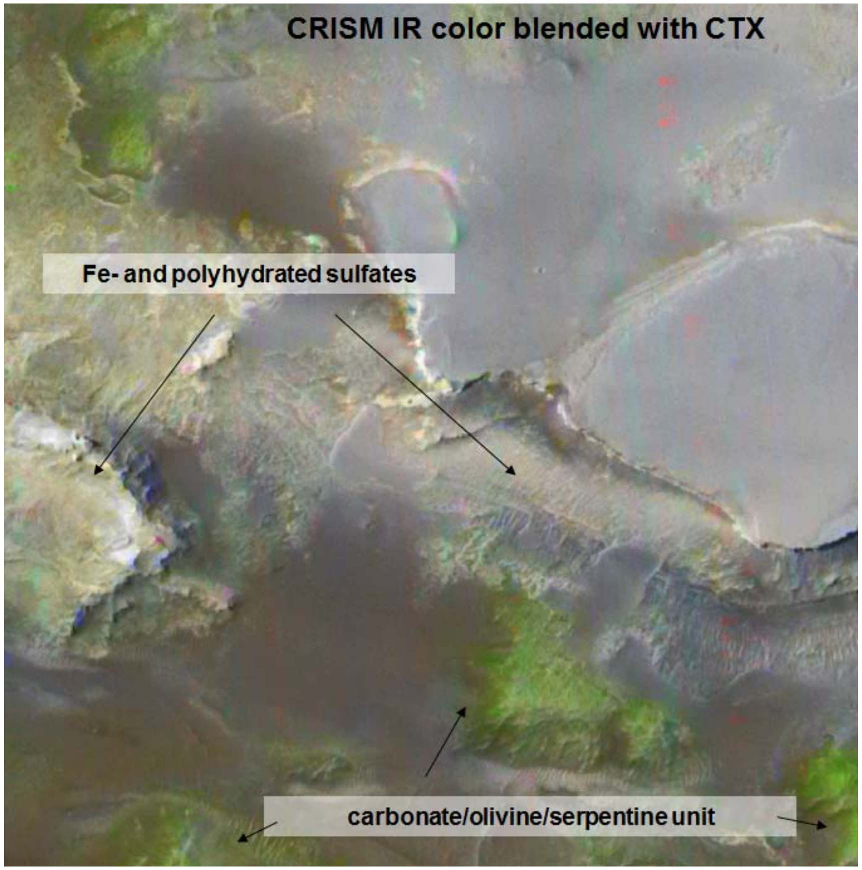


[Quinn & Ehlmann, in prep.]

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**

Cross the carbonate-jarosite contact



Ehlmann & Mustard, GRL, 2012

<u>Biosignature model:</u>

- Seeking organics entombed in polyhydrated sulfate sediments
- *Redox interfaces in Fe-redox reactions*

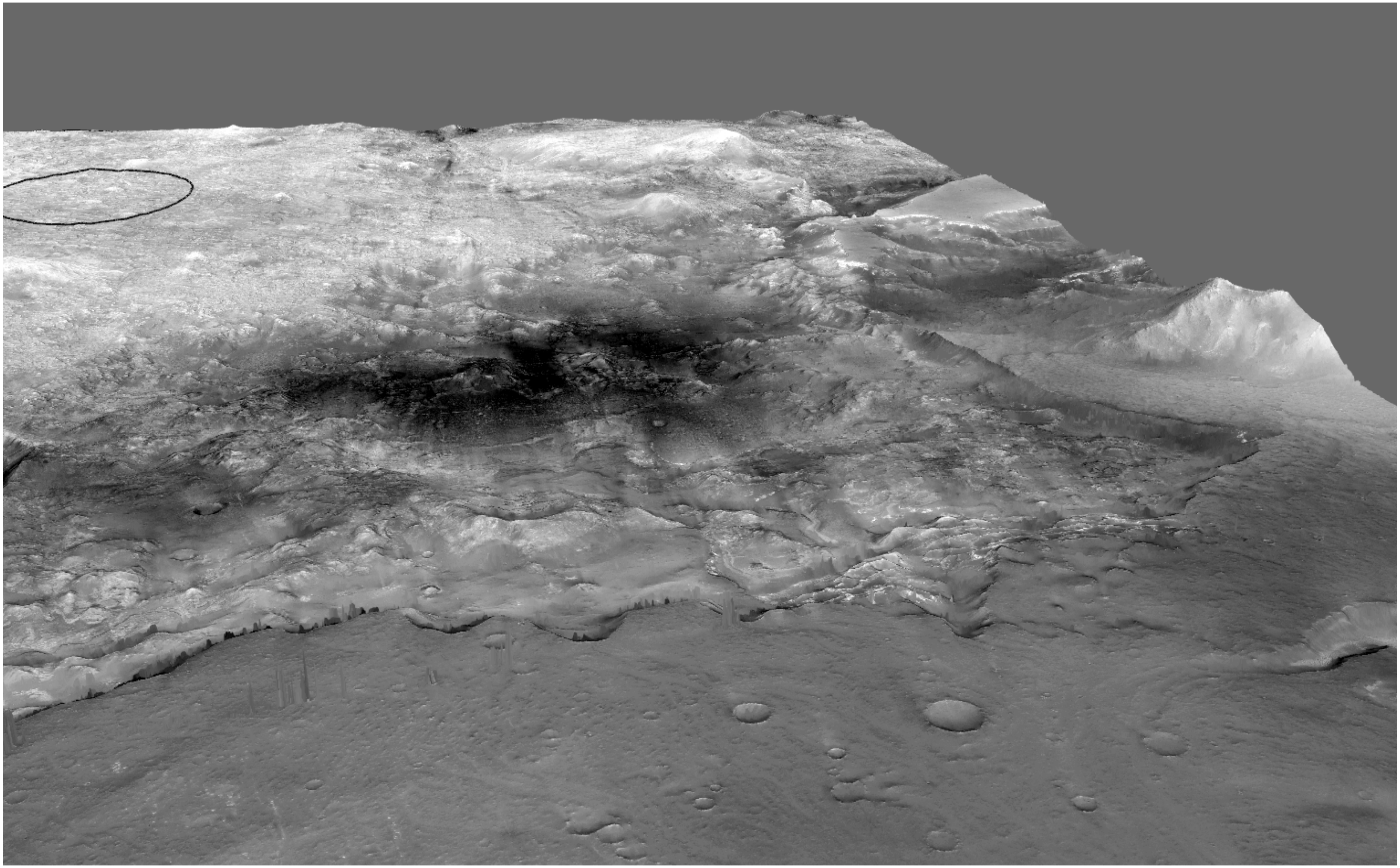
Northeastern Syrtis Major Mesas

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. <u>Here, in place</u>.
    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**: CO_2 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)

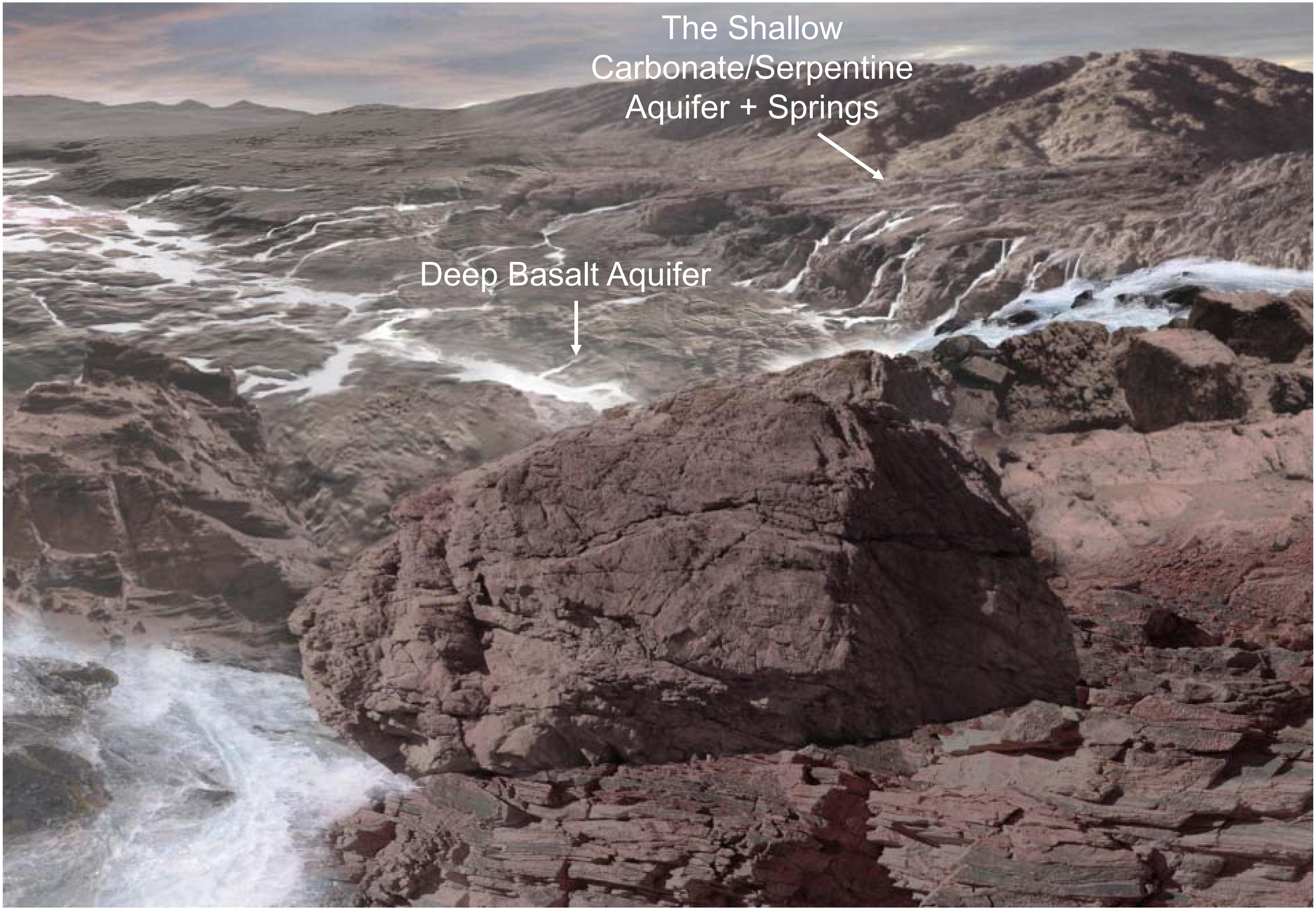
<u>Thus, fulfills all the objectives for Mars-2020 in situ exploration and sample return</u>

CTX DEM: 2x vertical exaggeration



By D. Berry for National Geographic

By D. Berry for National Geographic



By D. Berry for National Geographic

Northeast Syrtis ROI Science

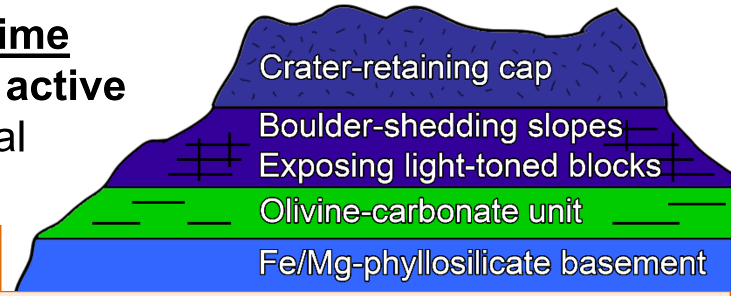
NES

submitted Dec 2016 to the Mars-2020 project by Mustard/Bramble/Ehlmann

Jet Propulsion Laboratory
California Institute of Technology

Mars 2020 Project

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** (mafic 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

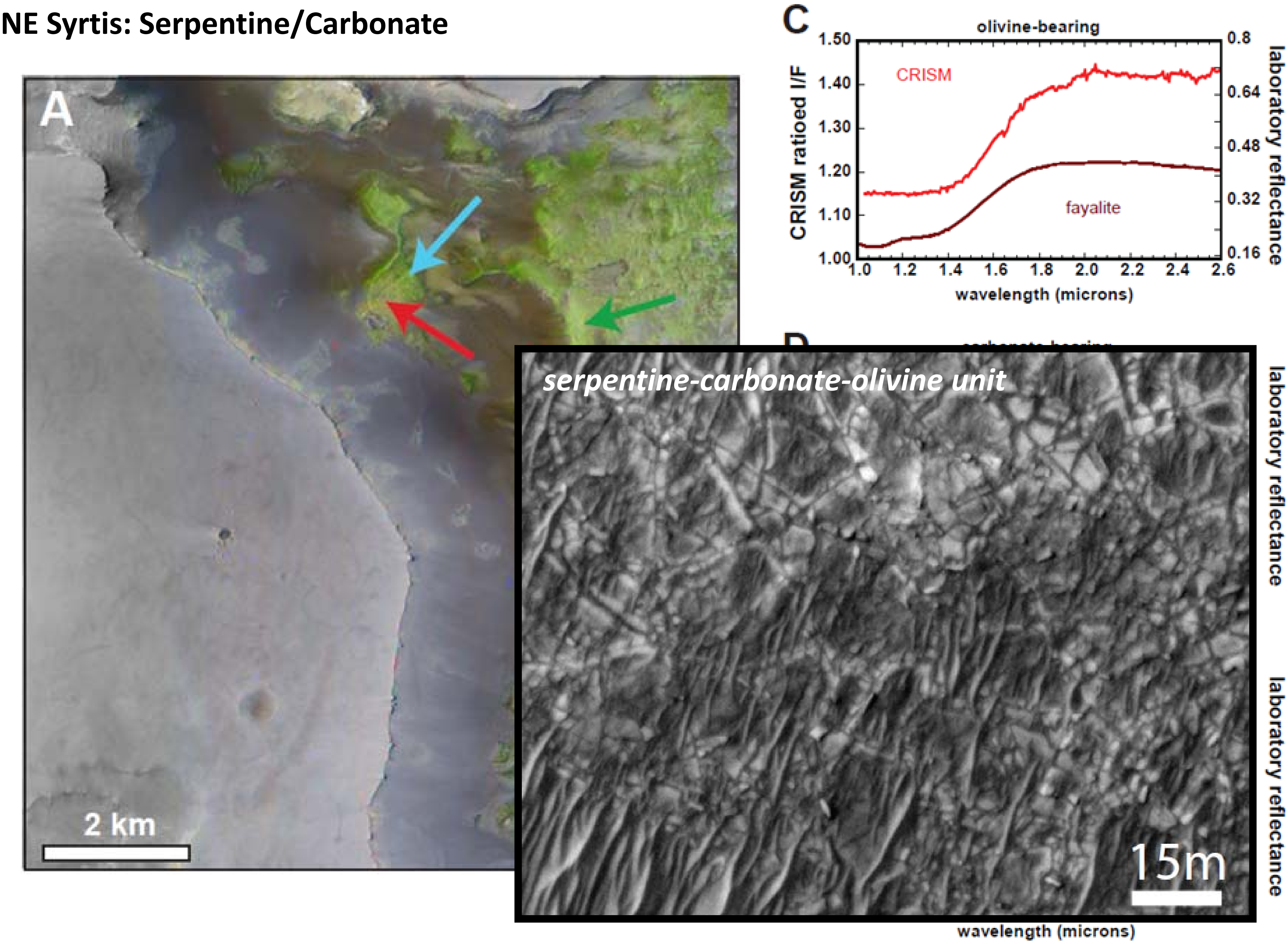
- **Regionally extensive carbonates** represent either near-subsurface mineralization of host rock or travertine-like mineral springs precipitation – either has **high biosignature preservation potential**
- The **Noachian clay basement and breccia blocks within preserve rocks from the time Mars had 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

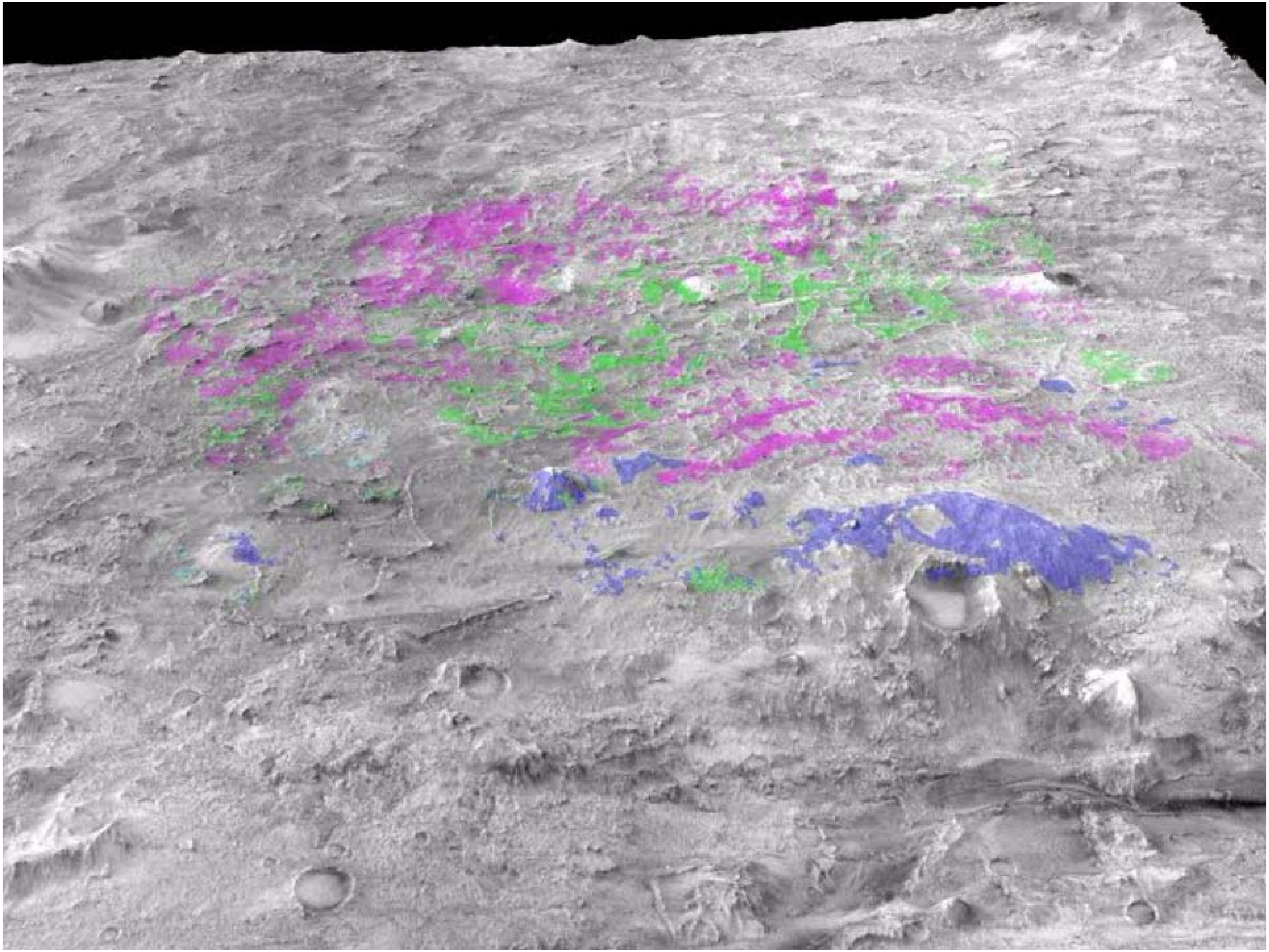
Cache scientifically compelling samples

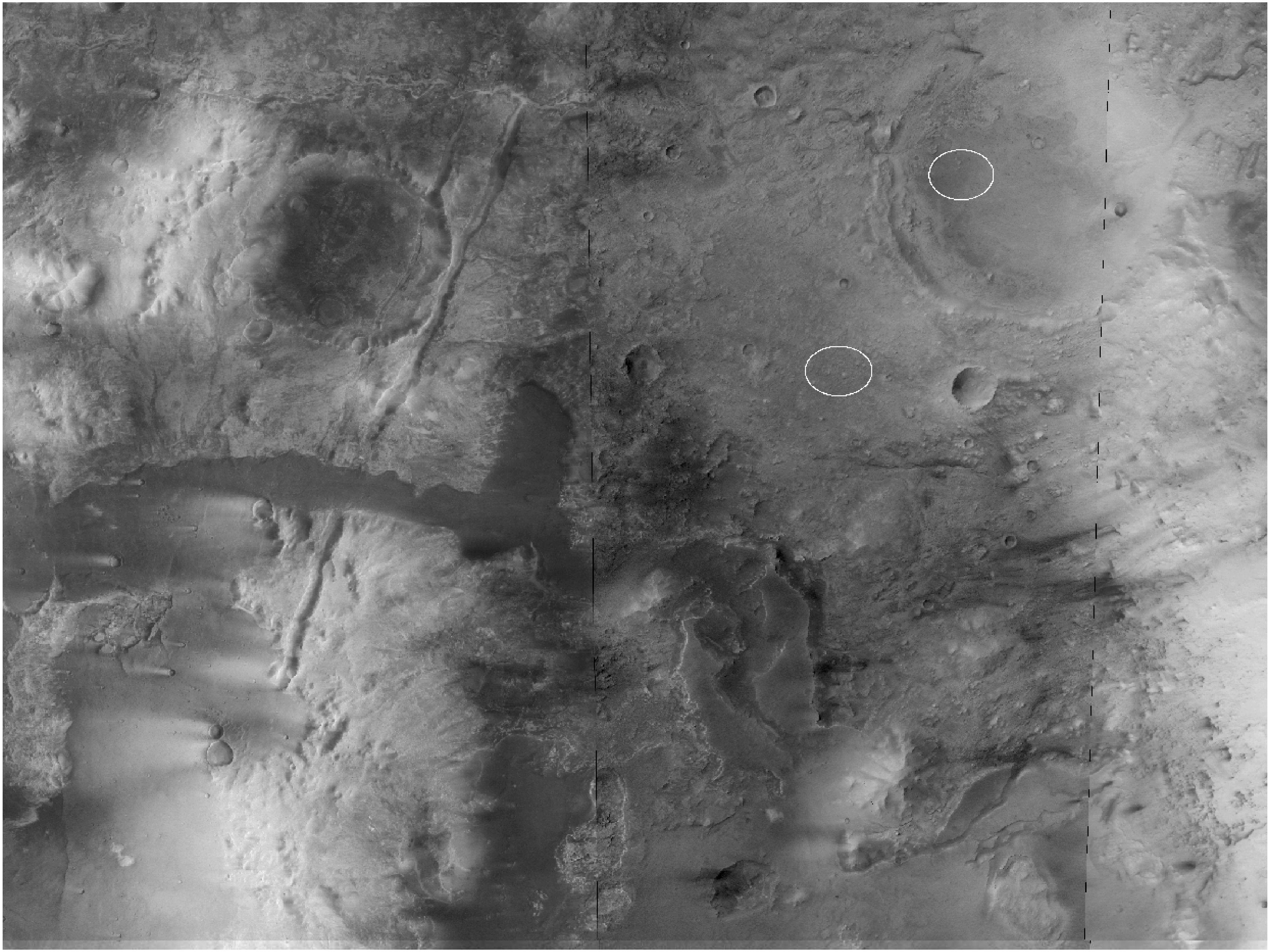
- **4 aqueous environments** (early clays, early carbonates, weathering horizons, *go-to sulfate sediments*) have distinct astrobio. potential, record of atm. evolution, volatile sequestration for traditional, clumped isotopes
- **4 age-date pins** for Martian chronology (1) Isidis-formed melt within 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

EXTRAS

NE Syrtis: Serpentine/Carbonate





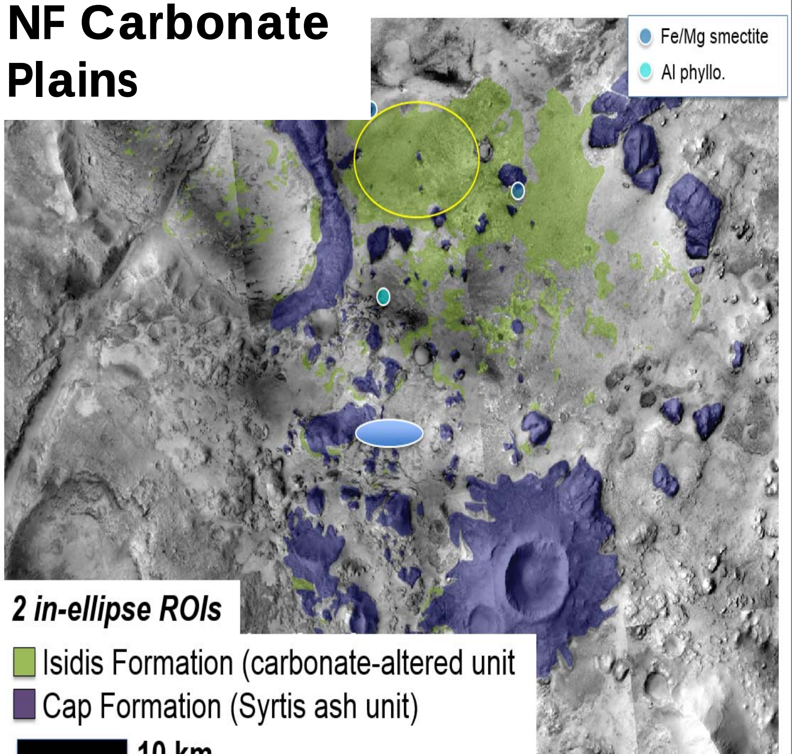


Testing the Ocean Hypothesis – PUT EARLY

- 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

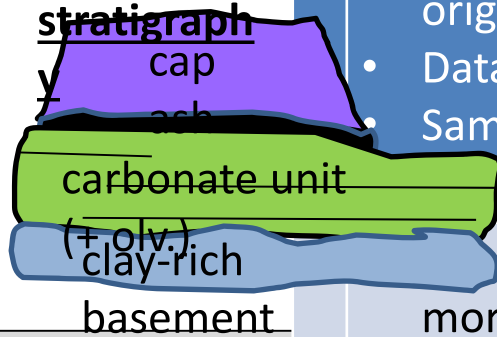
NF Carbonate Plains



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)

NF Carbonates stratigraphy



*IMPORTANT (based on bar conversations): N
assessment. Traversability report of the old e
preclude a vote for this site if you support th

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
- Datableigneous units for CFD calibration
- Sample Early N. to Early Hesp. isotopic record
  nviro change

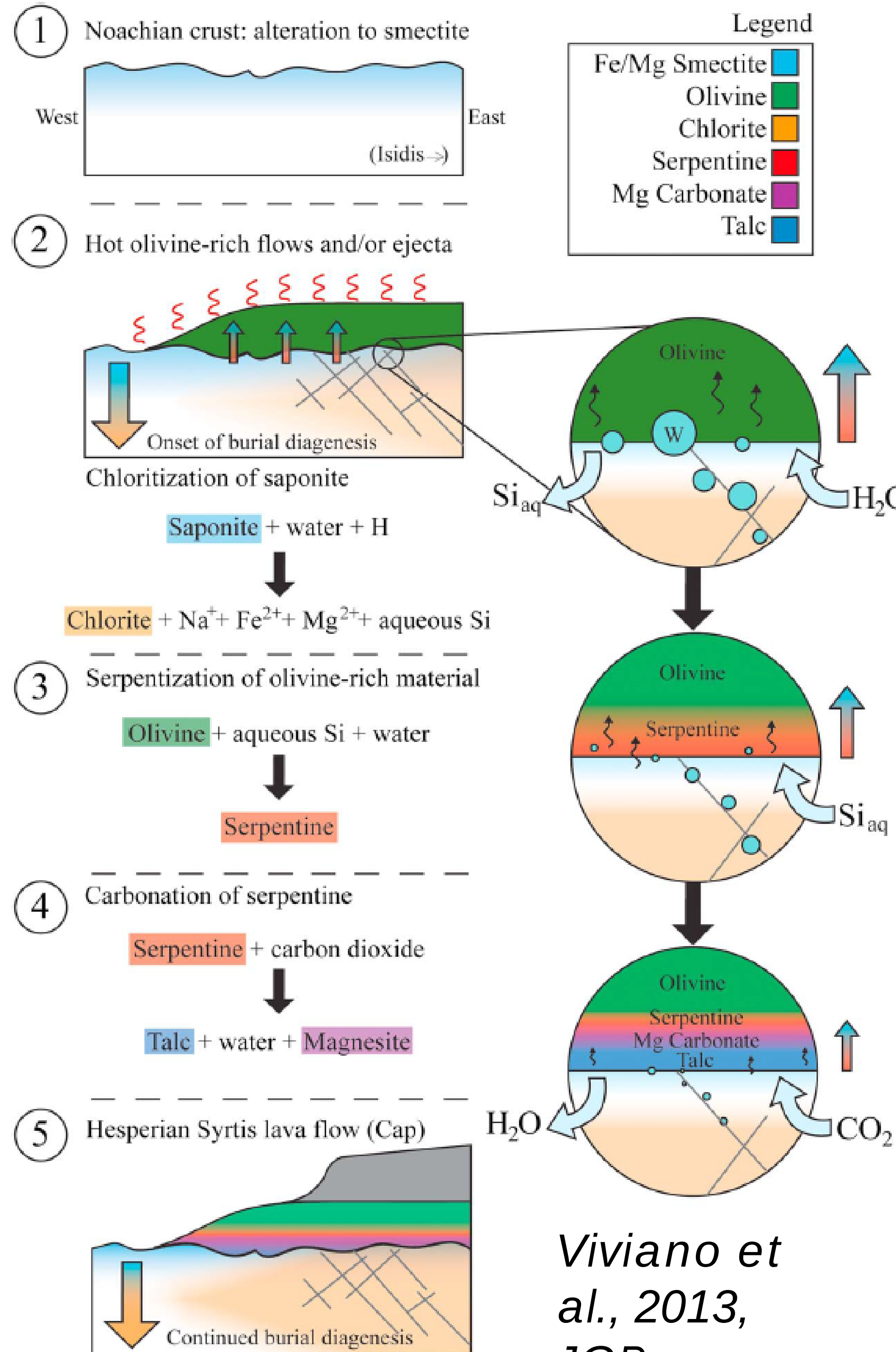
CONS

opic, mineralogical, chemical, /
morphological biosignatures can be prese in
multiple enviro settings; however, organics
preservation potential of carbonate will not be

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



Viviano et al., 2013, JGR

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