Nili Fossae Carbonate Plains

Land-on science to explore and sample early aqueous environments, reservoirs of carbon, and the history of Mars' igneous evolution

To lean more, download the 30+ papers on the broader region at ftp://ftp.gps.caltech.edu/pub/Ehlmann/mars2020

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2nd Mars 2020 Landing Site Workshop
August 4-6, 2015

Nili Fossae Carbonate Plains
Meets Mars-2020 Site Selection Criteria

Obj. A	1. **Geologic setting and history of the landing site can be characterized and understood** w/ orbital and in-situ obs.	green	-clear timing constraints (EN to EH) -multiple well-ordered strat. units -in situ petrology solves key questions
Obj. B	2a. Landing site w/ **ancient habitable enviro.**	green	-carbonate formation by neutral alk waters (HT or near surface)
	2b. **Rocks with high biosignature preservation potential** are available and **are accessible** to rover instr. astriobio. investigation.	green *or* yellow	-yes under HT hypothesis -yes under playa/basin hypothesis -maybe under weathering hypothesis
Obj. C	3a. Offers **abundance, diversity, and quality of samples suitable for addressing key astrobio. questions if/when they are returned** to Earth.	green	-record of critical EN To EH time period -multiple aqueous, potentially habitable environments -isotopic record of enviro change
	3b. Offers **abundance, diversity, and quality of samples for addressing key planetary evolution questions** if/when they are returned to Earth.	green	-yes under HT hypothesis -yes under shallow playa hypothesis -maybe under weathering hypothesis

Mars' Biggest Mysteries/Decadal-level questions

1) What is the nature of the Noachian crust/climate (>3.5 Gyr)?

2) Where is the carbon/water? (Mars' geochemical cycles?)

3) How heterogenous is the Mars mantle?

4) When did the dynamo cease? Impact on Habitability?

5) How old is the Martian surface?

*Are there biosignatures?

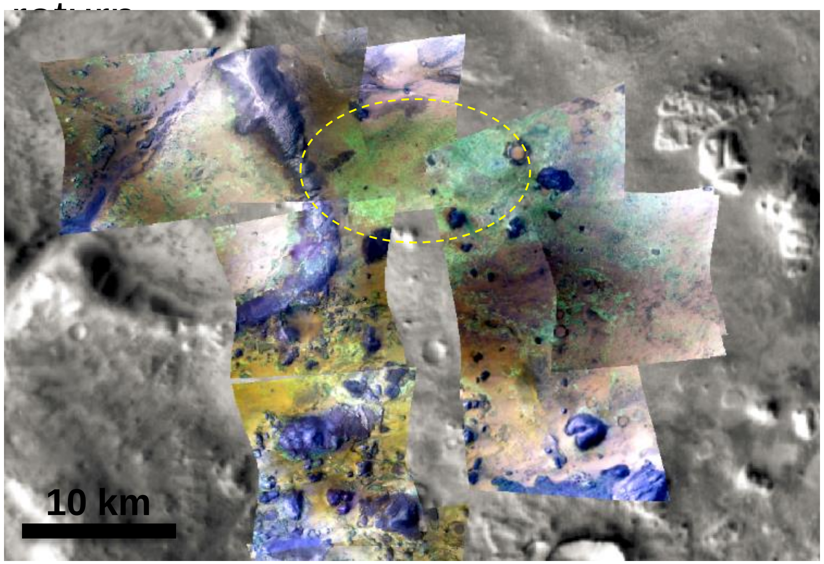
(1) Diverse, important questions required to drive return of cache

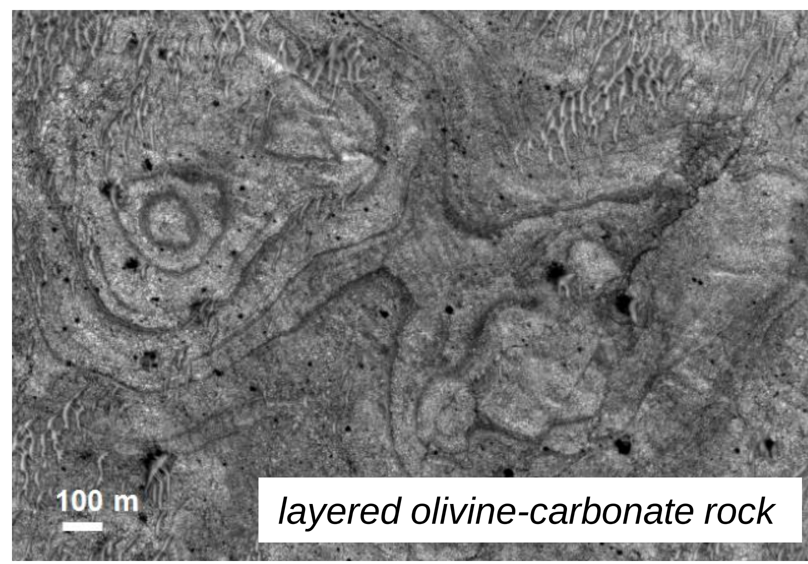
(2) Must explore/sample Pre-, Early-, Mid-Noachian

Nili Fossae Carbonate Plains Meets Mars-2020 Science Criteria

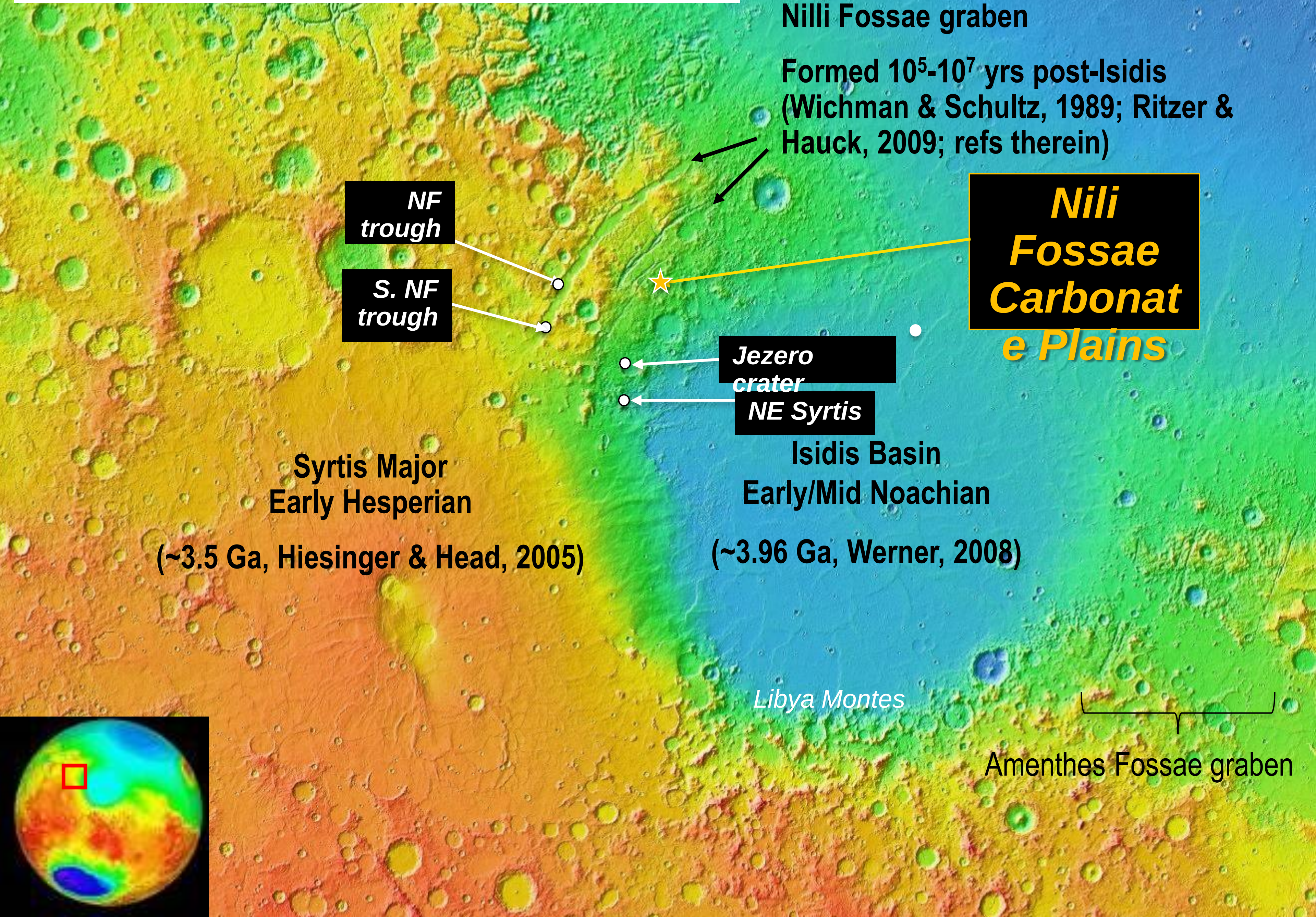
1. **Investigating Aqueous, Habitable Environments**: Largest exposure of carbonate-bearing rock on Mars, formed by precipitation from neutral/alkaline liquid water *[Ehlmann et al., 2008, Science; Niles et al., 2013, SSR]*
2. **Planetary Evolution & Understanding Sources and Sinks of the Martian Atmosphere** *[Edwards & Ehlmann, 2015, Geology; Hu et al., in rev., Nat. Comm.]*
3. **Planetary Evolution & Igneous Processes**: Capping later mafics overly the largest olvine-rich (ultramafic?) rock unit on Mars, comprised of fluid lavas or impact-excavated mantle cumulates *[Hoefen et al., 1997, Science; Hamilton & Christensen, 2005, Geology; Mustard et al., 2007; 2009, JGR; Tornabene et al., 2012, JGR]*

Thus, site fulfills key science objectives for Mars-2020 in situ science and sample return

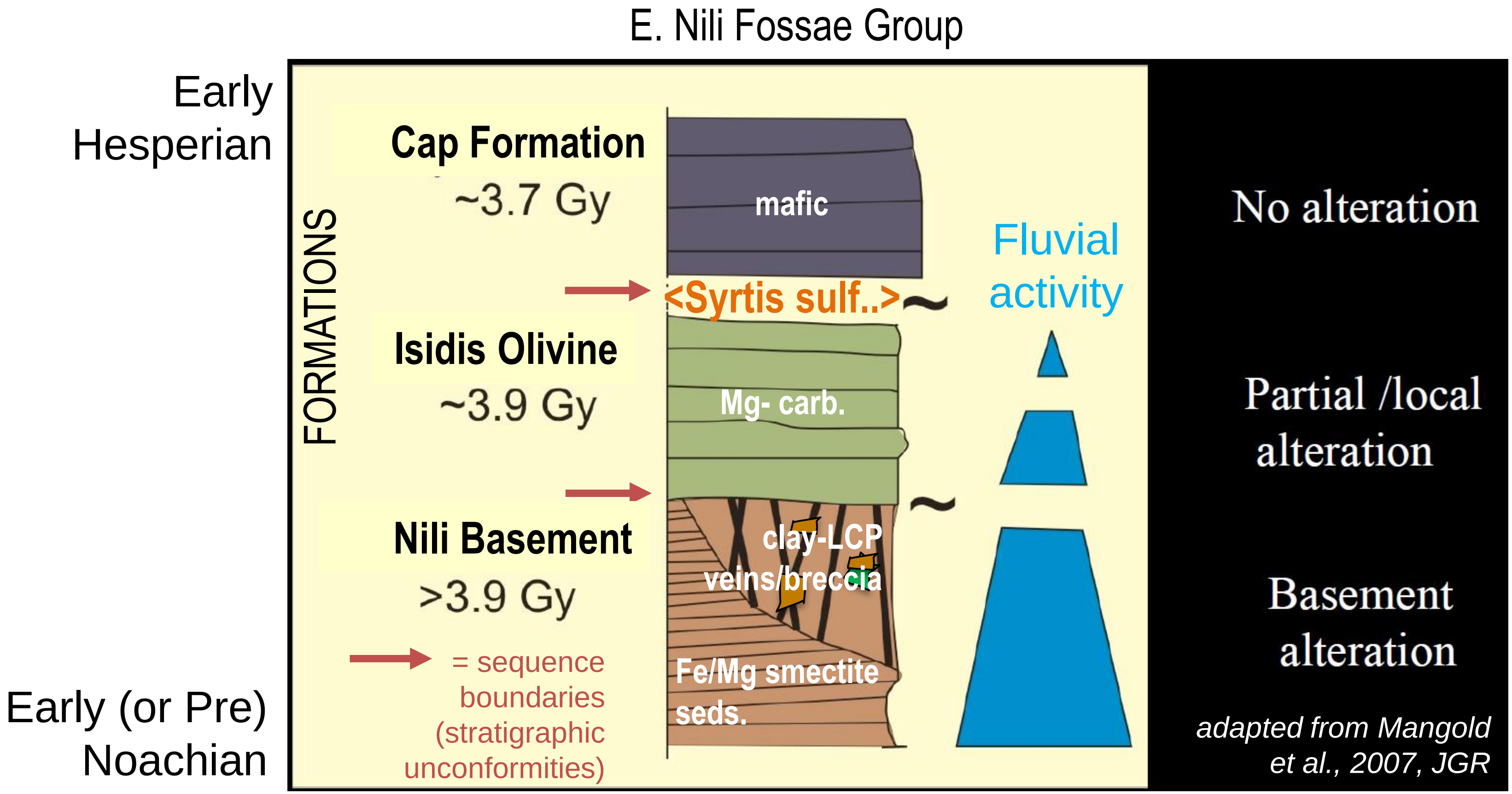




Three large-scale temporal constraints



Eastern Nili Fossae Group: Distinctive Lithostratigraphic Sequences

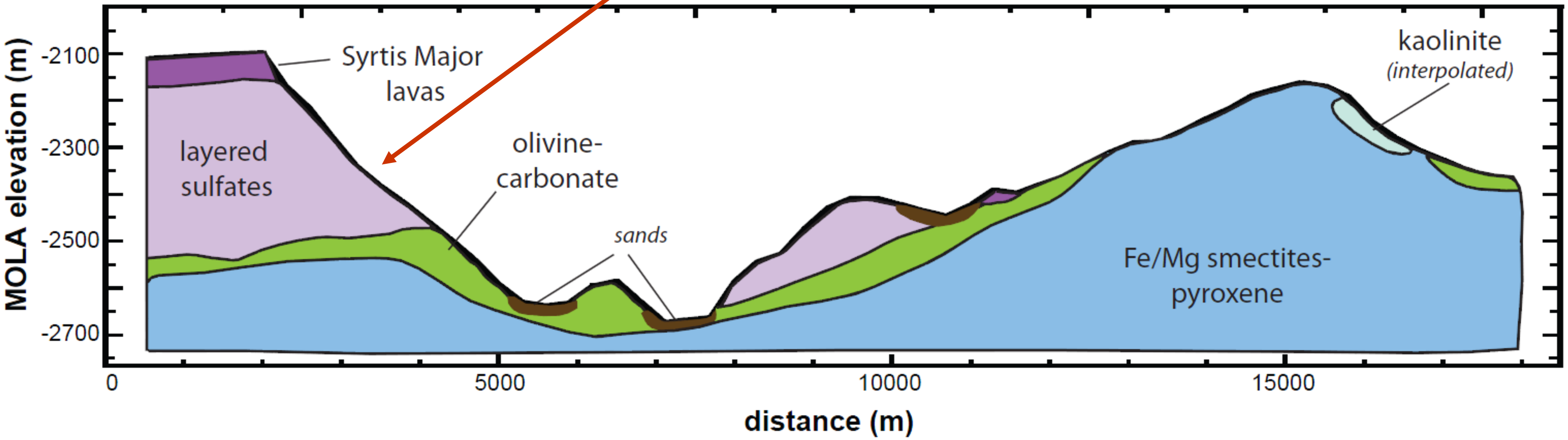


- Nili Basement Formation: regional in extent. Units in this formation near NF Carbonate Plains site are similar to units described for Nili Trough and NE Syrtis
- Isidis Olivine Formation is restricted to the Eastern Nili Fossae, variably bears the Mg-carbonate
- Cap Formation: Syrtis lavas are not present at Carbonate Plains landing ellipse; a Syrtis ash unit, apparently contemporaneous, is.

Part of a Regionally Extensive, Time-Bracketed and Well-Understood Section

Syrtis Sedimentary Sulfate Formation at NE Syrtis site is absent at NF Carbonates site; otherwise, same formations

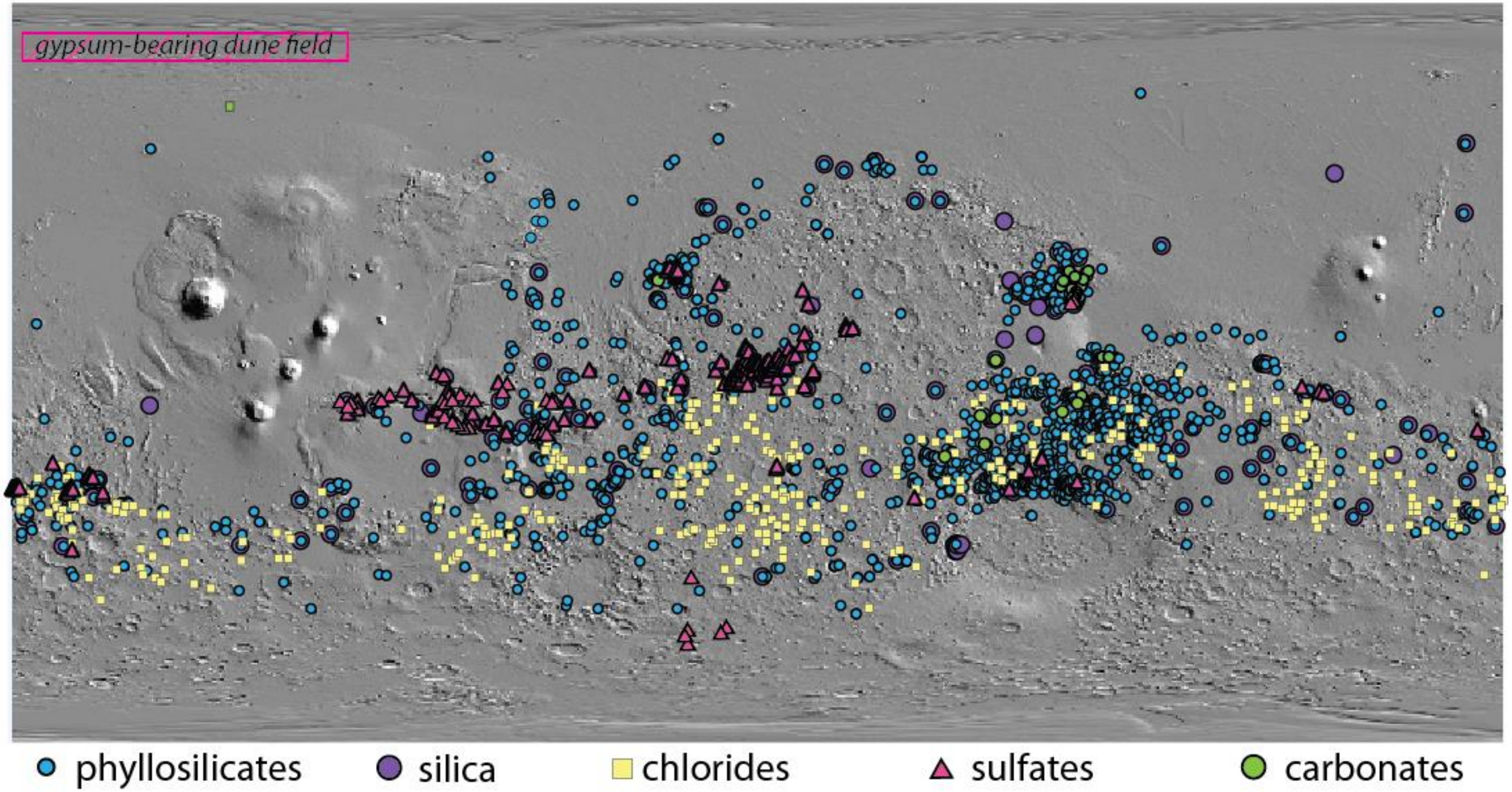
Ehlmann & Mustard, GRL, 2012



- Similar to NE Syrtis stratigraphy (100s km away) except no sulfates within rover drive distance and Syrtis Formation caprock is demonstrably not lava (low TI=ash)
- Age Brackets are the same:
  - Lower (oldest): Age of the Isidis impact disrupted the Fe/Mg smectite/pyroxene unit (parts are brecciated) (Early Noachian, ~3.9 Ga; Werner, 2008, Icarus)
  - Upper (youngest): Overlying mafics, Hesperian Syrtis Major volcanic province (Early Hesperian, ~3.5 Ga, Hiesinger & Head, 2004, JGR)

NF Carbonate Landing Site:
A Globally Significant Locale…

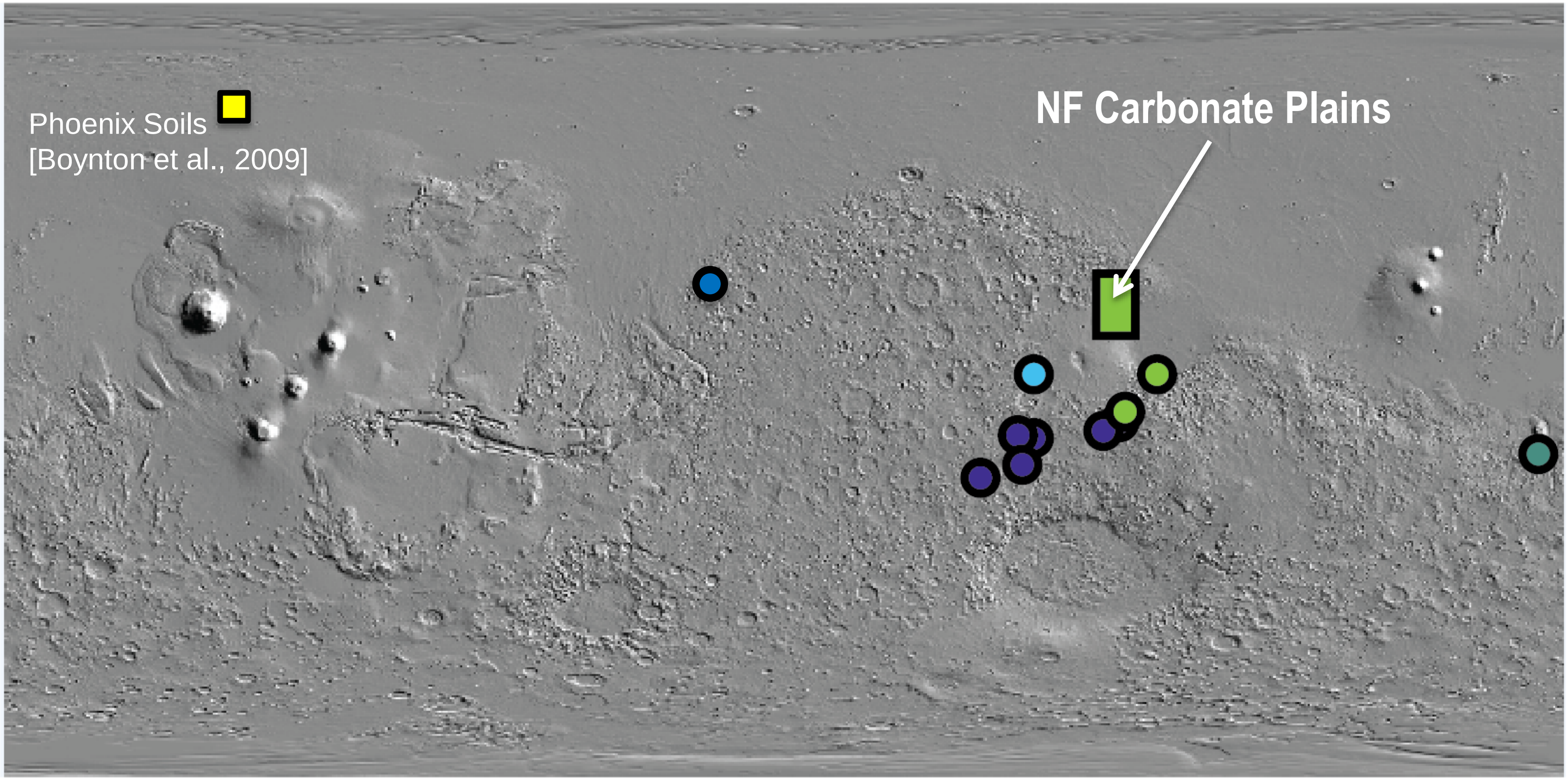
Carbonate is rare among alteration minerals, in spite of global sampling and exposure of other phases…



Ehlmann & Edwards, 2014, Ann. Rev. Earth Plan. Sci.

NF Carbonate Plains is the largest, most contiguous, and most well-exposed Noachian carbonate bearing rock unit

(vs. those in crater walls/interiors and loose soils)



Mg-rich carbonate (Ehlmann et al., 2008)

$Mg_{0.62}Fe_{0.25}Ca_{0.11}Mn_{0.02}$carbonate (Morris et al., 2010)

Ca,Fe-carbonate (Michalski & Niles, 2010)

Ca,Fe-carbonate (Wray et al., 2011)

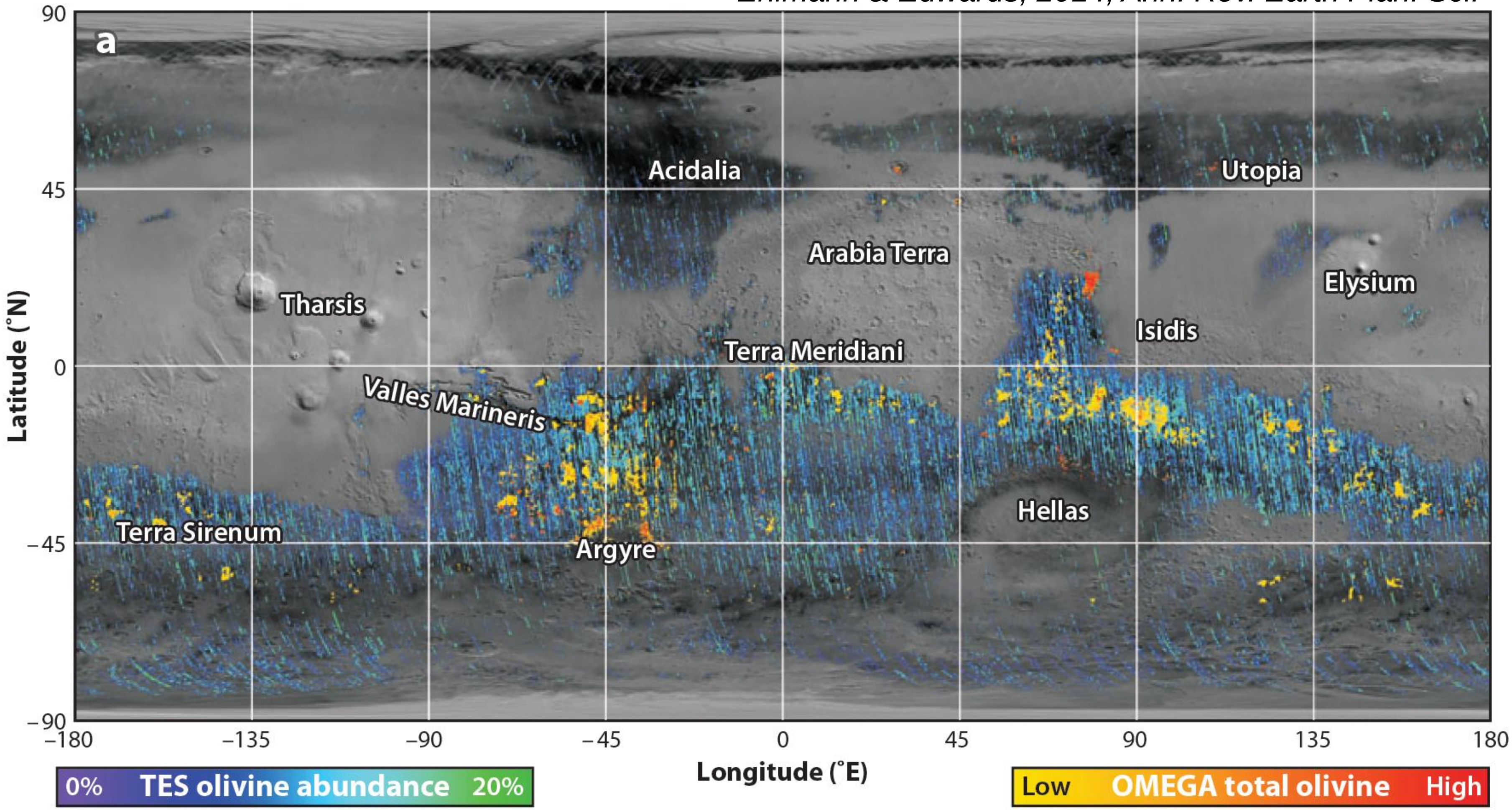
Ca,Mg- & Mg,Fe- carbonate in soils (Sutter et al., 2012)

Mg-carbonate (Michalski et al., 2013)

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

NF Carbonate Plains is also the largest contiguous exposure of high-olivine abundance rocks

Ehlmann & Edwards, 2014, Ann. Rev. Earth Plan. Sci.

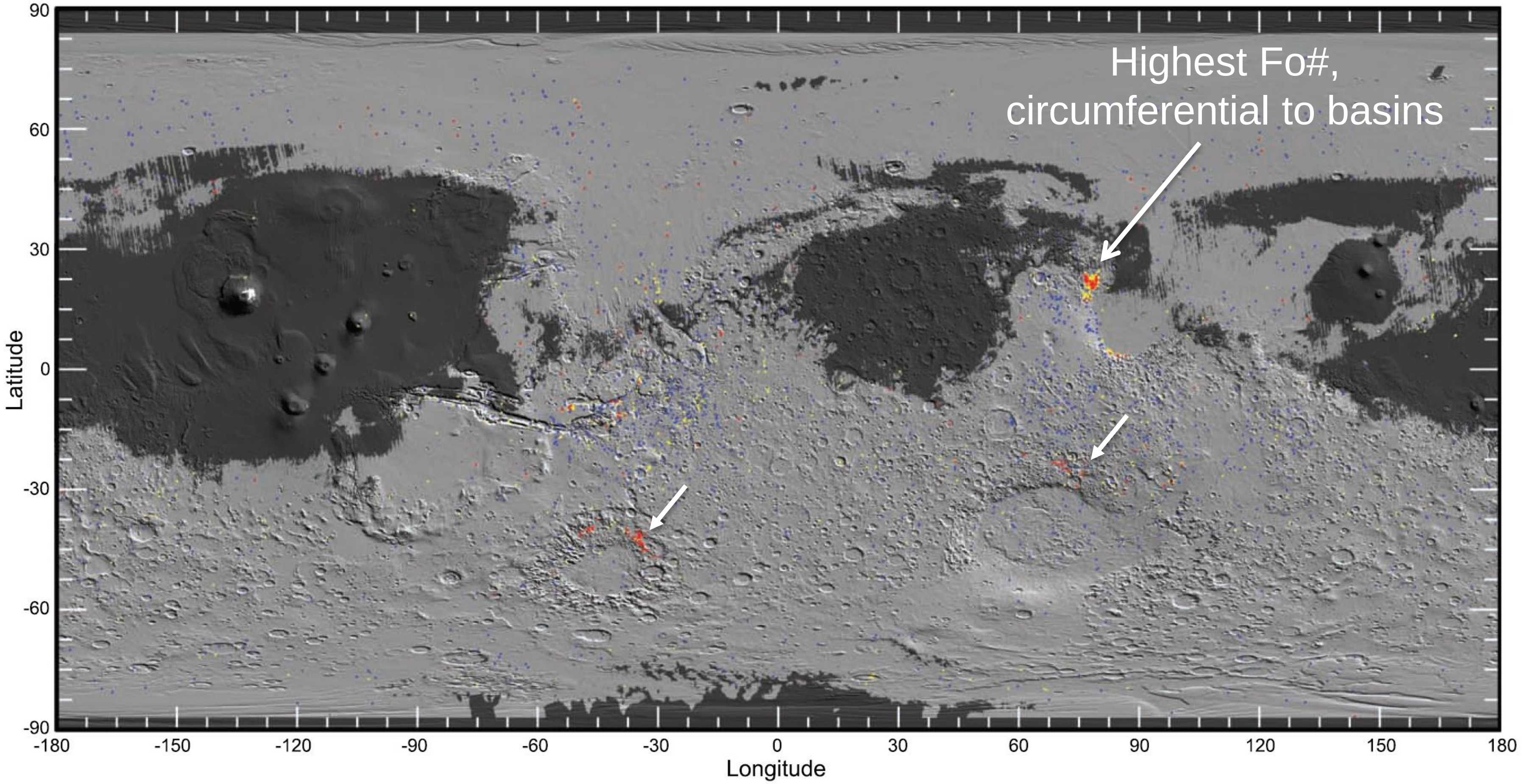


Koeppen & Hamilton, 2008, JGR

Ody et al., 2013, JGR

Includes high-Mg olivine from primitive melts or mantle

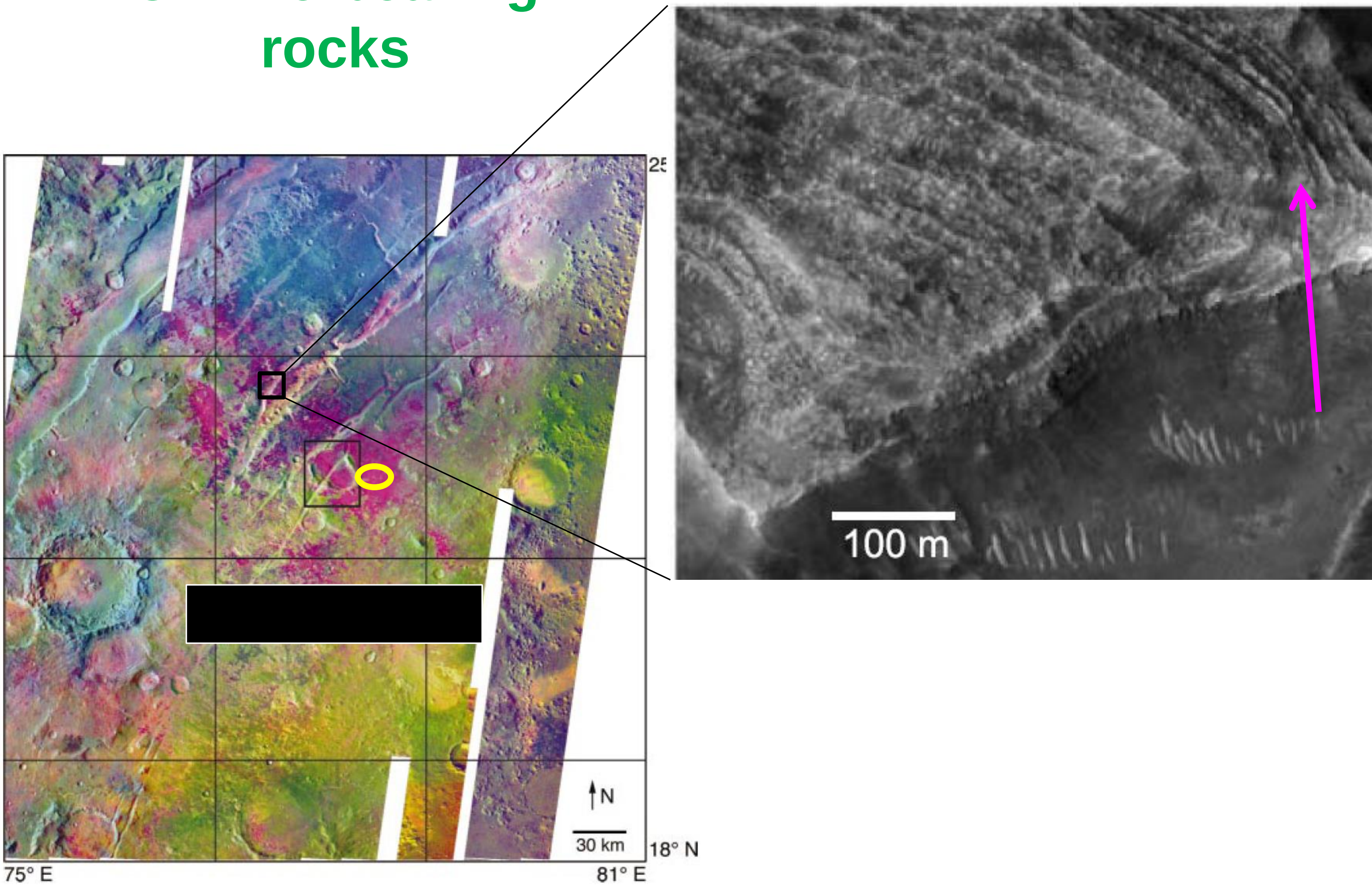
Koeppen & Hamilton, 2008, JGR



Fo75-100 Fo58-74 Fo42-57

Olivine-bearing rocks

Layered olivine-rich rocks, Nili Fossae

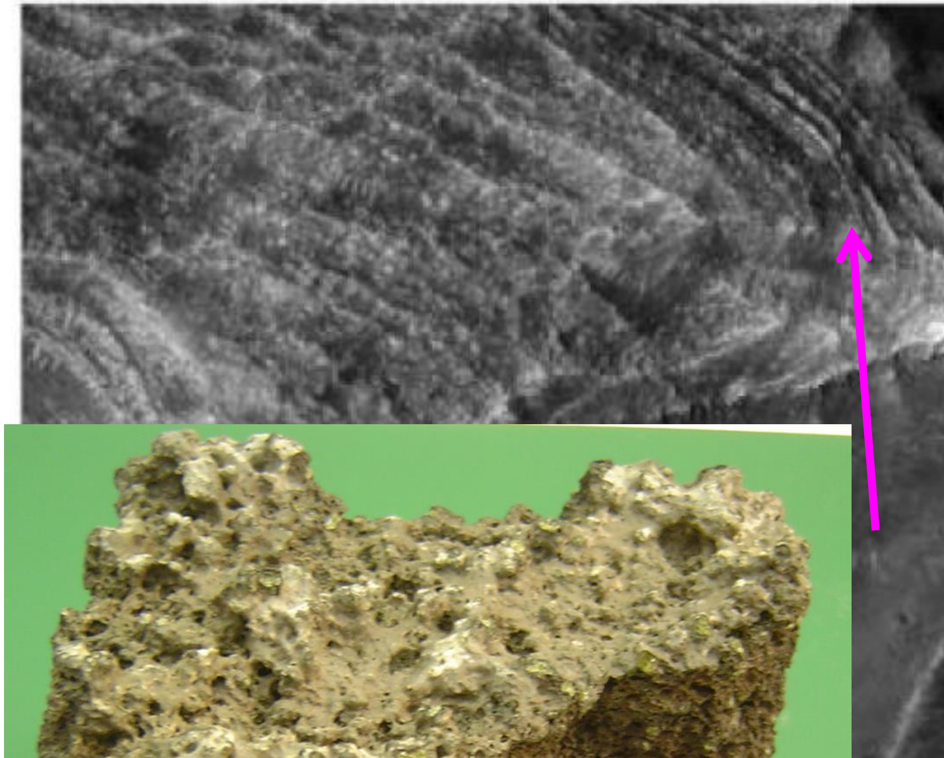


Hamilton et al, 2005, Geology

Isidis Olivine=phenocryst-rich lavas?

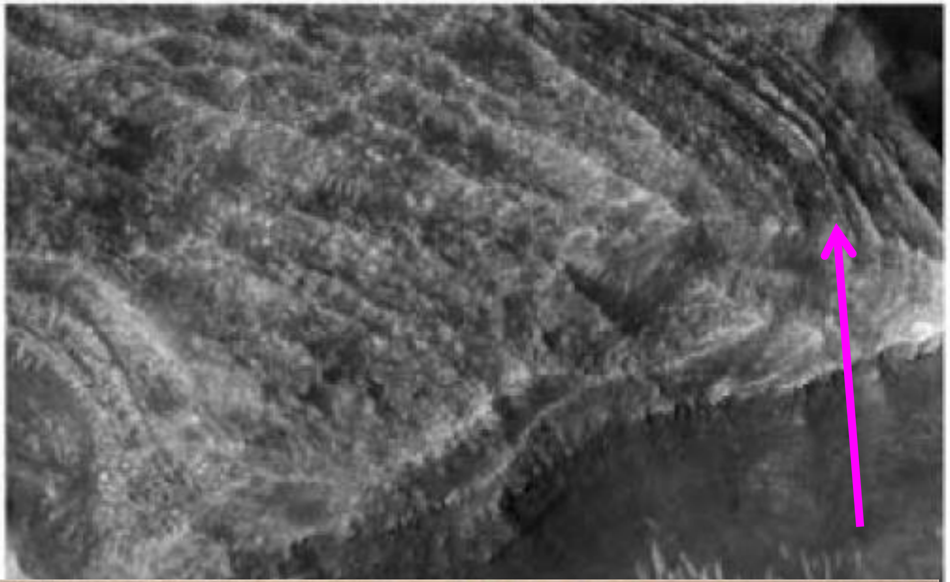
Kilauea, Hawaii

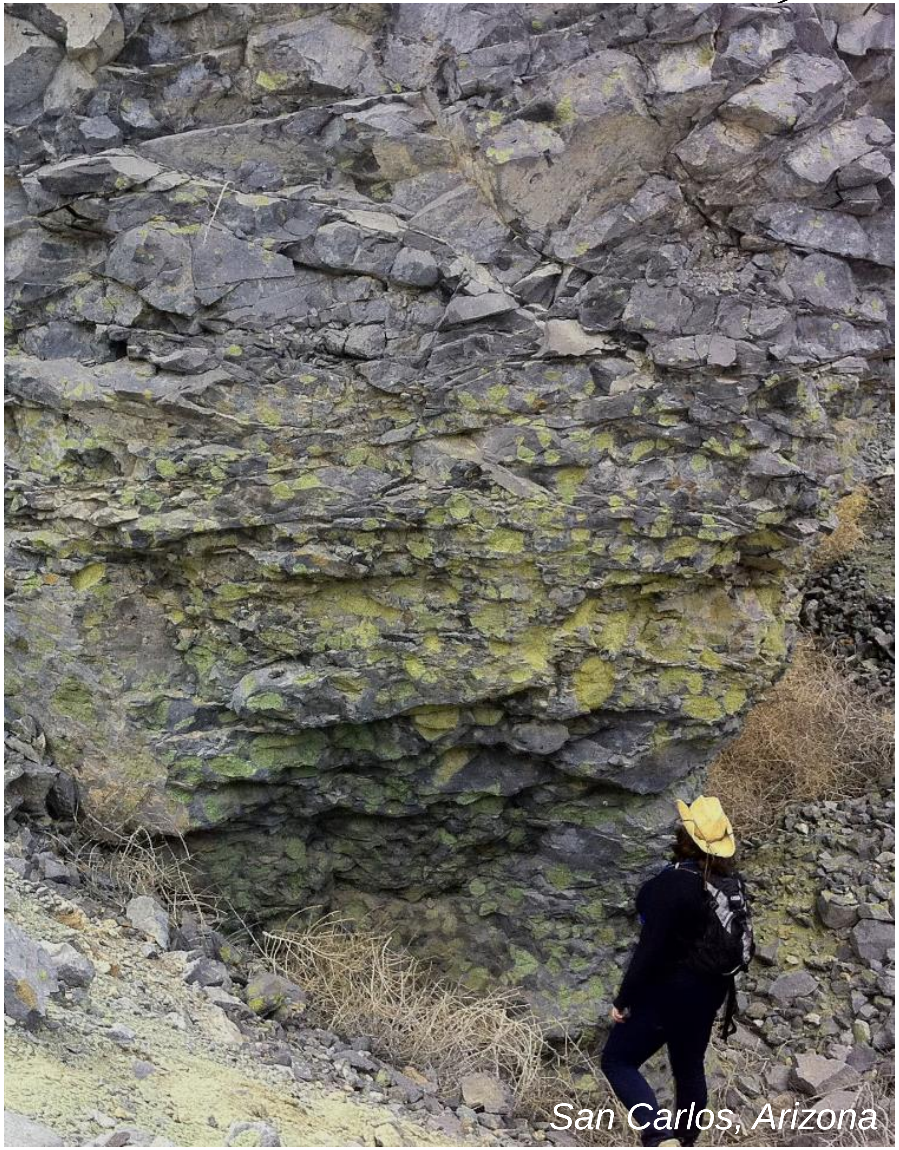
Layered olivine-rich rocks, Nili Fossae



Isidis Olivine=mantle cumulates, e.g. from impact melt, e.g.?

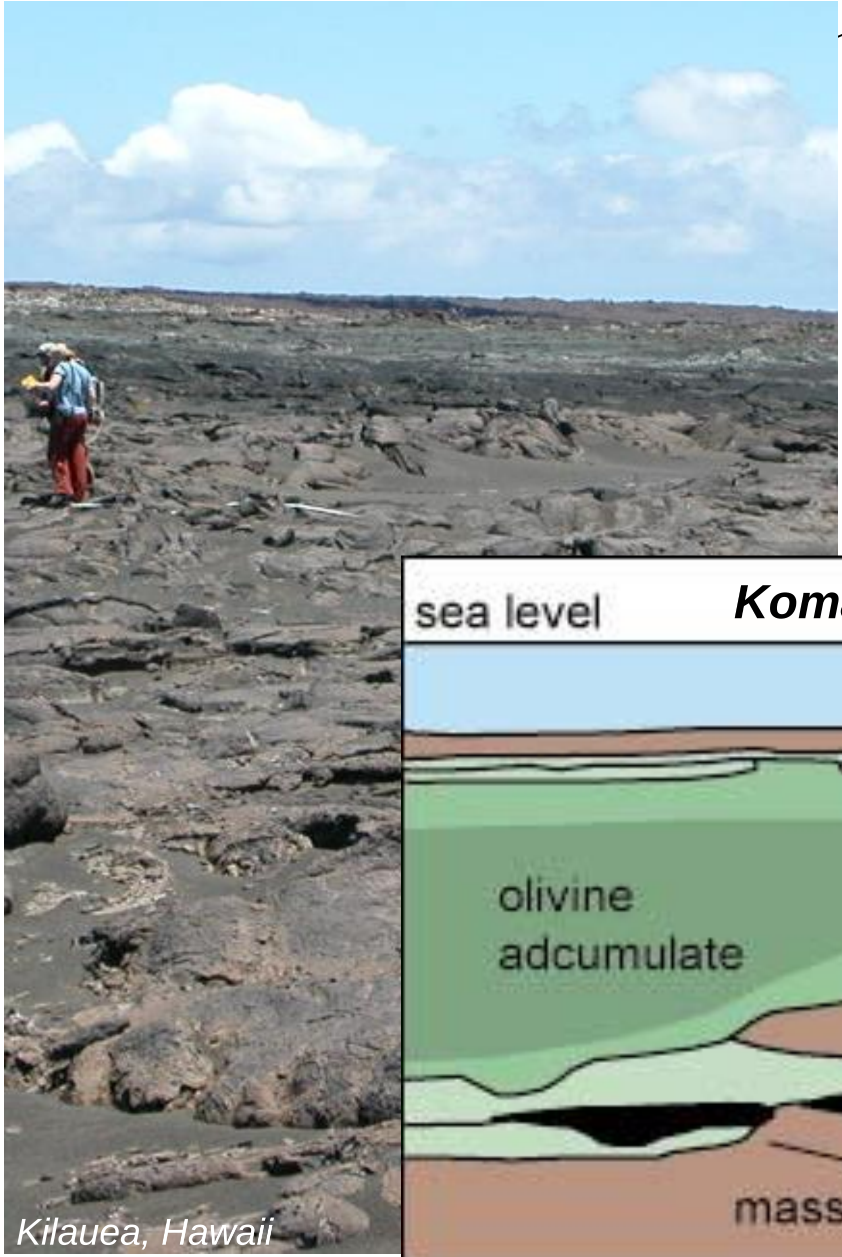
Layered olivine-rich rocks, Nili Fossae



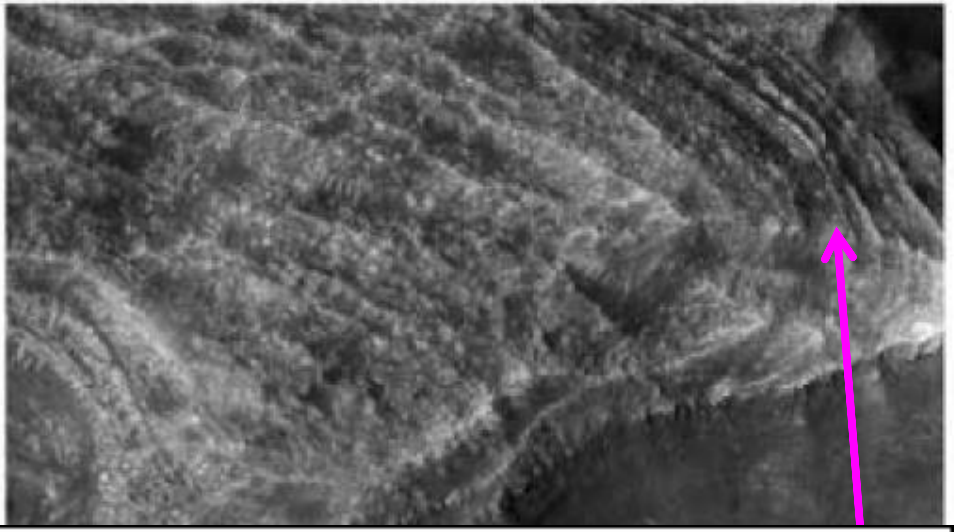


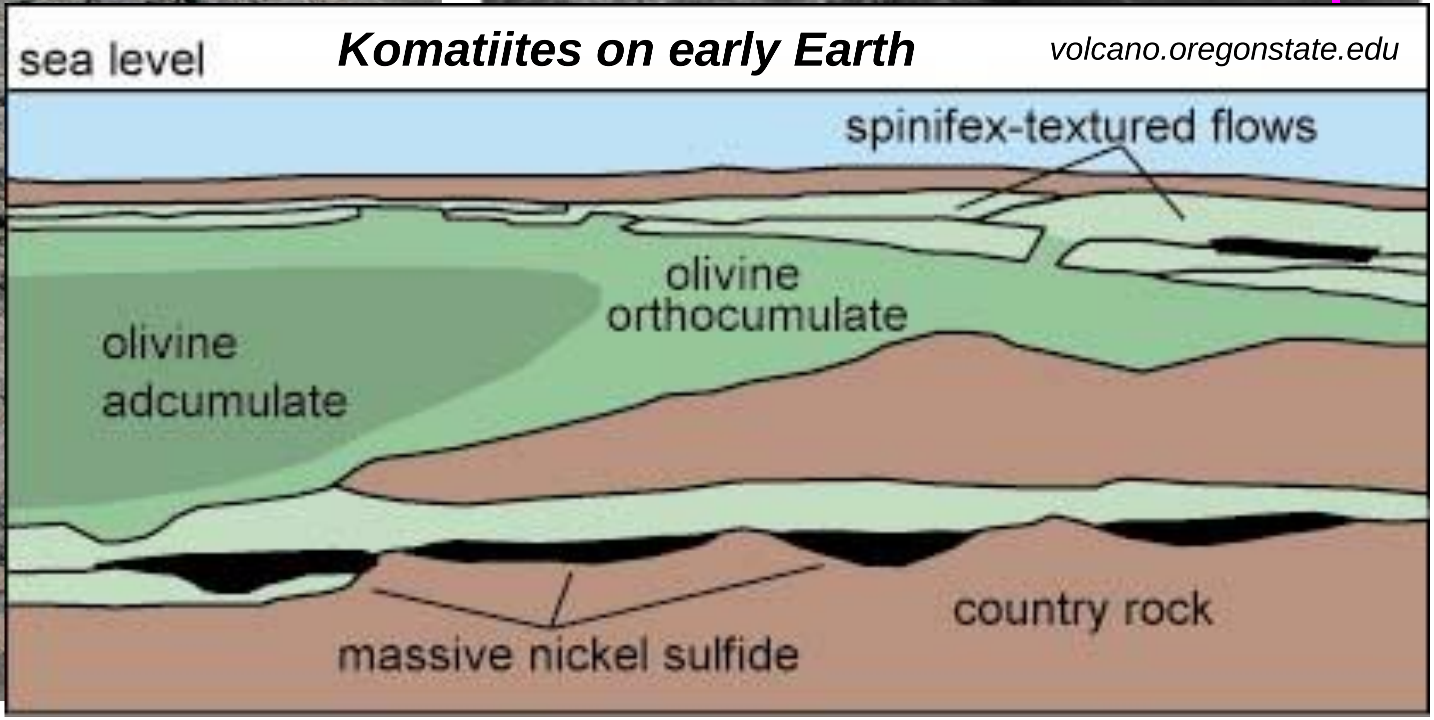
(known imperfect analog: in this case, very explosive lava)

Isidis Olivine=Komatiites?



Layered olivine-rich rocks, Nili Fossae

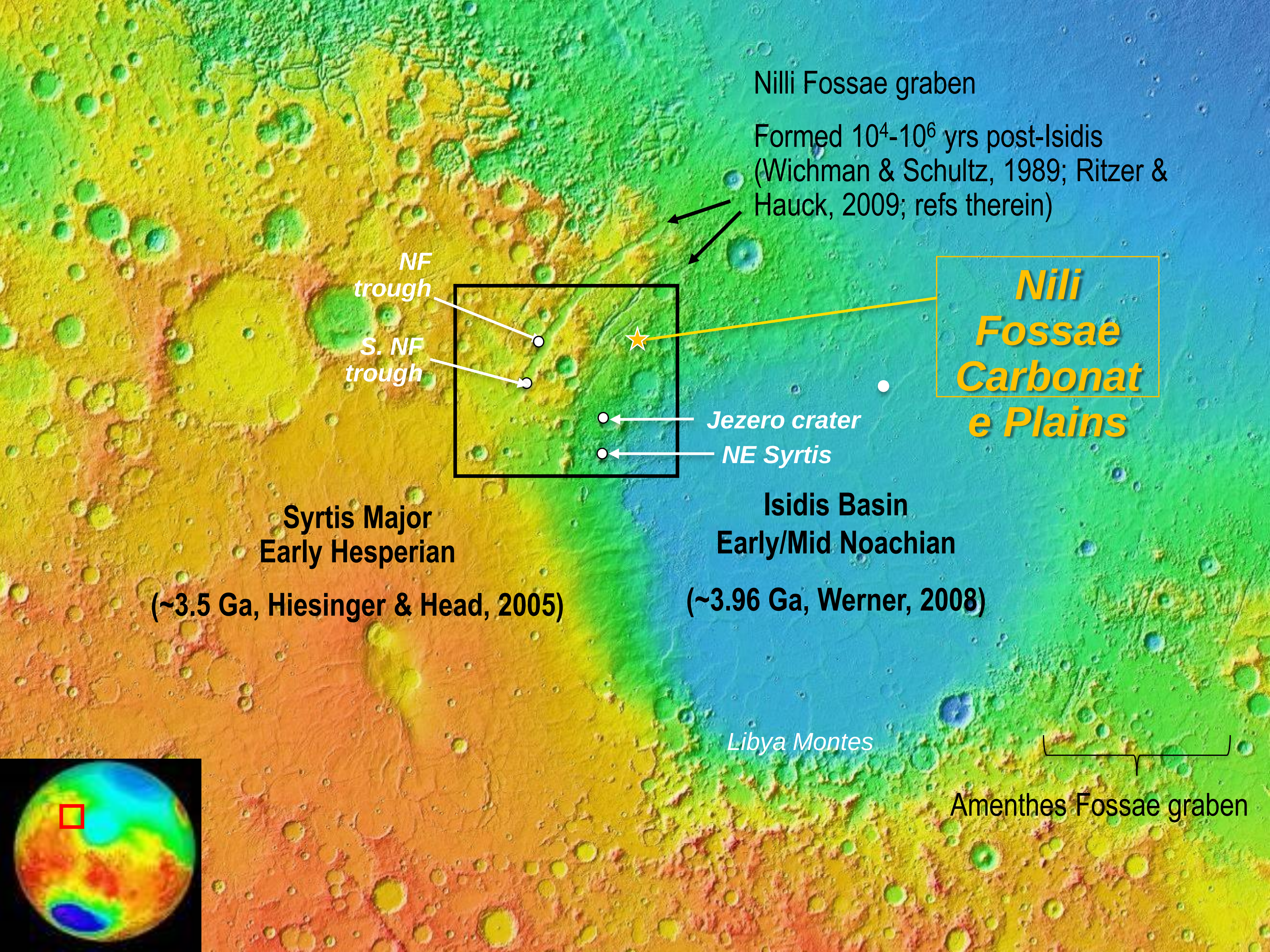


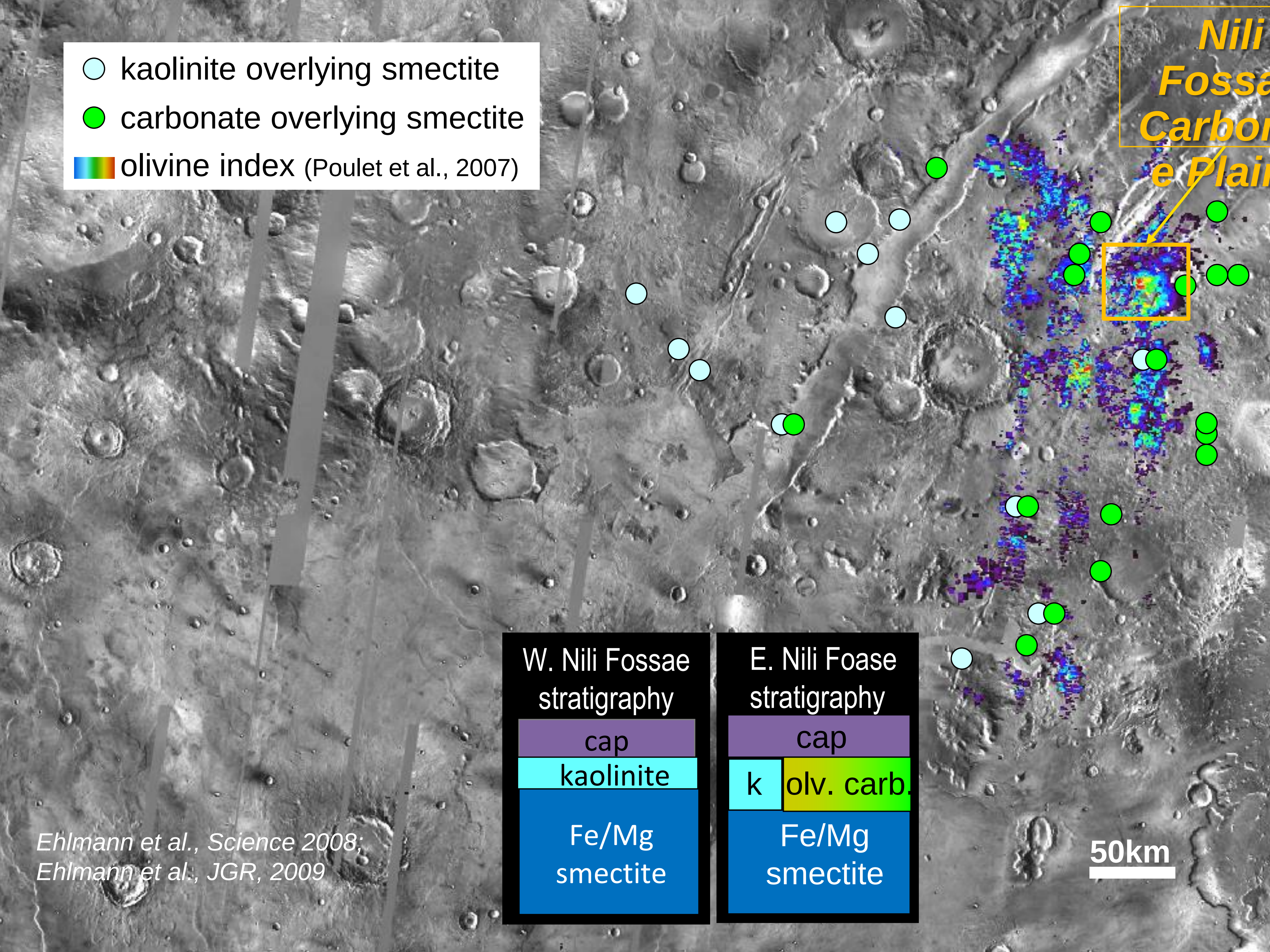


Two Unique Large-Scale Compositional Units: Carbonate & Olivine

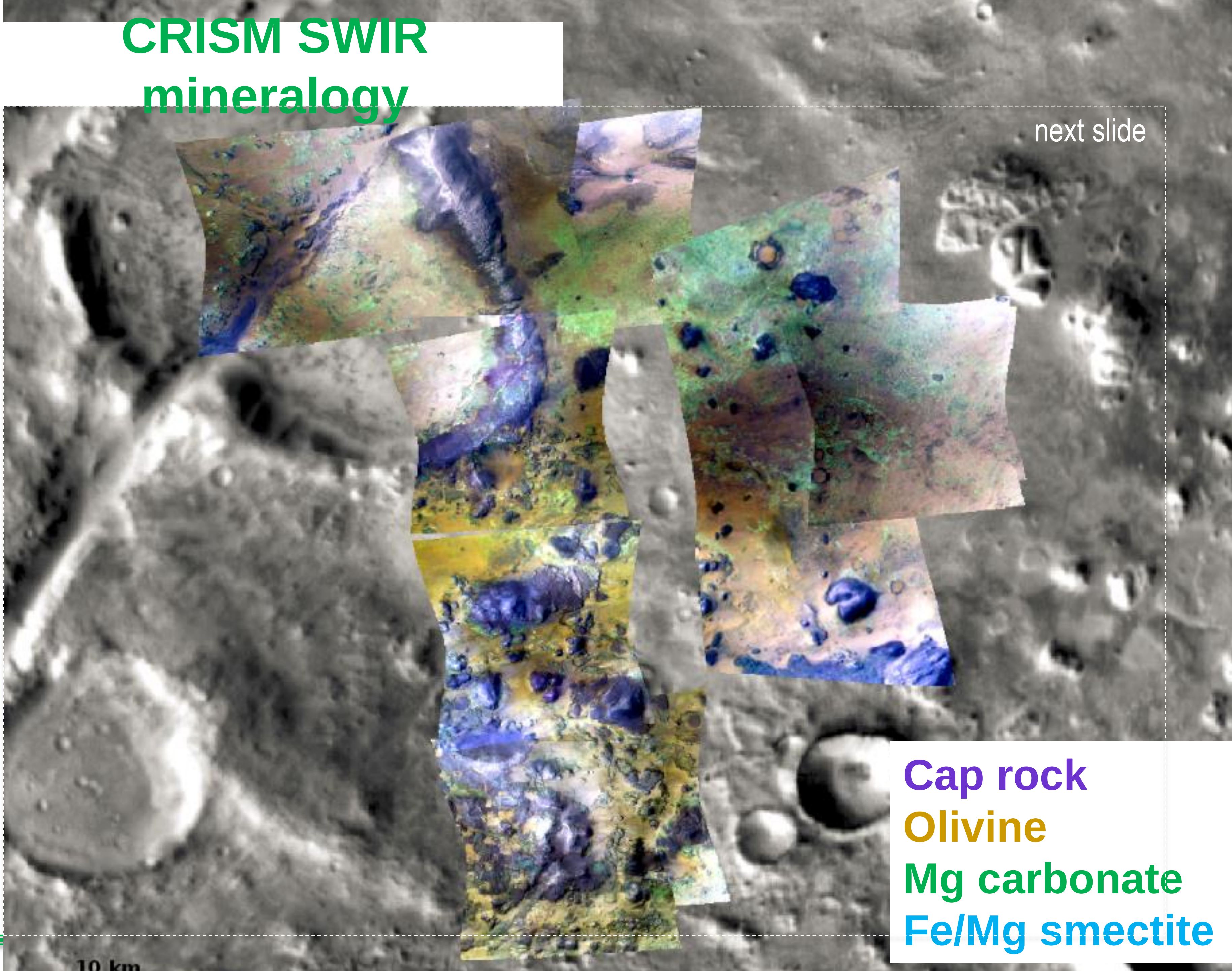
- Well-examined with mature data analyses (MGS, Odyssey, Mars Express, MRO…). Much scientific literature characterizing the formations at Nili Fossae-Syrtis Major
  - Download the 30+ papers on the region at ftp://ftp.gps.caltech.edu/pub/Ehlmann/mars2020
  - Competing origin theories require *in situ*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

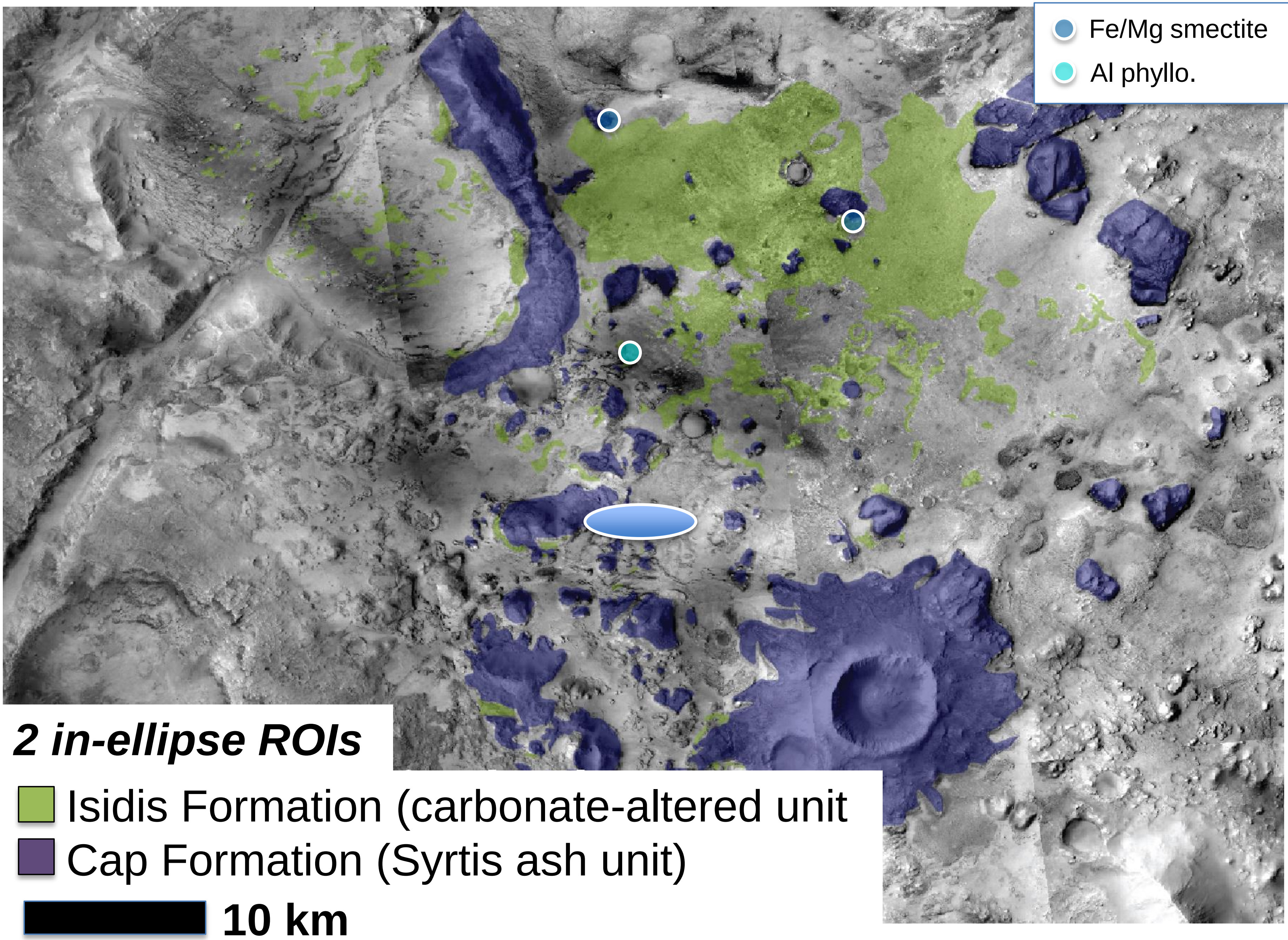
To the NF Carbonates Site…

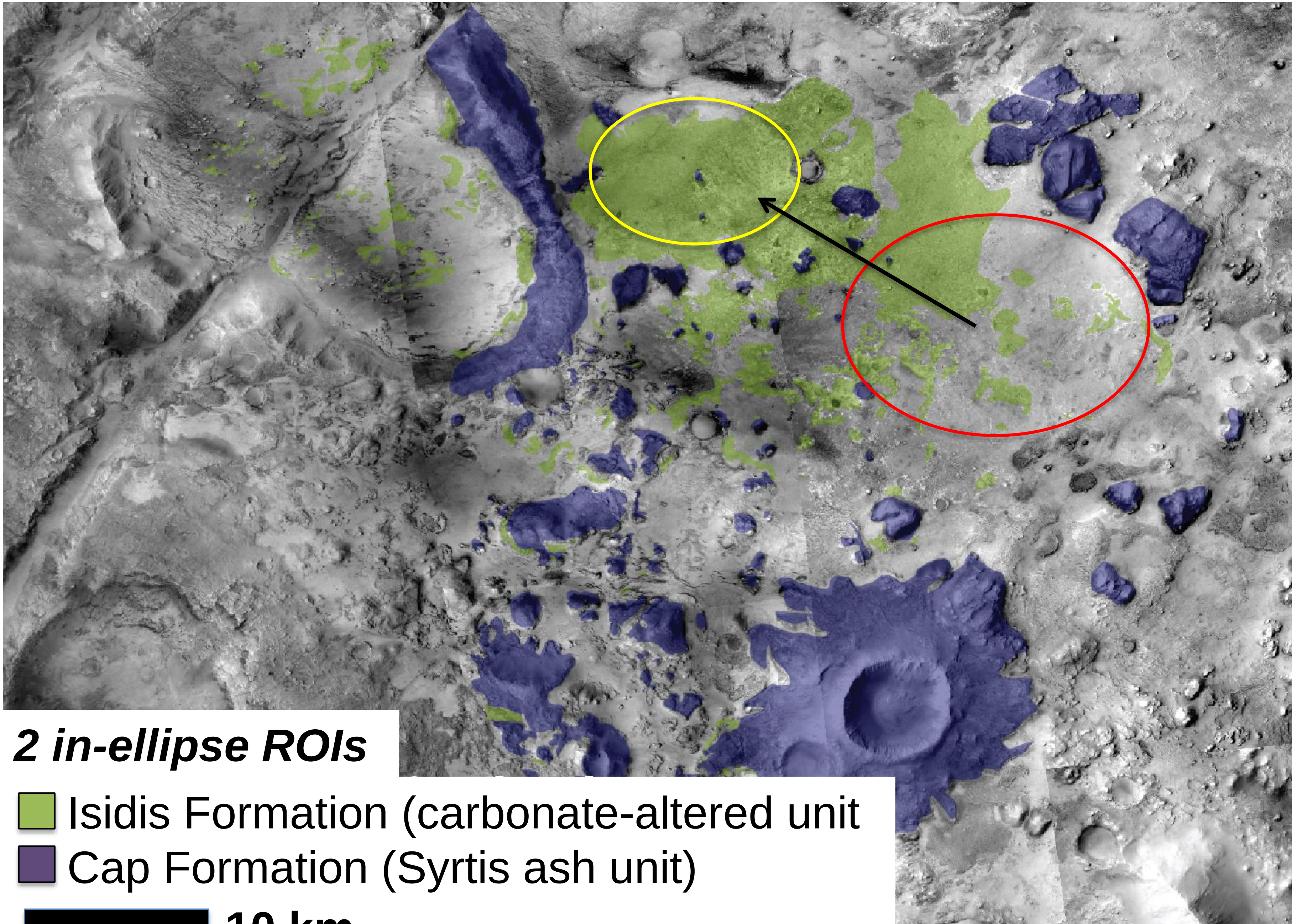

Nilli Fossae graben
Formed 10^4-10^6 yrs post-Isidis (Wichman & Schultz, 1989; Ritzer & Hauck, 2009; refs therein)
NF trough
S. NF trough
Nili Fossae Carbonate Plains
Jezero crater
NE Syrtis
Syrtis Major
Early Hesperian
(~3.5 Ga, Hiesinger & Head, 2005)
Isidis Basin
Early/Mid Noachian
(~3.96 Ga, Werner, 2008)
Libya Montes
Amenthes Fossae graben


kaolinite overlying smectite
carbonate overlying smectite
olivine index (Poulet et al., 2007)
Nili Fossae Carbonate Plain
W. Nili Fossae stratigraphy
cap
kaolinite
Fe/Mg smectite
E. Nili Foase stratigraphy
cap
k
olv. carb.
Fe/Mg smectite
50km
Ehlmann et al., Science 2008;
Ehlmann et al., JGR, 2009

CRISM SWIR mineralogy




Fe/Mg smectite
Al phyllo.
2 in-ellipse ROIs
Isidis Formation (carbonate-altered unit
Cap Formation (Syrtis ash unit)
10 km



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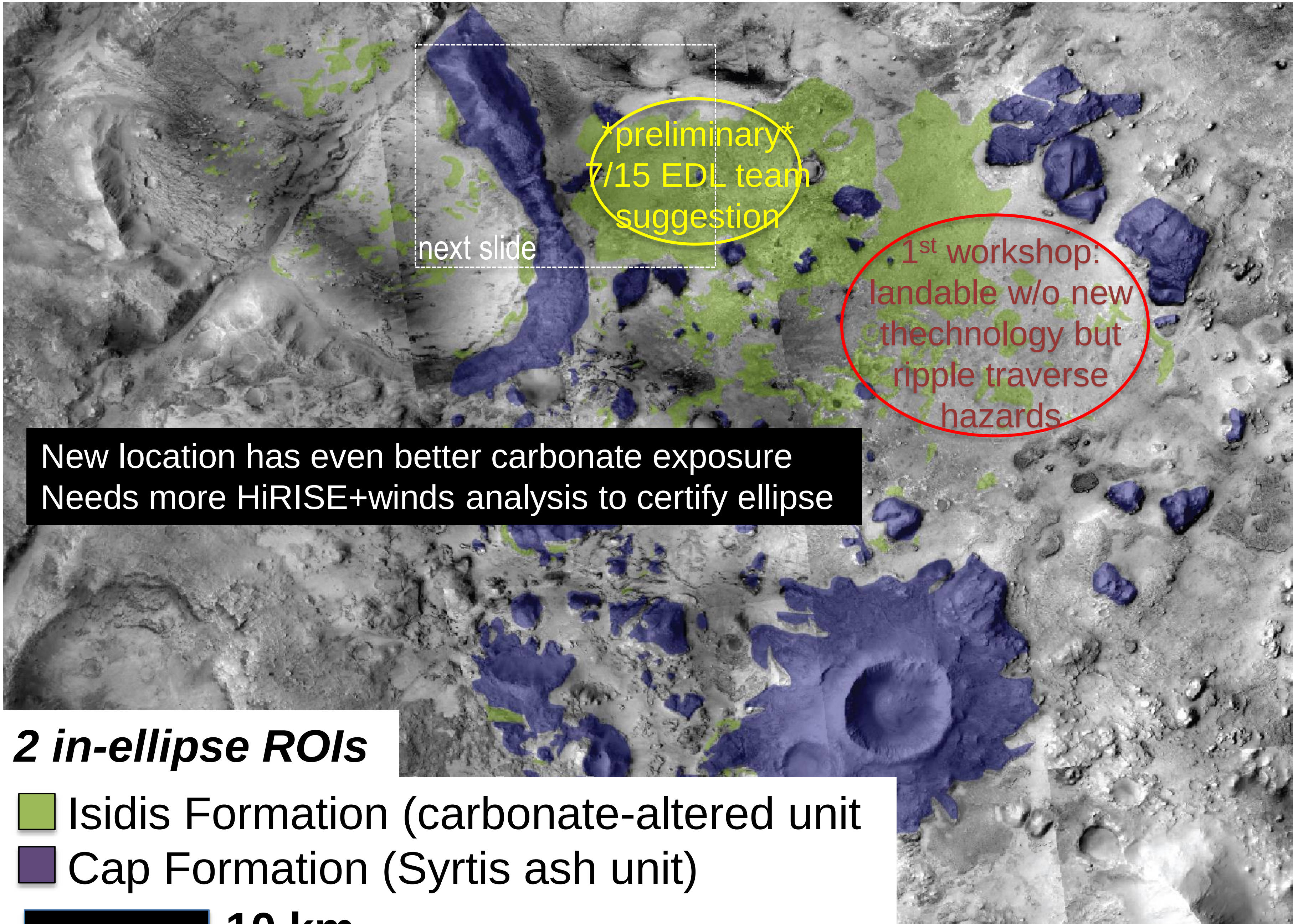


New location has even better carbonate exposure
Needs more HiRISE+winds analysis to certify ellipse

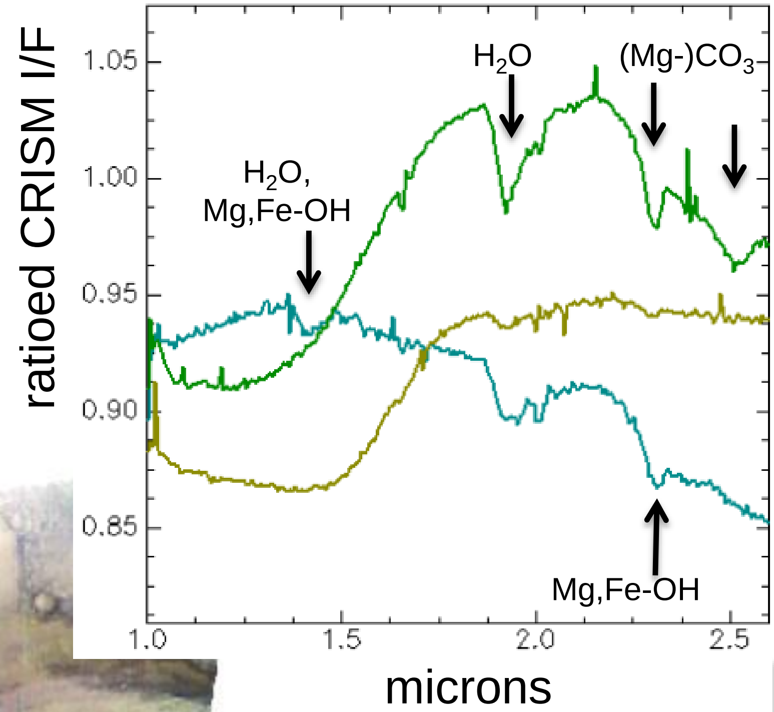
2 in-ellipse ROIs

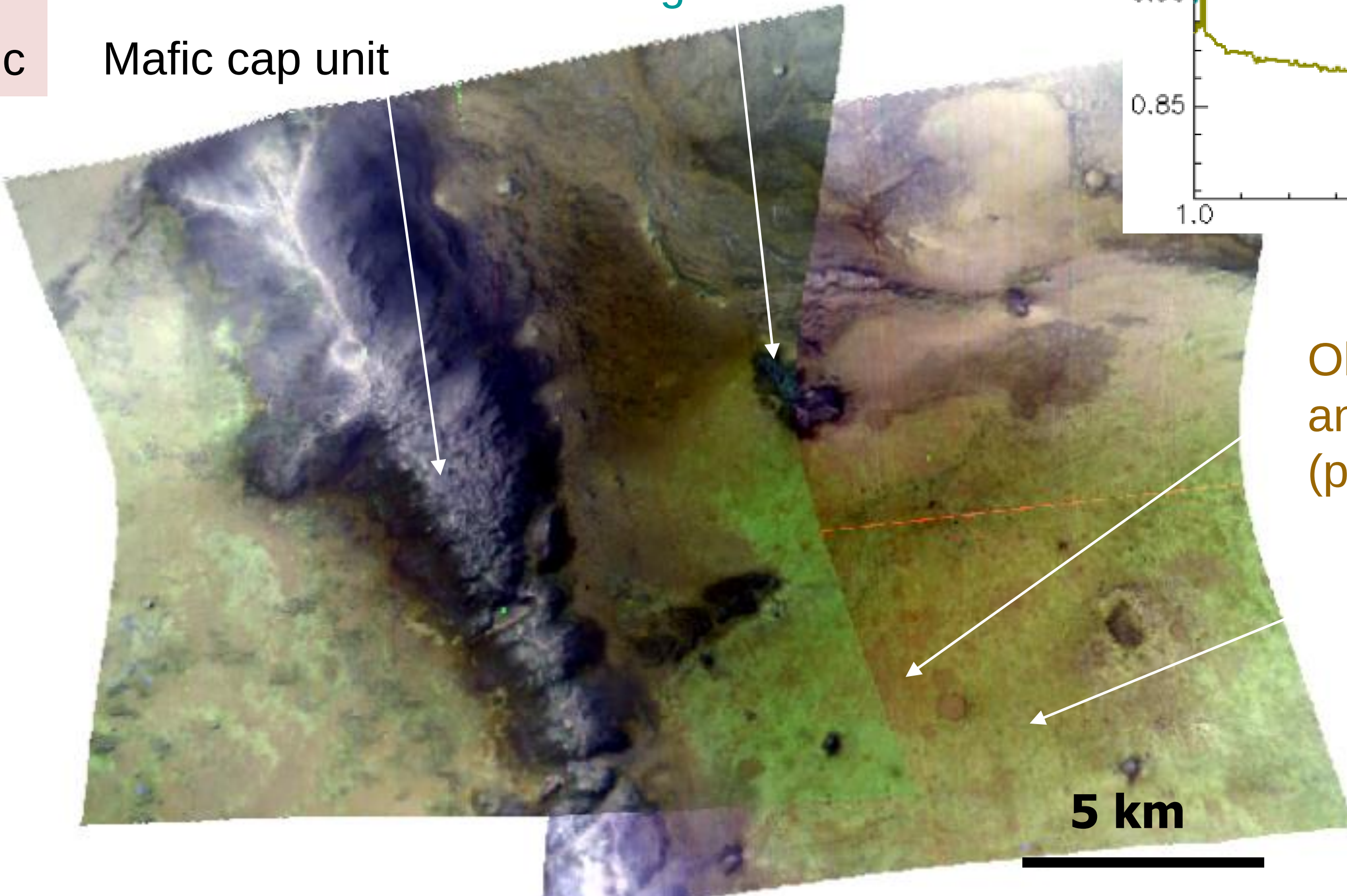
- Isidis Formation (carbonate-altered unit
- Cap Formation (Syrtis ash unit)

10 km

Mineralogy & Exposure of 3 Lithostratigraphic Sequences

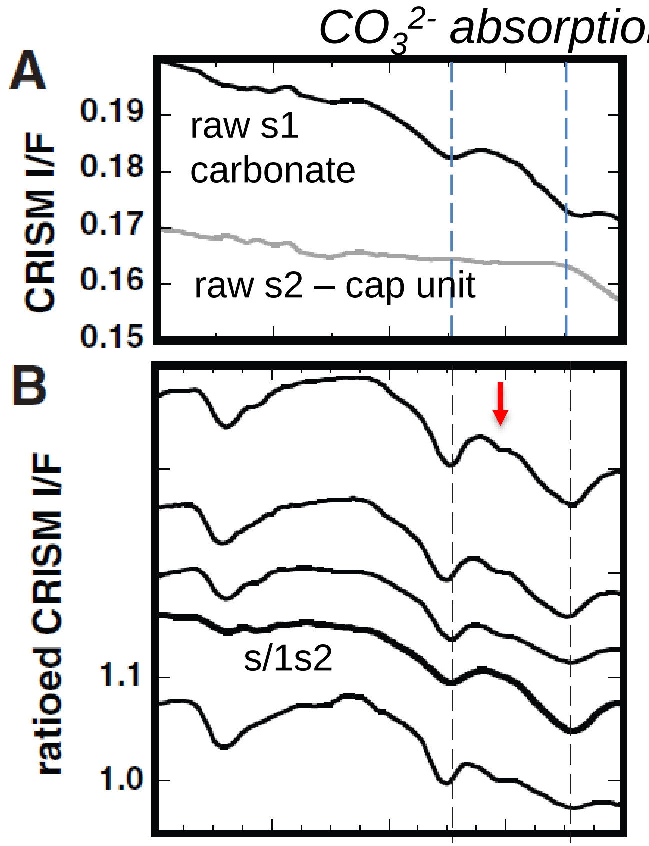
Carbonate and olivine, caprock in ellipse
Knobs with Fe/Mg smectite at surroundings





Carbonate Spectroscopy: The Gory Details! (sorry ;))

(Ehlmann et al., 2008, Science redux; read details and refs there)



<u>What is Known/Knowable</u>

- Mg-rich carbonate
- With Fe (1-µm band: see paper)
  - *either* (Fe,Mg)CO_3 solid sol'n
  - *or* with intermixed Fe(II) phase, e.g. olivine
- Hydrated
  - "Grungy" carbonate (poorly xll)
  - Intermixed hydrated carbonate (favored at very low T)

- Intermixed Fe/Mg phyllosilicates (smectite? serpentine? poorly xll talc?)
  - "In some CRISM spectra of …carbonate-bearing materials, intimate or spatial mixing is indicated by a wavelength shift and narrowing at 2.3 µm and broadening at 2.5 µm that is accompanied by the appearance of a weak band at 2.4 mm."

Carbonate Abundance: 5-20 wt% (0.25-12 mbar)

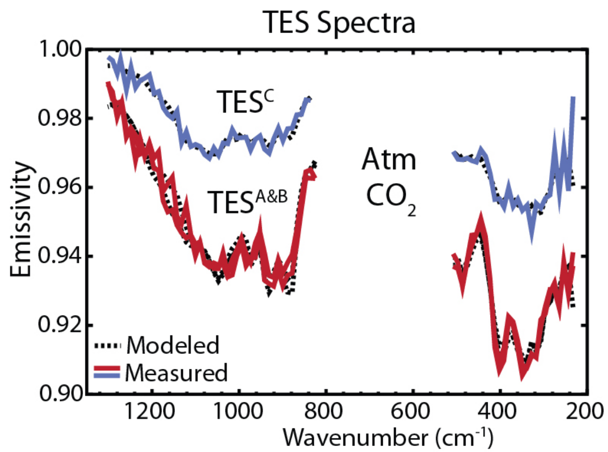


Table S1. TES model mineral abundances (%)

Mineral	TES^A&B	TES^C	Syrtis Type^b
Pyroxene	21 (8)	27 (7)	32 (3)
Olivine	21 (4)	4 (5)	5 (3)
High-Si Phases	24 (8)	20 (7)	19 (10)
Carbonate	15 (4)	10 (1)	7 (1)
Feldspar	11 (7)	30 (10)	27 (6)
Other^a	8 (3)	9 (3)	10 (2)
RMS Fit Error	0.35	0.35	0.14

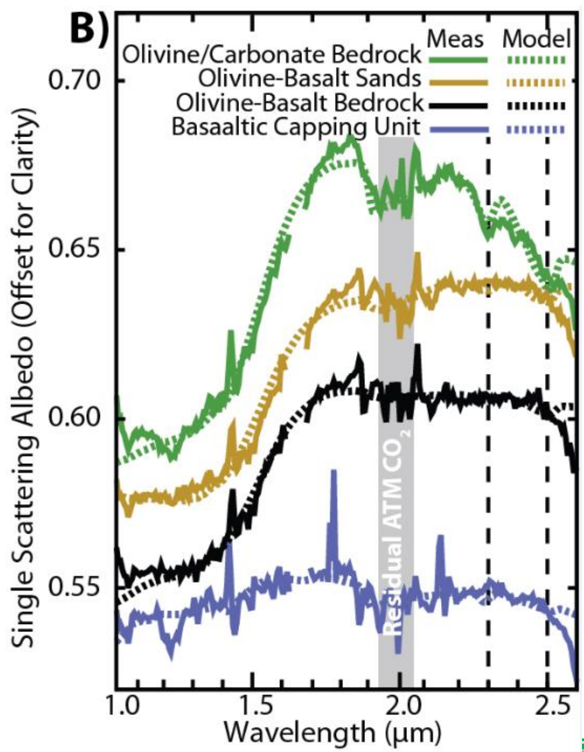


Table S2. CRISM Derived abundances (wt % & grain size)

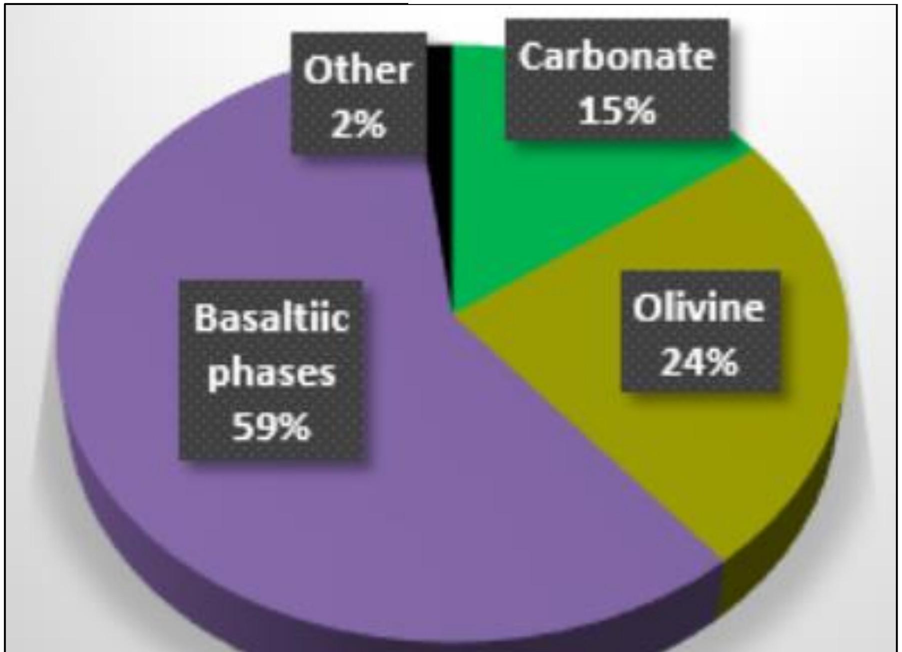
Phase	Carbonate Bedrock	Dark Bedrock	Dunes	Capping Unit
Carbonate	15 (1 mm)	1 (12μm)	8 (1mm)	1# (23μm)
Olivine	24 (~1mm)	26 (~1mm)	25 (~1mm)	5 (384μm)
Basalt	59 (950μm)	70 (560 μm)	65 (770μm)	89 (394μm)
Other*	2	2	2	5
RMS Fit Error	0.0038	0.0023	0.0033	0.0023

Edwards & Ehlmann, Geology, accepted

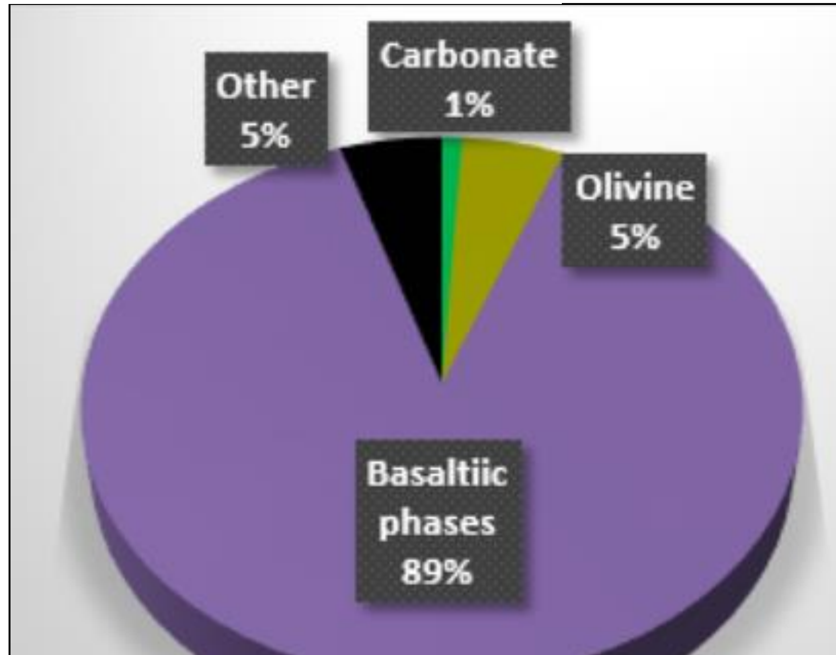
Carbonate Abundance: ≤20 wt% (0.25-12 mbar)

TES Spectra

Formation Mineralogy

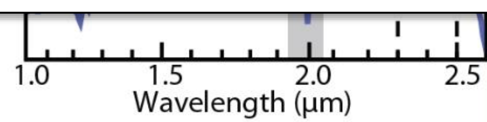


Isidis Olivine Formation (carbonate-bearing unit)

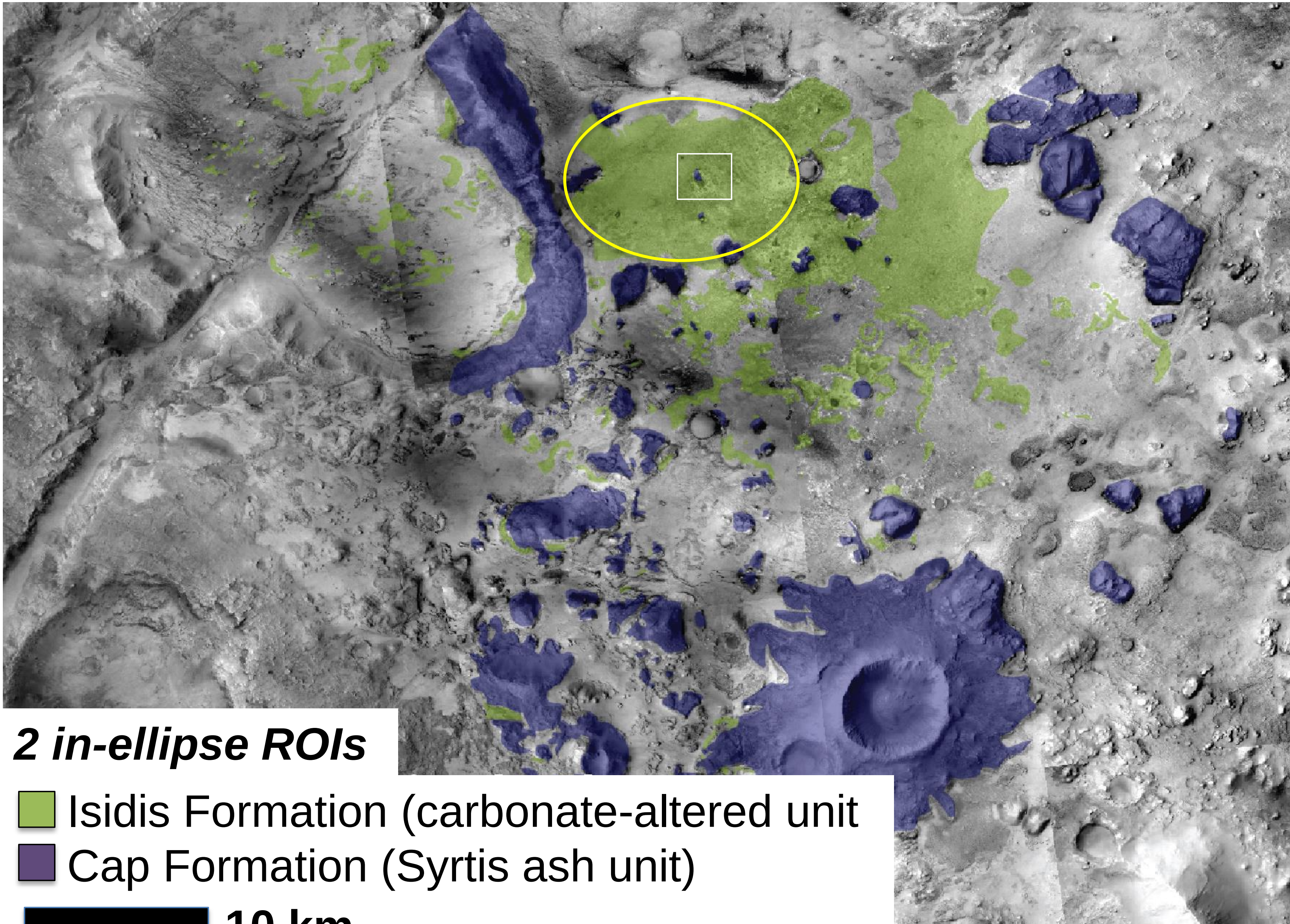


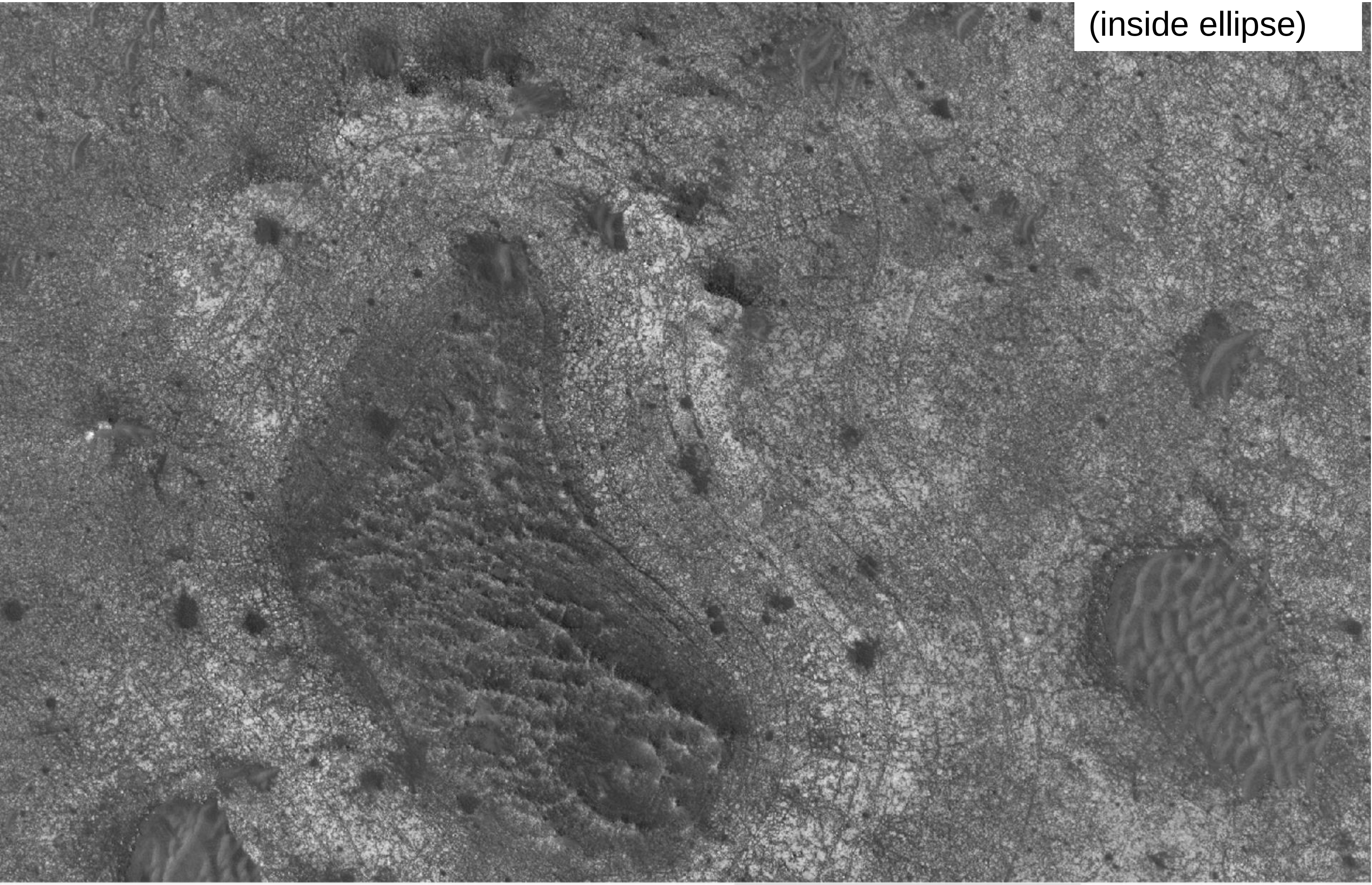
Capping Formation (probable ash unit)

(basaltic phases are lumped; include pyroxenes, feldspars, glasses)



Edwards & Ehlmann, Geology, accepted


2 in-ellipse ROIs
Isidis Formation (carbonate-altered unit
Cap Formation (Syrtis ash unit)
10 km

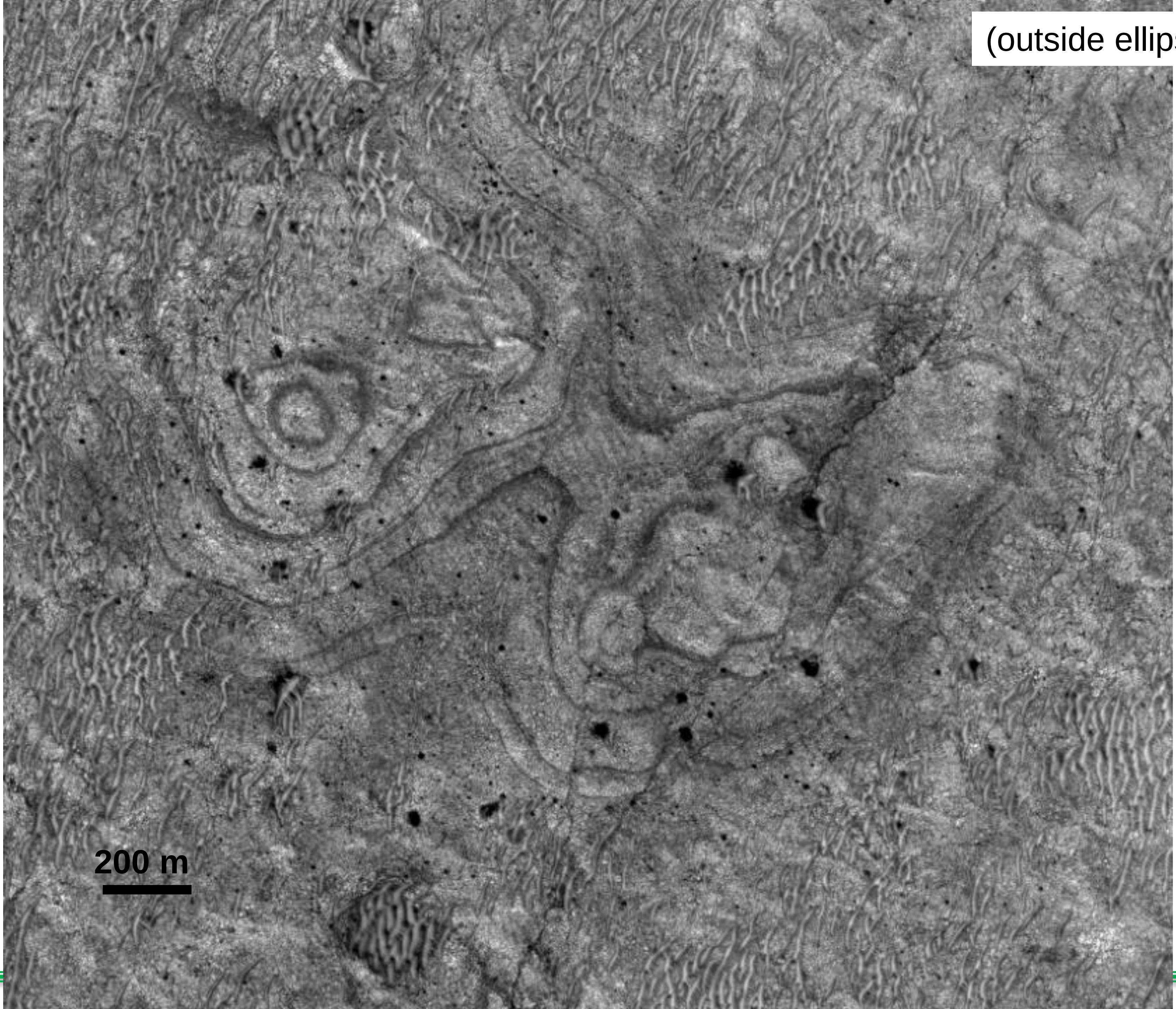


HiRISE ESP_038385_2020

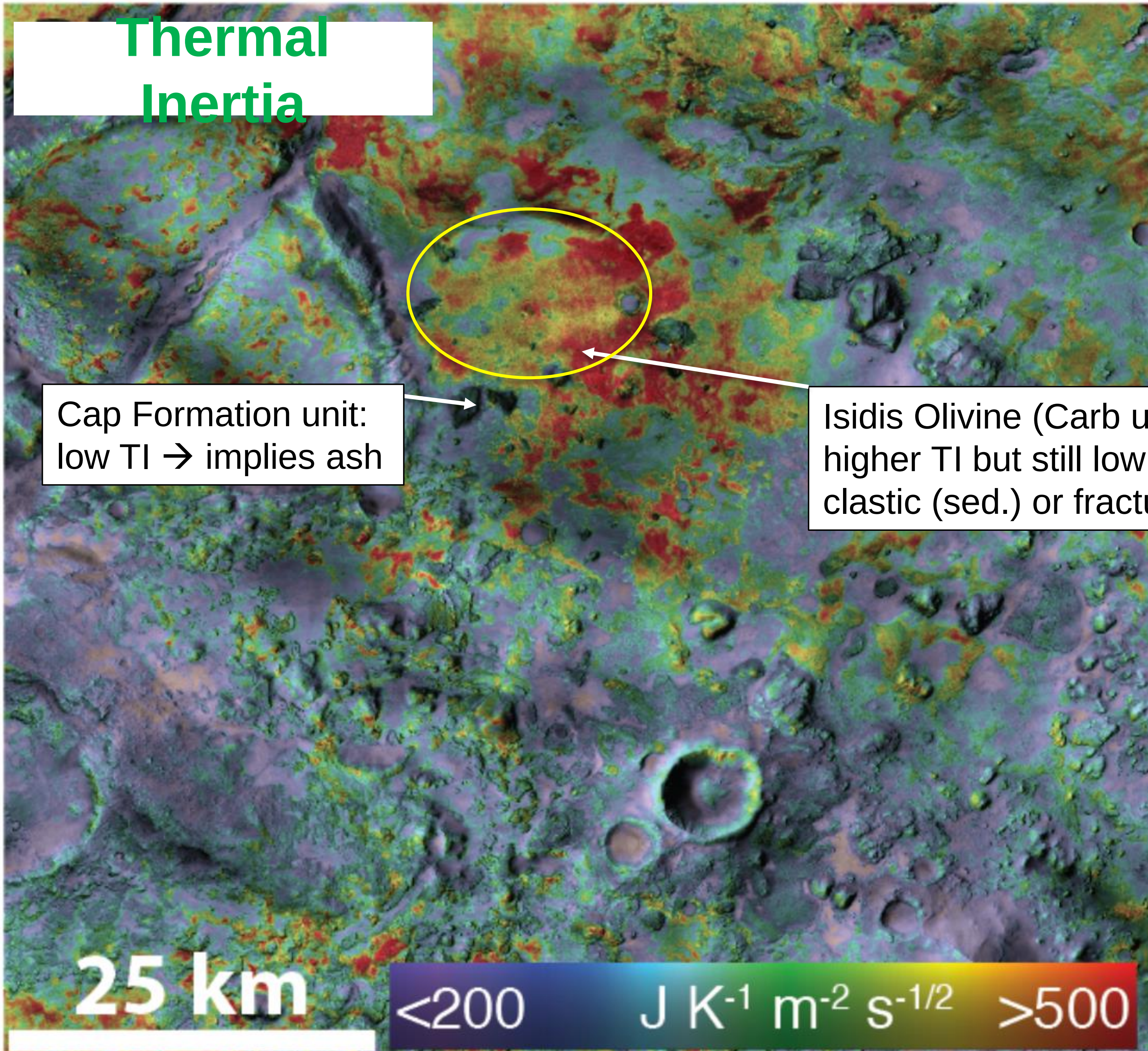
250 m

HiRISE ESP_038385_2020

30 m

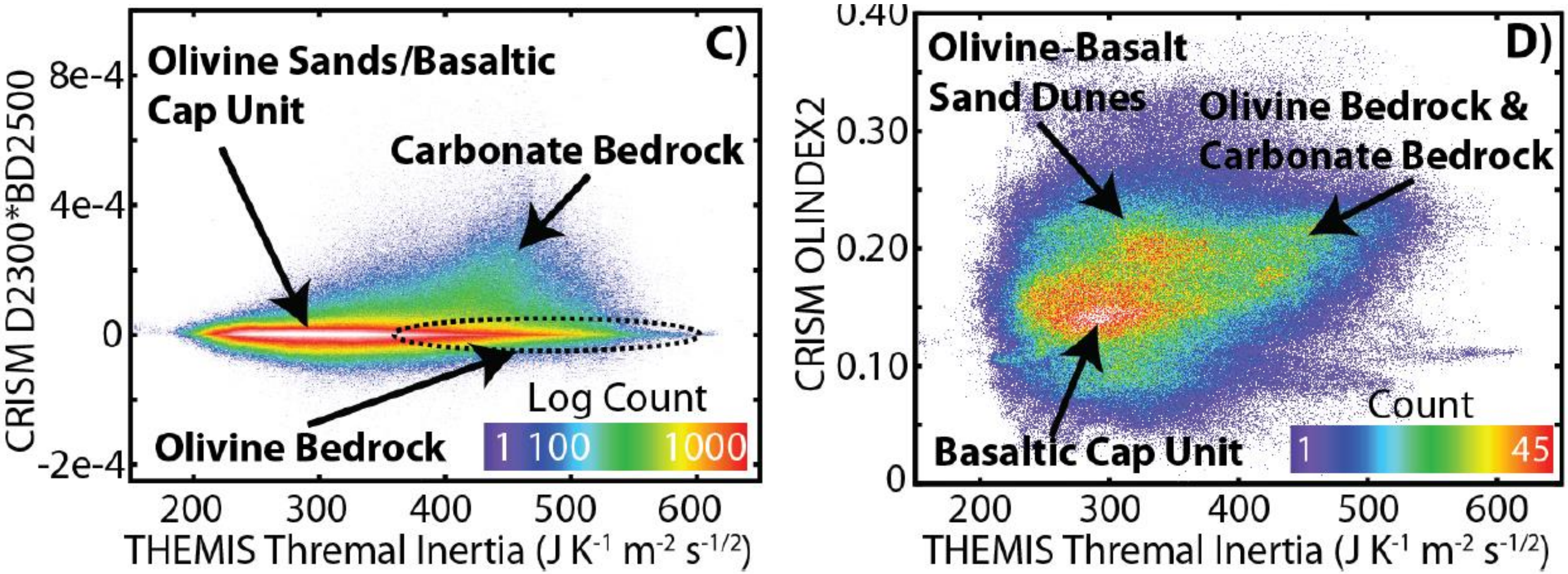

(outside ellipse)
200 m

Thermal Inertia



Edwards & Ehlmann, in press, Geology

TI & mineralogy & morphology distinguish key units



Edwards & Ehlmann, in press, Geology

- Bedrock TI is consistent with fractured igneous rock or clastic/sed. rock
- Physical erosion and aeolian transport “clean” eroded, coarse olivine grains from olivine-carbonate bedrock to form olivine-rich/carbonate poor dunes
- Low TI Mafic Caprock (even lower than unconsolidated sand) is consistent with emplacement as volcanic ash from Syrtis Major

Key Isidis Olivine Formation: Carbonate Unit Origin Hypotheses

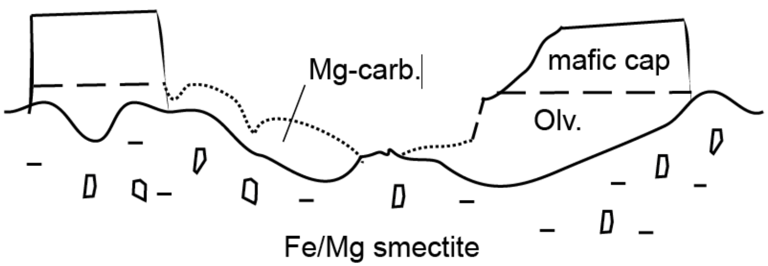
Possible Mg-carbonate formation mechanisms

(Möller, 1989 – terrestrial occurences 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,

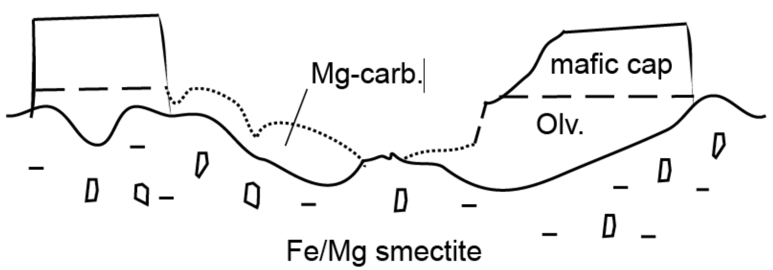
(1) Olivine-rich rock and (2) its interaction with water seem to be essential

Possible Mg-carbonate formation mechanisms

(Möller, 1989 – terrestrial occurences)

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

Probably not. "Shelf" of Isidis basin, but hard to explain why olivine would be enriched in sedimentary lake beds



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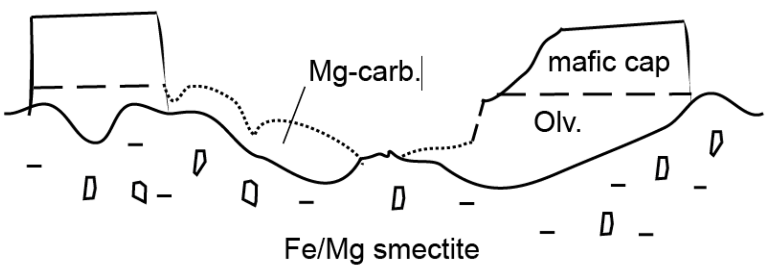

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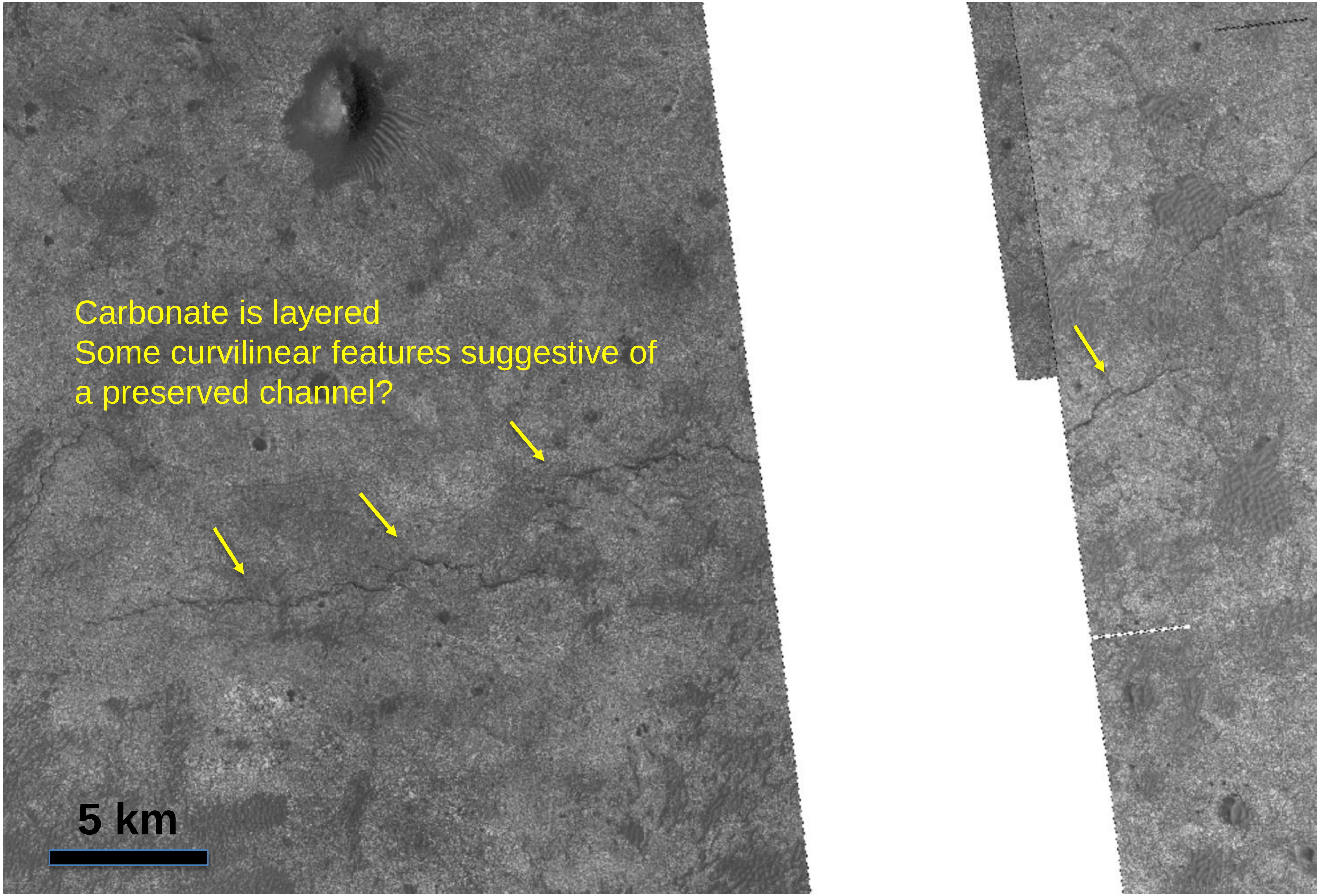


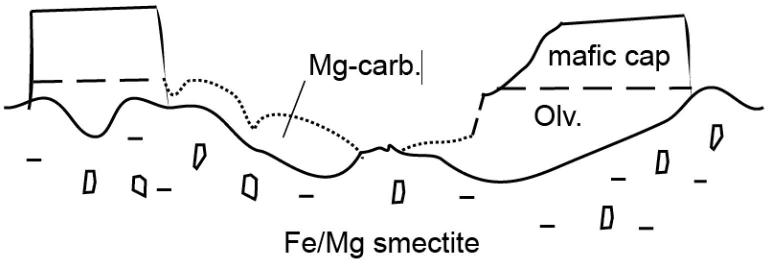
Carbonate is layered
Some curvilinear features suggestive of
a preserved channel?
5 km

Possible Mg-carbonate formation mechanisms

(Möller, 1989 – terrestrial occurences)

Maybe. Some (weak) morph, TI evidence consistent. But no clear basins (but see Merid.)

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



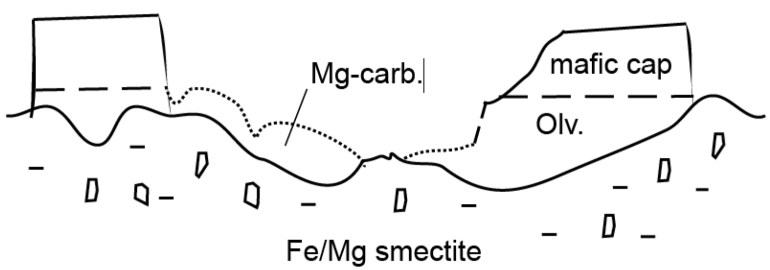
For Mg-carbonates on Mars,

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

Possible Mg-carbonate formation mechanisms

(Möller, 1989 – terrestrial occurences)

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



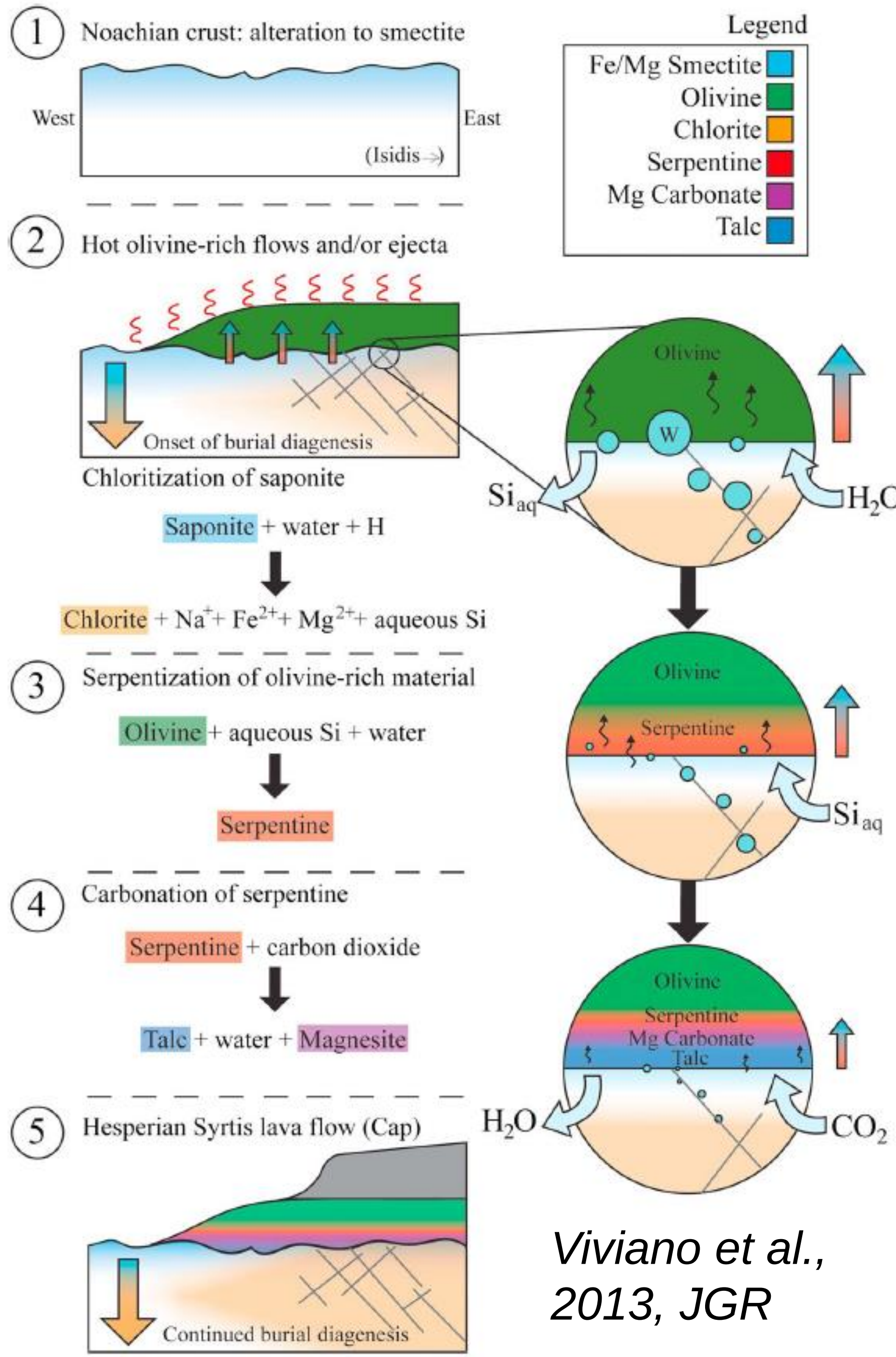
For Mg-carbonates on Mars,

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

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



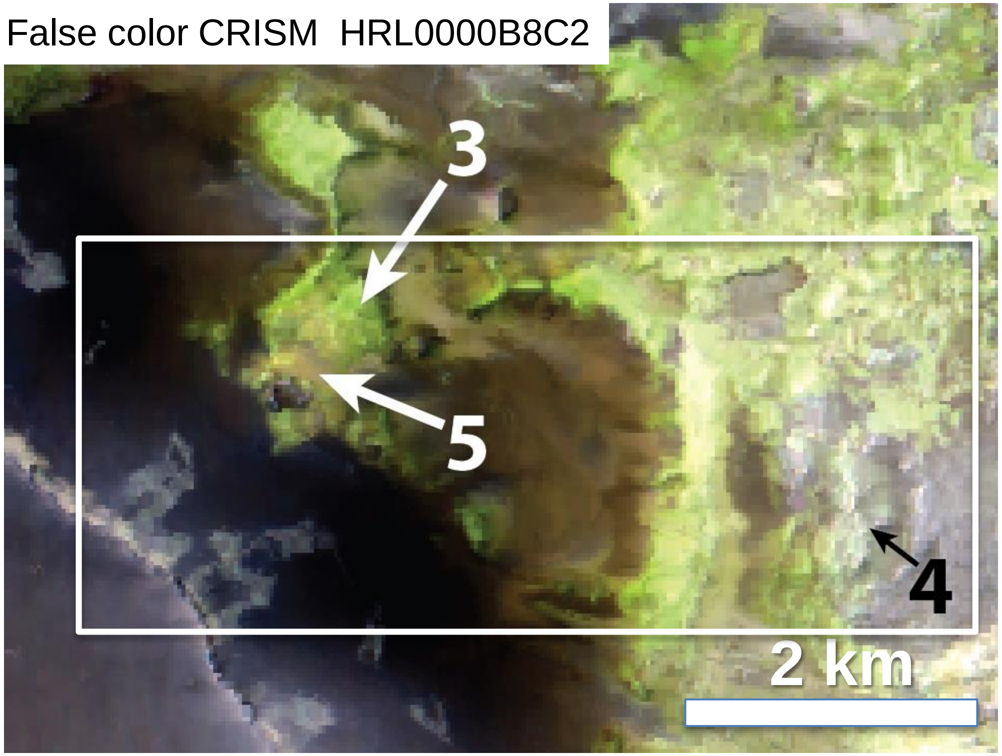
Viviano et al., 2013, JGR

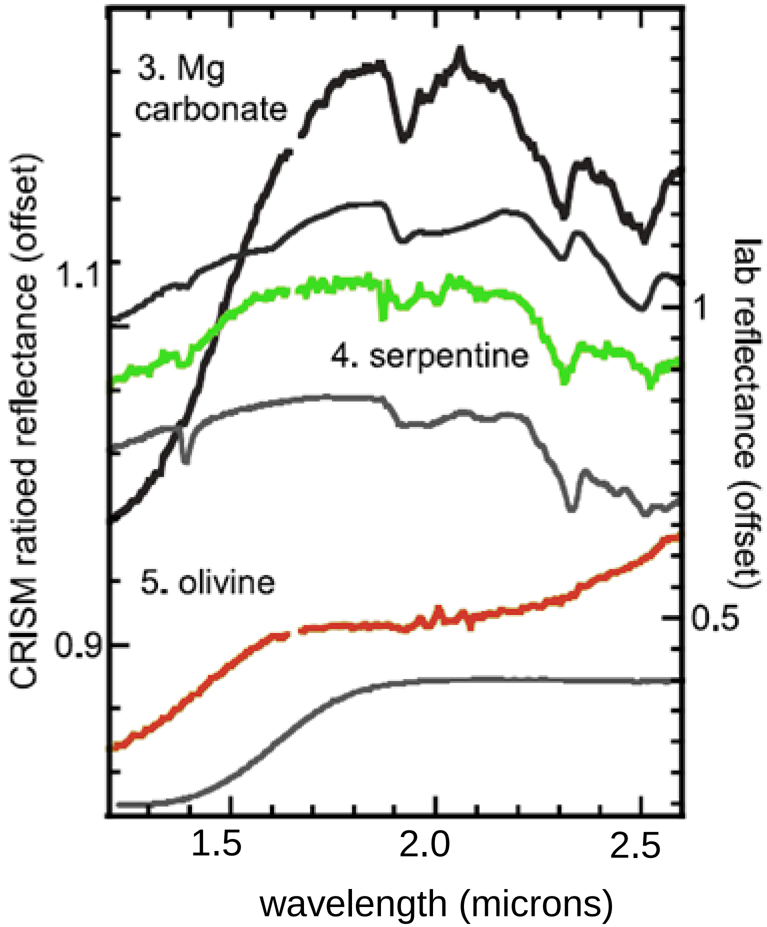
So What is the Largest Carbonate-Bearing Unit on Mars?

insights from elsewhere in the formation…

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

False color CRISM HRL0000B8C2





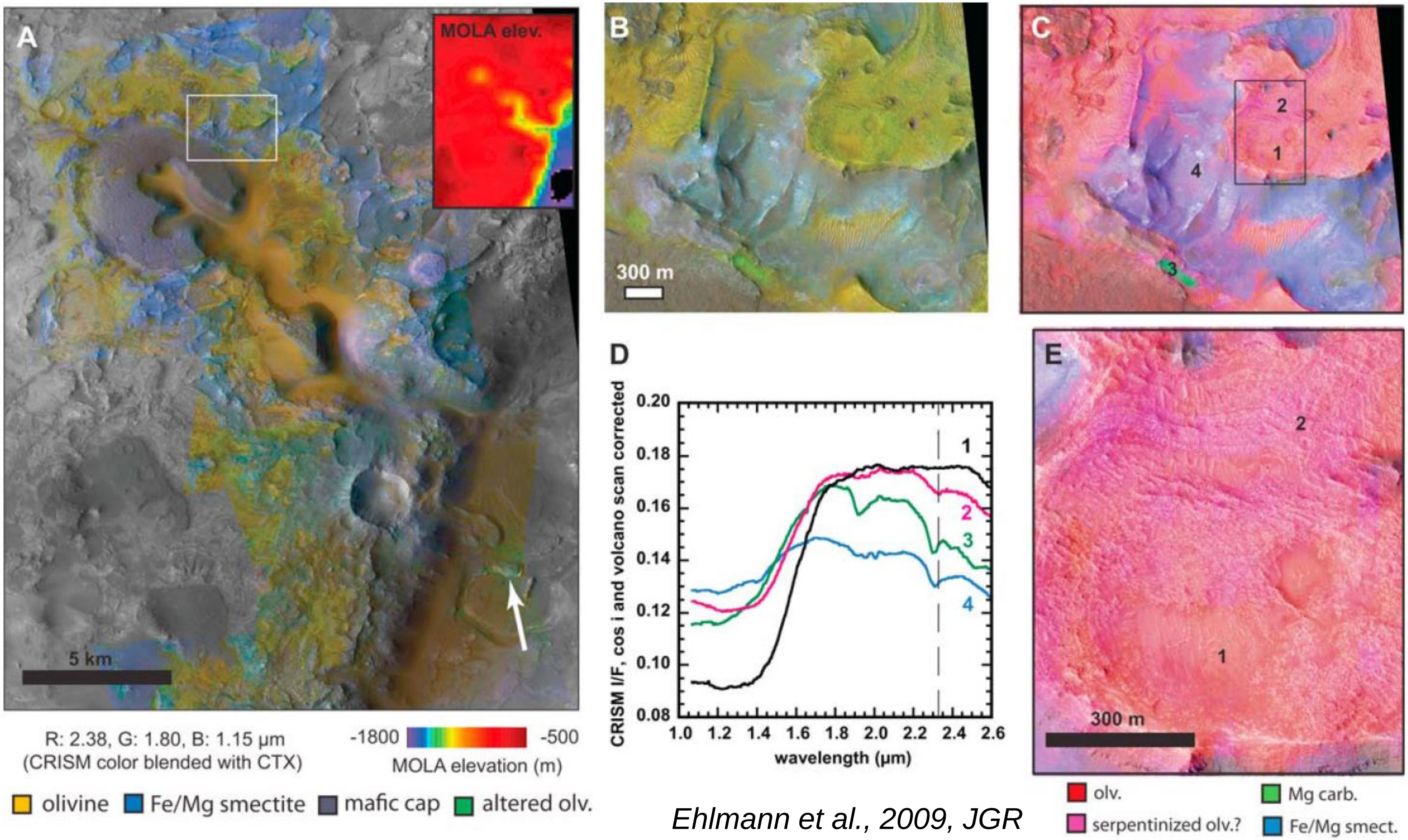
<u>south of NE Syrtis ellipse</u>

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

Insights from West of the NF Carbonate Ellipse: Carbonate+ phase with 2.32-um absorptions discretely mappable in Isidis Olivine Formation

Observed elsewhere in the region – 100 km due west of the ellipse.

Ehlmann et al., 2009, JGR; Ehlmann et al., 2010, GRL; Ehlmann & Mustard, 2012, GRL



Ehlmann et al., 2009, JGR


A possible analog
Samail ophiolite, Oman

Zones of Serpenitinization and Tracing the Process through Carbonate Chemistry

influx of surface waters

Mg^{+2}-HCO_3^{-1}-Type Waters

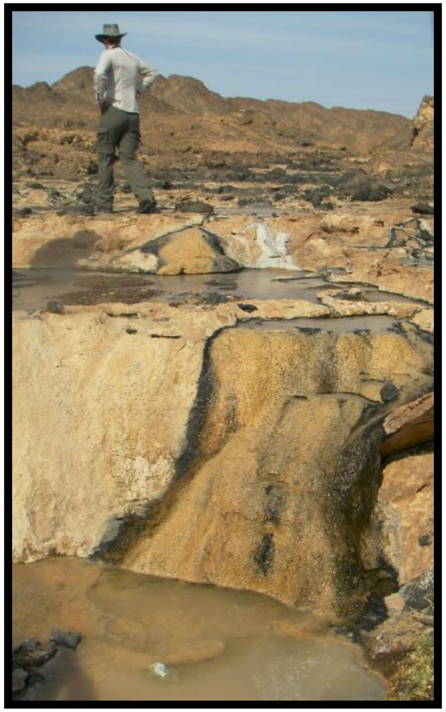
Mg-carbonate precipitation

Mg(Fe,Ca)-rich (ultra)mafic rocks (olivine, pyroxene)

<zone of ongoing serpentinization>

→ $(Fe,Mg)_3Si_2O_5(OH)_2 + Mg(OH)_2 + H_2$

outflow



Ca^{+2}-OH^{-1}-Type Waters

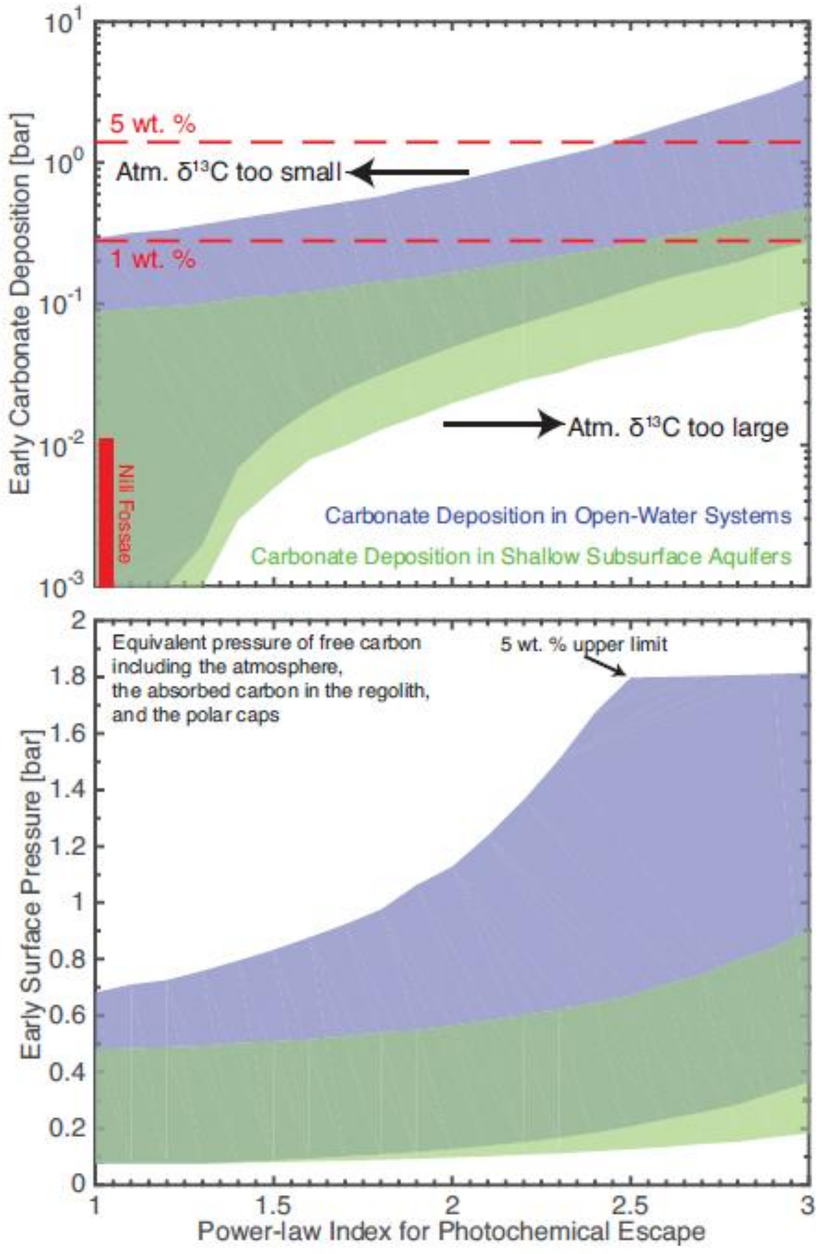
Ca-carbonate precipitation

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

Carbonates: A Key to Past Climate/Habitability

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

Hu et al., in review: "The uncertainty in surface pressure is dominated by the uncertainties in the photochemical and sputtering escape rates, <u>as well as the geological settings of early carbonate formation</u>."



Nili Fossae Carbonates Rubric

Landing Site Factor	Mars 2020 Mission and Decadal Priority Science Factors																							
	Environmental Setting for Biosignature Preservation and Taphonomy of Organics								Type 1A & 1B Samples: Aqueous Geochemical Environments indicated by Mineral Assemblages									Type 2 Samples: Igneous		Context: Martian History Sampled, Timing Constraints				
	Deltaic or Lacustrine (perennial)	Lacustrine (evaporitic)	Hydrothermal (<100°C) surface	Hydrothermal (<100°C) subsurface	Pedogenic	Fluvial/Alluvial	No diagenetic overprinting	Recent exposure	Crustal phyllosilicates	Sedimentary clays	Al clays in stratigraphy	Carbonate units	Chloride sediments	Sulfate sediments	Acid sulfate units	Silica deposits	Ferric Ox./Ferrous clays	Igneous unit (e.g, lava flow, pyroclastic, intrusive)	2nd Igneous unit	Pre- or Early-Noachian Megabreccia	Oldest stratigraphic constraint	Youngest stratigraphic constraint	Stratigraphy of units well-defined	Dateable surface, volcanic (unmodified crater SFD)
NF Carb. Plains		~	~	~	~			●	○		○	●					○	●	●		EN	EH	●	~

Likely serpentinization-related based on data nearby (Ehlmann et al., GRL, 2010) but certainly one of these hypotheses, **providing insight into the creation and persistence of neutral/alkaline Martian enviros, carbon sequestration**

scarps being eroded by sand in ellipse

Land-on largest carbonate deposit on Mars (Ehlmann et al, Science, 2008)

Reported in CRISM data (Greenberger & Mustard, LPSC, 2012)

Land-on primitive lavas, impact cumulates (Hamilton & Christensen, Geology, 2005; Mustard et al., JGR, 2007, 2009)

strat. consistent over 100s km; bracketed by volc units with unmod. CFD

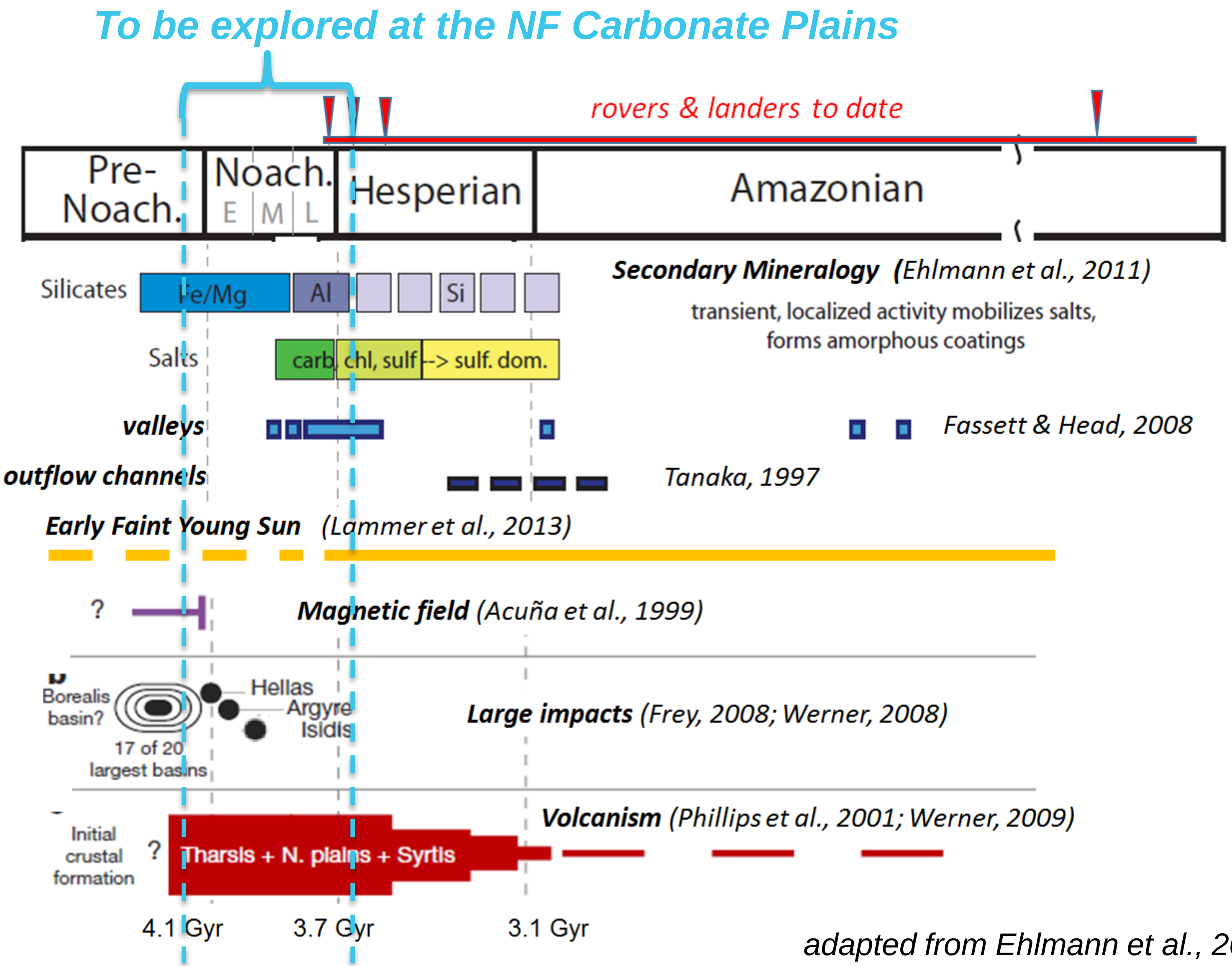
Nili Fossae type stratigraphies with weathering (kaolinite atop Fe/Mg crustal clays) accessible with drive and perhaps in ellipse knobs (Ehlmann et al., JGR, 2009)

Hesperian basaltic cap unit, likely ash from TI (Edwards & Ehlmann, Geology, 2015)

Isidis (Werner, Icarus, 2008)

Syrtis (Hiesinger & Head, JGR 2004)

Send Mars2020 Rover to Explore Habitable Noachian Mars



adapted from Ehlmann et al., 2011, Nature

Mars' Biggest Mysteries/Decadal-level questions

1) What is the nature of the Noachian crust/climate (>3.5 Gyr)?

2) Where is the carbon/water? (Mars' geochemical cycles?)

3) How heterogenous is the Mars mantle?

4) When did the dynamo cease? Impact on Habitability?

5) How old is the Martian surface?

*Are there biosignatures?

(1) Diverse, important questions required to drive return of cache

(2) Must explore/sample Pre-, Early-, Mid-Noachian

Nili Fossae Carbonate Plains
Meets Mars-2020 Site Selection Criteria

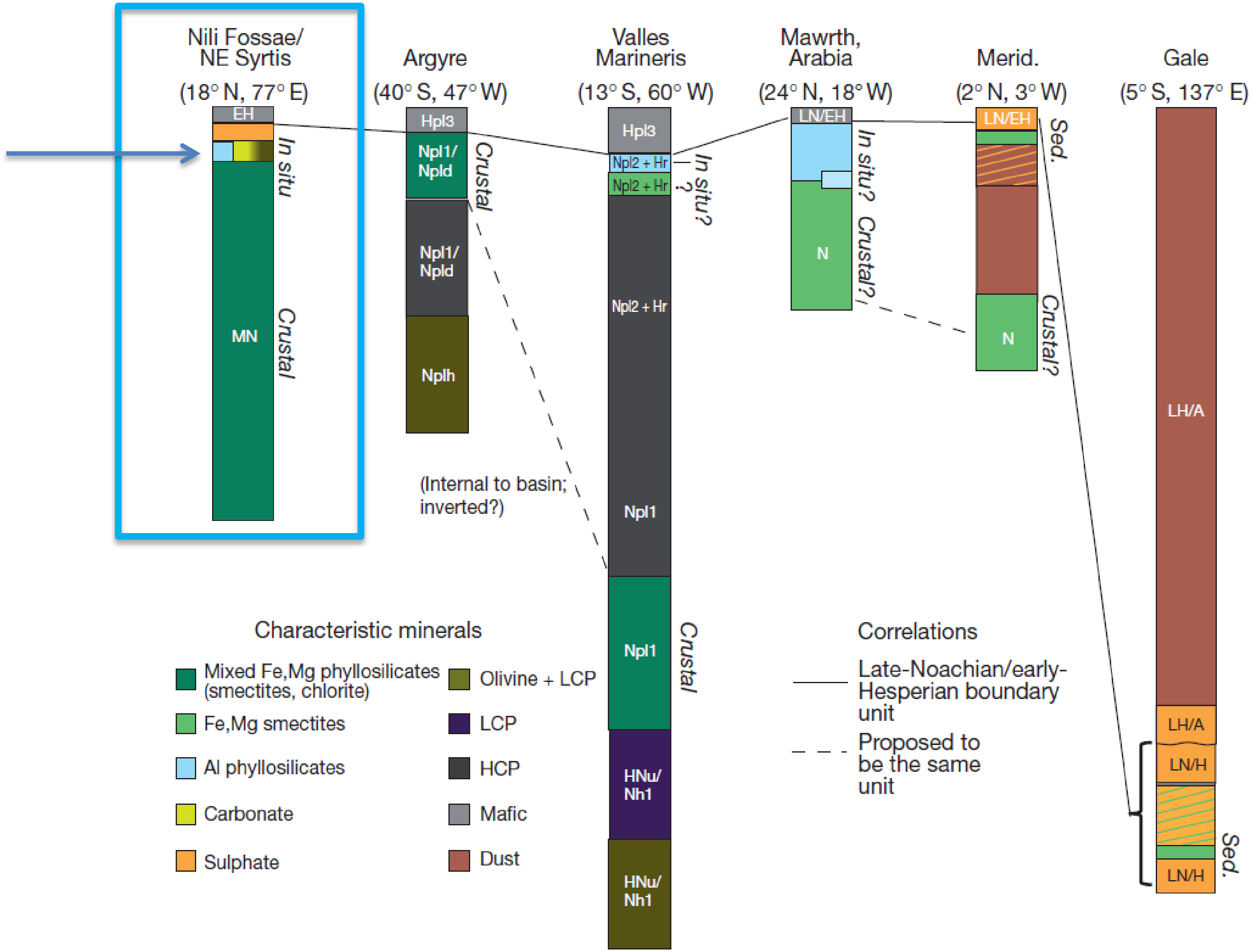
Obj. A	1. **Geologic setting and history of the landing site can be characterized and understood** w/ orbital and in-situ obs.		-clear timing constraints (EN to EH) -multiple well-ordered strat. units -in situ petrology solves key questions
Obj. B	2a. Landing site w/ **ancient habitable enviro.**		-carbonate formation by neutral alk waters (HT or near surface)
	2b. **Rocks with high biosignature preservation potential** are available and **are accessible** to rover instr. astriobio. investigation.	*or*	-yes under HT hypothesis -yes under playa/basin hypothesis -maybe under weathering hypothesis
Obj. C	3a. Offers **abundance, diversity, and quality of samples suitable for addressing key astrobio. questions if/when they are returned** to Earth.		-record of critical EN To EH time period -multiple aqueous, potentially habitable environments -isotopic record of enviro change
	3b. Offers **abundance, diversity, and quality of samples for addressing key planetary evolution questions** if/when they are returned to Earth.		-yes under HT hypothesis -yes under shallow playa hypothesis -maybe under weathering hypothesis

Extras

Nili Fossae Carbonate Plains: A Summary

- Download the 30+ papers on this key region at
  ftp://ftp.gps.caltech.edu/pub/Ehlmann/mars2020
- Immediate Access to Land-On Primary Science
  - Extensive aqueous alteration to form Fe,Mg-carbonate with intermixed phase
    - Determining the relative importance of sedimentation, weathering, and hydrothermal processes for early aqueous environments
    - How much carbonate? Stored by what process? Important questions for understanding the global reservoir, answerable in situ and with returned samples
    - No later overprinting by an “acid bath”
  - High-Mg mafic/ultramafic rocks
    - preserves a record of early igneous processes or a record of impact processes and mantle-derived cumulates
- In situ exploration of a key stratigraphy of ancient crustal clays, carbonate, kaolinite, basaltic ash caprock to explore changing habitable environments and geological processes
- Diverse, fundamental questions about ancient Mars are accessible here, providing decades of work on returned samples

Key Martian Stratigraphies

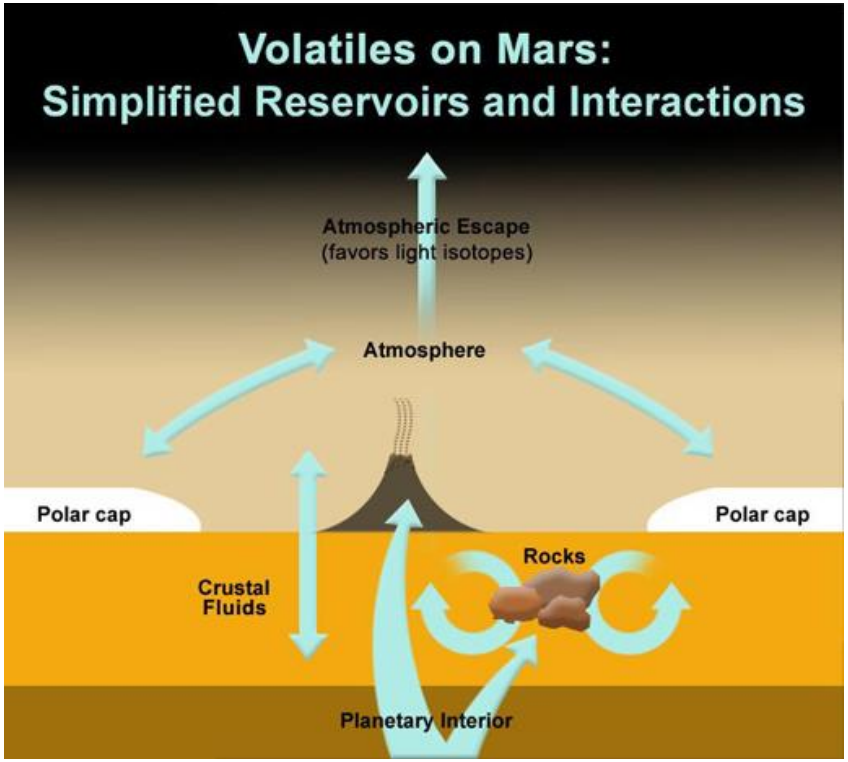


Ehlmann et al., 2011, Nature

Where there is carbonate, it is special

- Some aqueous environments were neutral to high pH and never experienced an overprinting acidic period
- Carbonate formed in conjunction with olivine near-surface alteration (weathering, lacustrine) and/or serpentinization

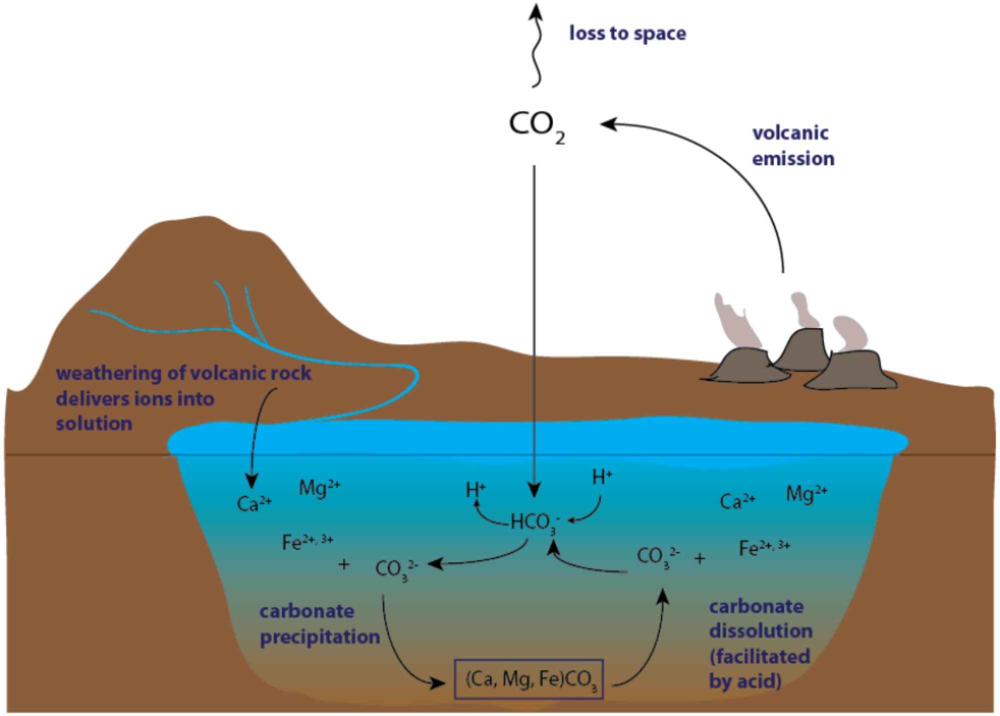
- Aqueous activity in Nili Fossae extended well into the Hesperian (Mangold et al., 2007, JGR)
- Heart of figuring out the "case of the missing atmosphere"—how/when sequestered in carbonate? What was the process and what does this imply about aqueous—potentially habitable—environments on early Mars?



MSL press release (Leshin graphic)

In Search of the "Missing" Martian Carbonate

- Carbonate: a minor phase in Martian dust, soils (<5 wt. %) [Lellouch et al., 2000; Bandfield et al., 2003; Leshin et al., 2013] and in Martian meteorites [e.g. Bridges, 2001]
- Predicted to be a sink for the early Martian atmosphere as a common, weathering product with water and CO_2-atmosphere
- Implications of carbonate paucity:
  - Acidic conditions precluded carbonate formation and preservation? [Fairen et al., 2004; Bullock & Moore, 2007; Mukhin, 1996]
  - Low pCO_2 when liquid water was present at the surface? [Chevrier et al., 2007; Halevy et al., 2007]
  - Waters driving aqueous alteration on Noachian Mars were not in contact with the atmosphere? [Ehlmann et al., 2011]
  - After ~4 Gyr, always low atmospheric pressure [Hu, Kass, Ehlmann, Yung, in review]



Is NF Carbonates site at all typical of Mars or just "weird"?

- Special because high-Mg olivine taps primitive lavas or mantle cumulates
- Other olivine/carbonate-bearing rocks like this may exist on Mars but be smaller and with less clear stratigraphic context and timing, e.g. small Comanche outcrop at the Spirit site
- Mars2020 Primary mission: Special opportunity to investigate a key preserved habitable environment, a key process for geochemical cyling, and a unit that may tap Mars' mantle
- Mars 2020: Extended mission: access to regionally-extensive type stratigraphy with typical alteration assemblage with Fe/Mg and Al phyllosilicates

<u>GUSEV CRATER:</u>

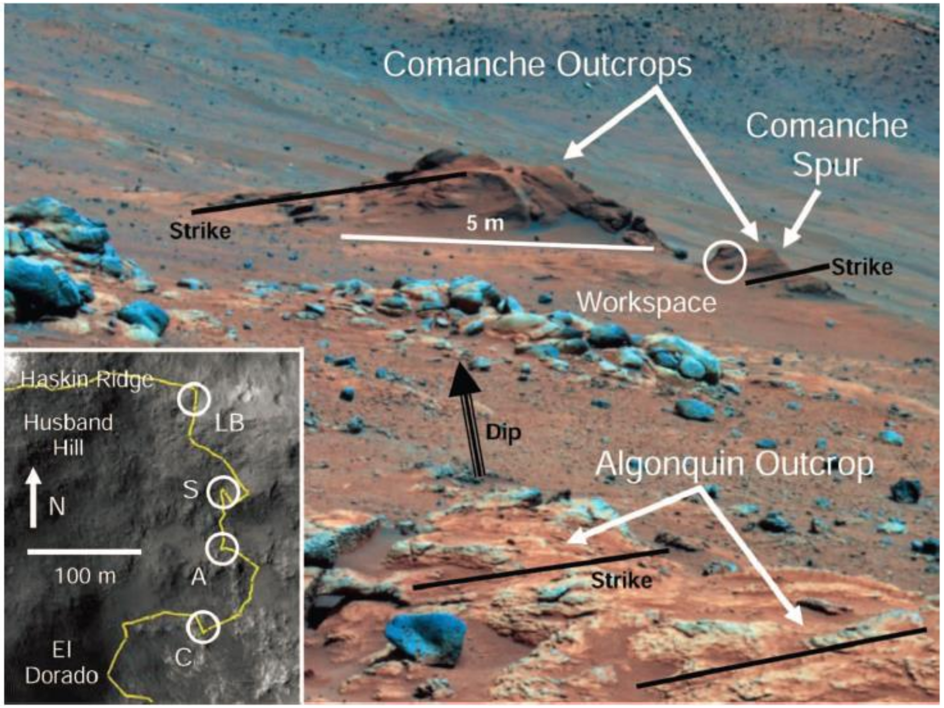
(Morris et al., 2010, Science)

40% olivine

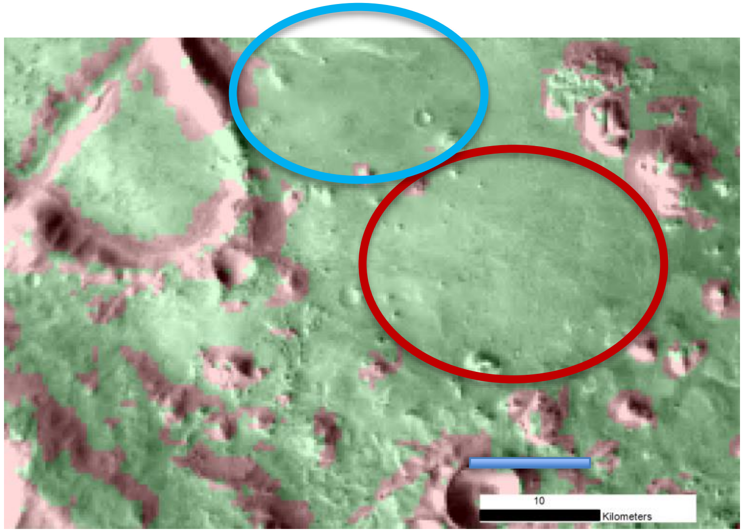
35% amorphous silicate

25% carbonate

$(Mg_{0.62}Fe_{0.25}Ca_{0.11}Mn_{0.02})CO_3$.



Preliminary Landing Site Safety

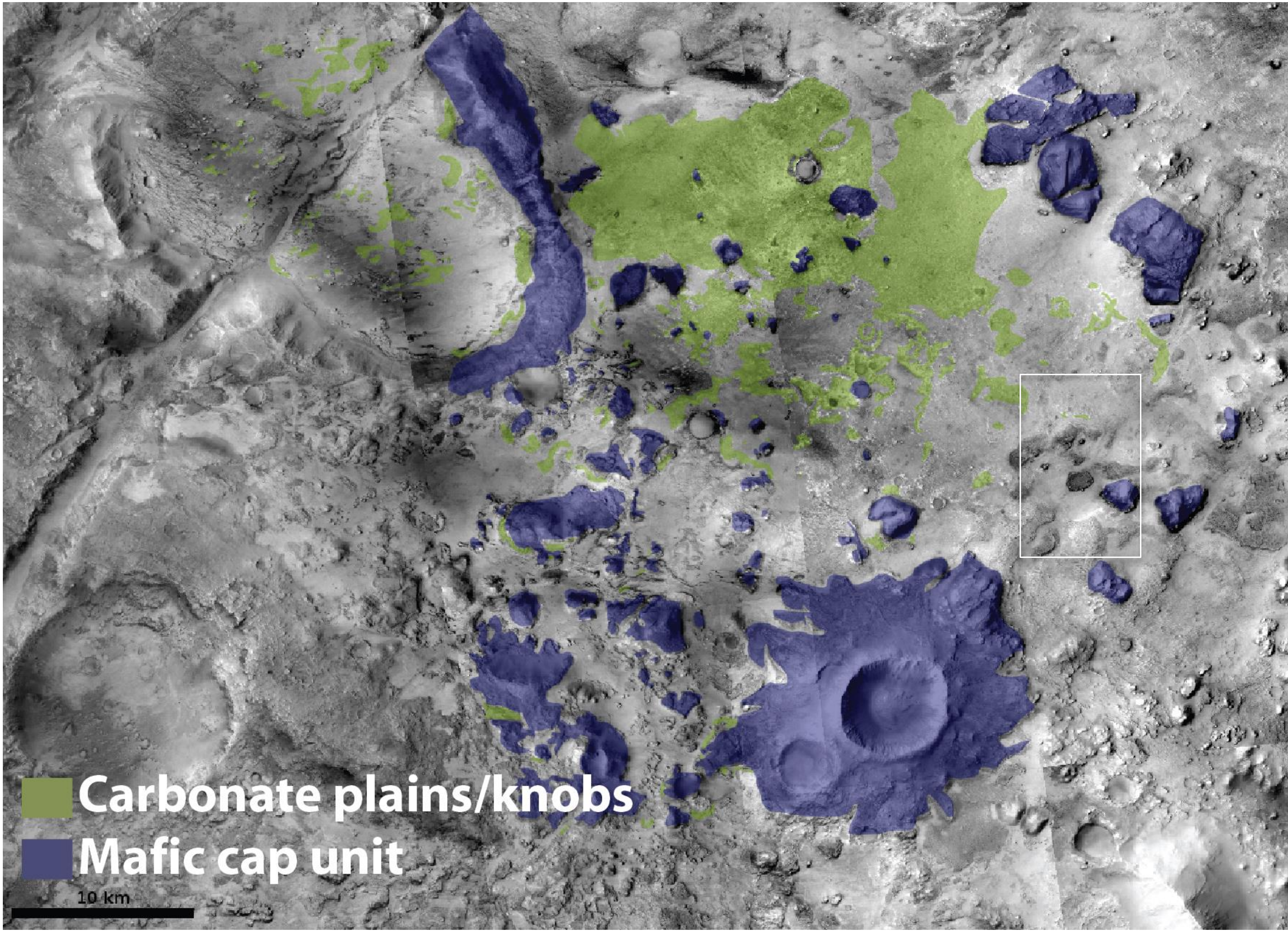


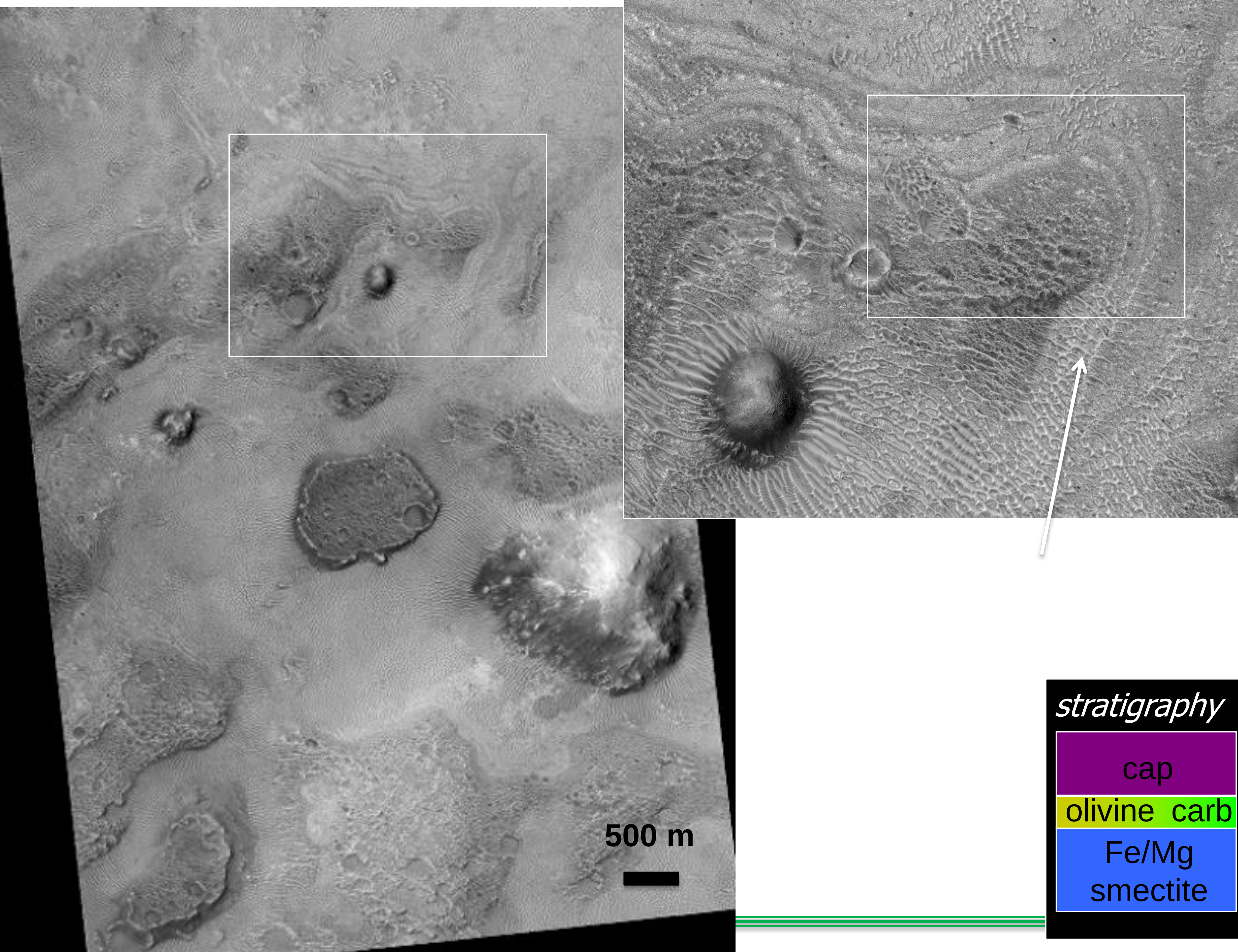
25km x 20km 18km x 14km

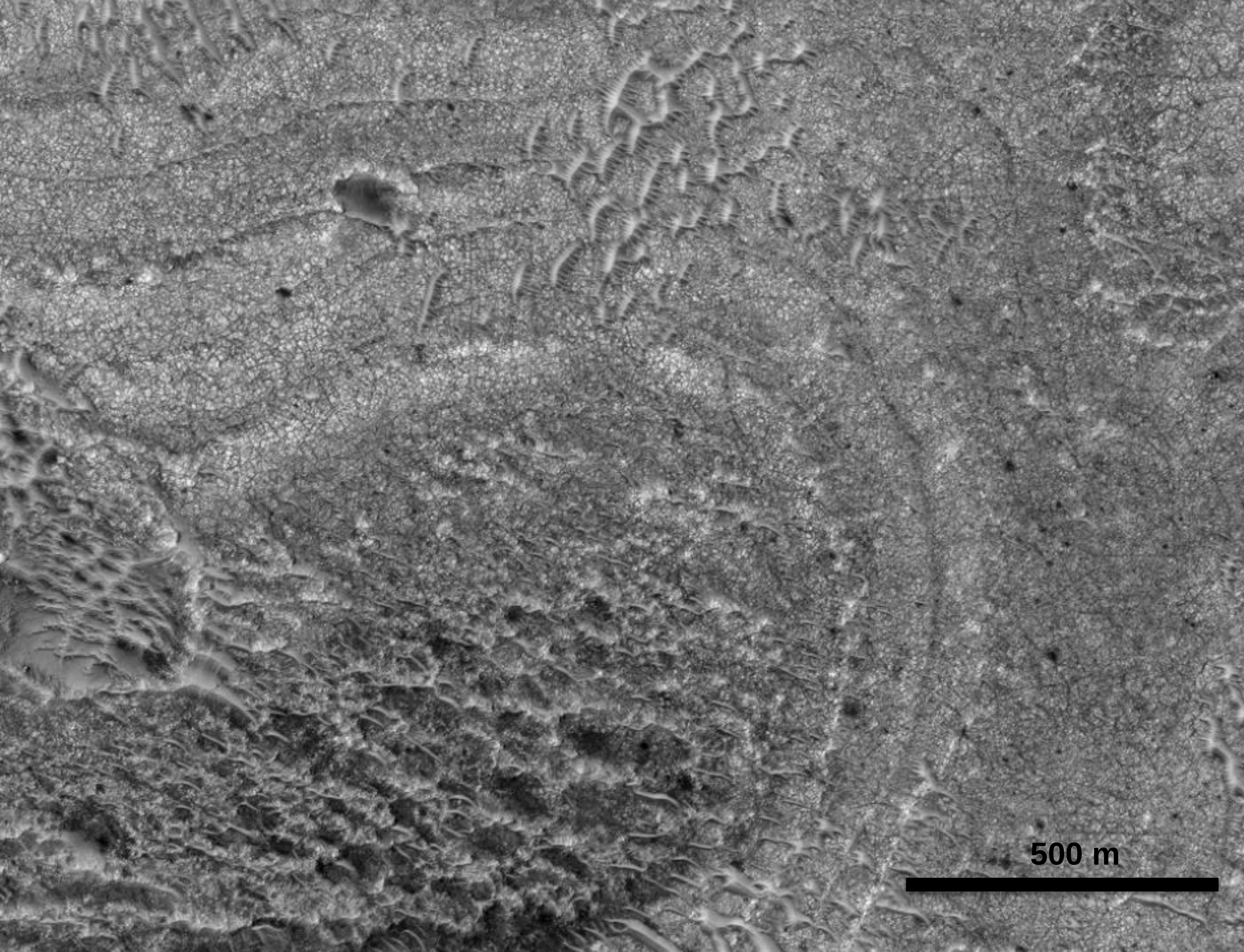
1st workshop; landable, but too many sand hazards for traverse

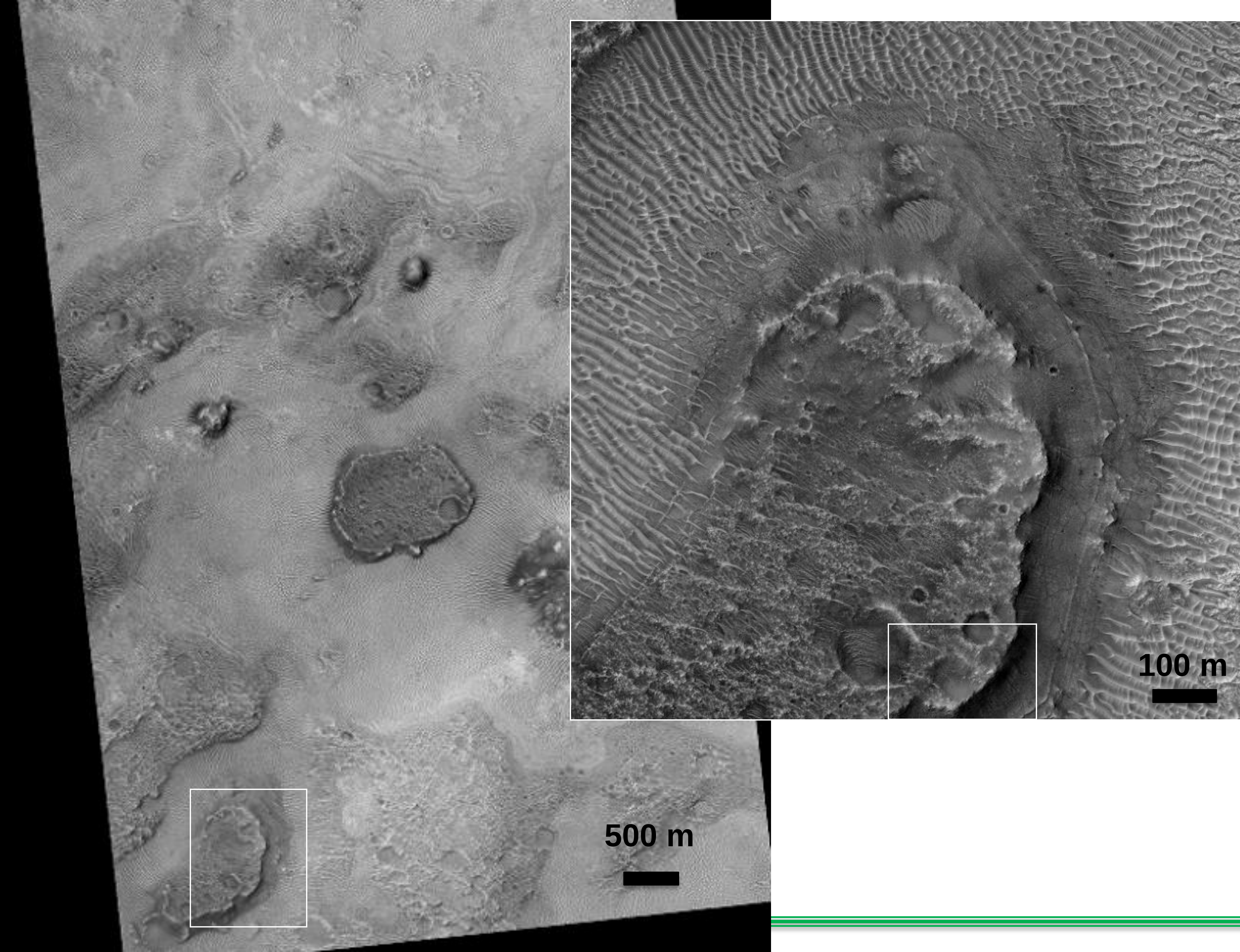
EDL team suggestion; final ellipse size likely to shrink and fit between scarps but higher-fidelity modeling needed

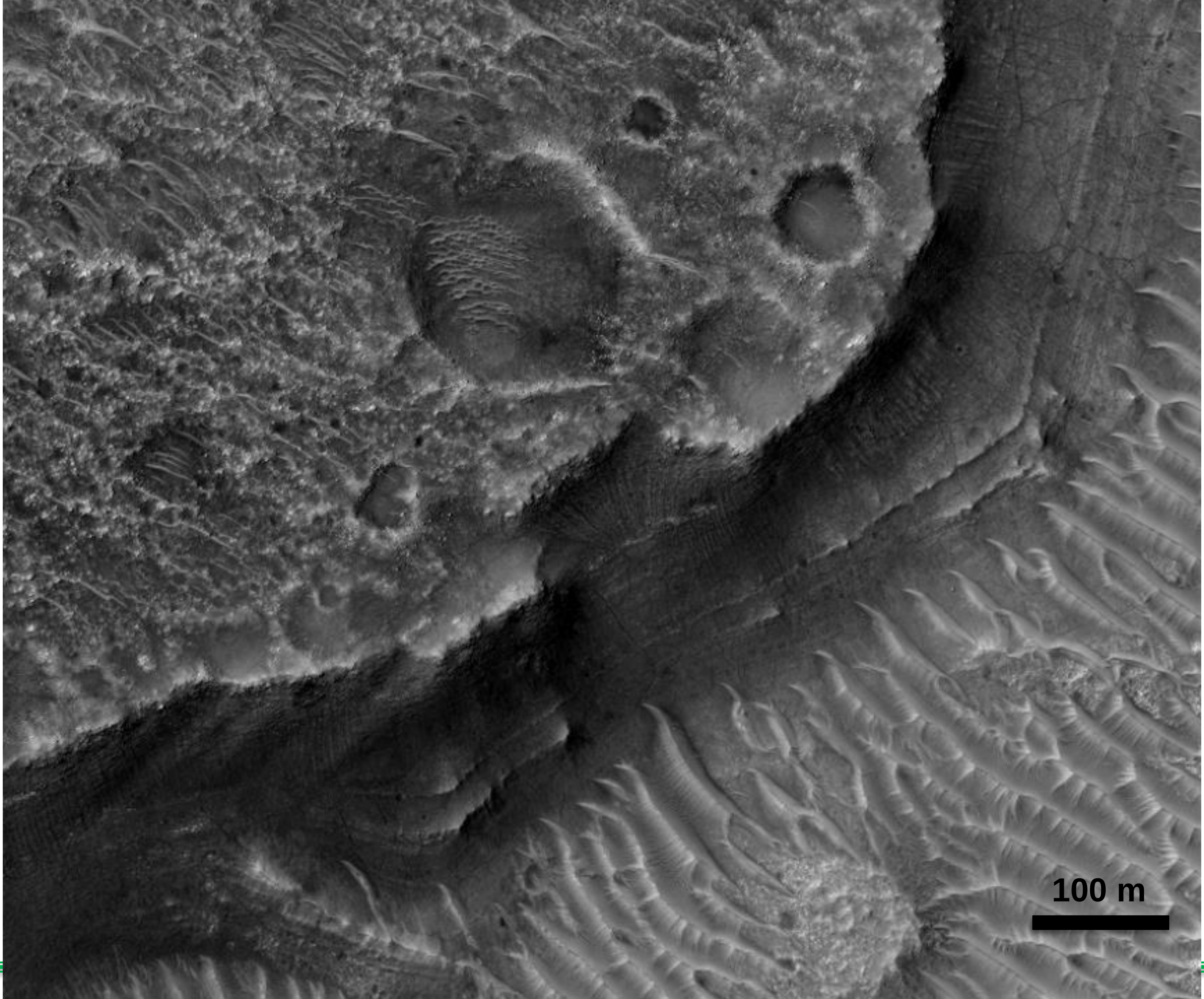
Criteria	Requirement	Actual
Elevation	< +0.5 km	-1.5 km
Latitude	±30°	21.7°
Relief	<100 m on 1km-1,000 m baselines	overall flat; few scarps on margins
Slopes	<25°-30° on 2-5 m baselines	✔
Rocks	~7% rock abundance	✔
Radar Reflectivity	-20 to +15 dB at Ka band	✔
Thermal Inertia/ Albedo	>100 J $m^{-2}s^{-0.5}K^{-1}$ <0.25	>230 $m^{-2}s^{-0.5}K^{-1}$ <0.19

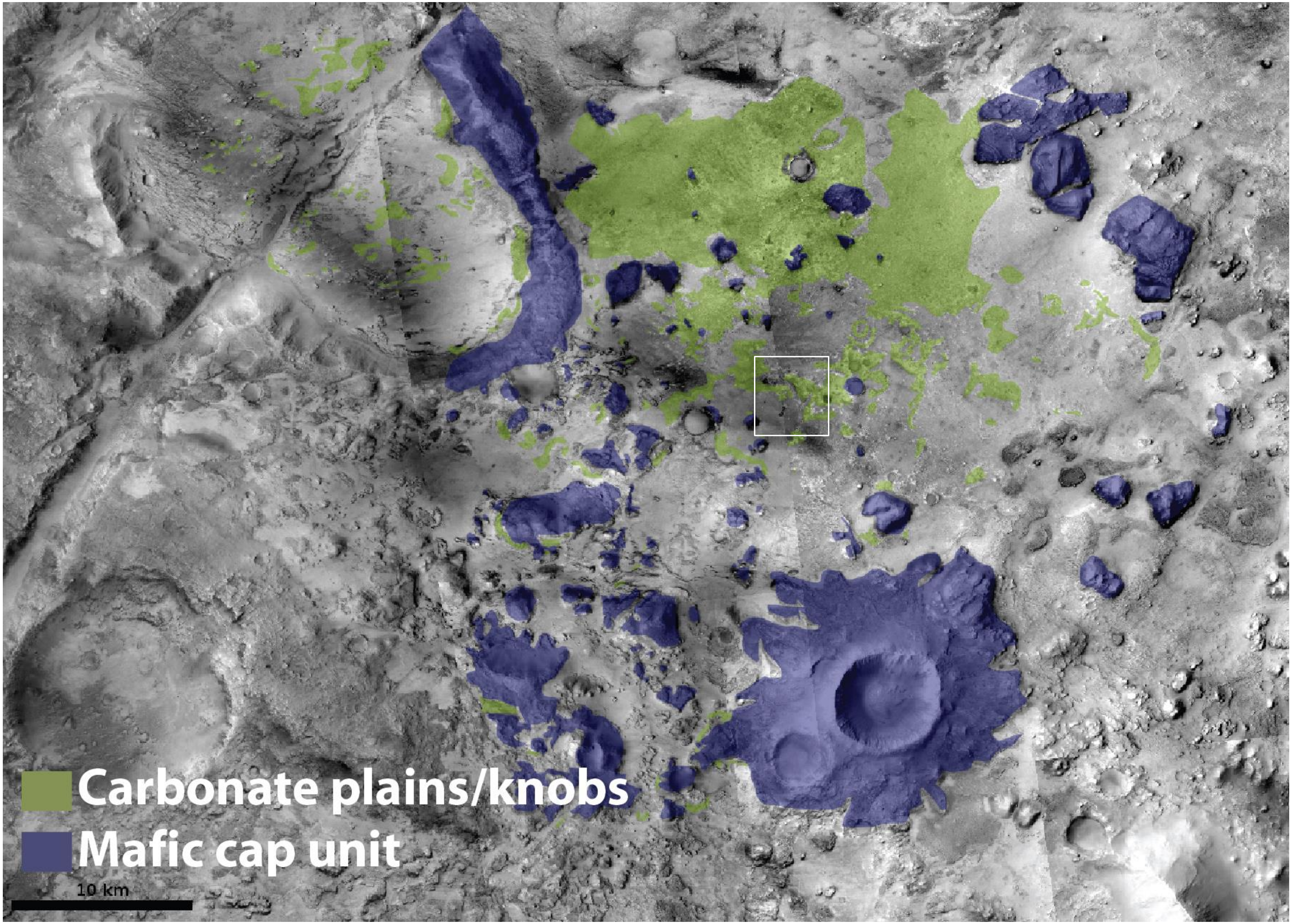

Carbonate plains/knobs
Mafic cap unit
10 km

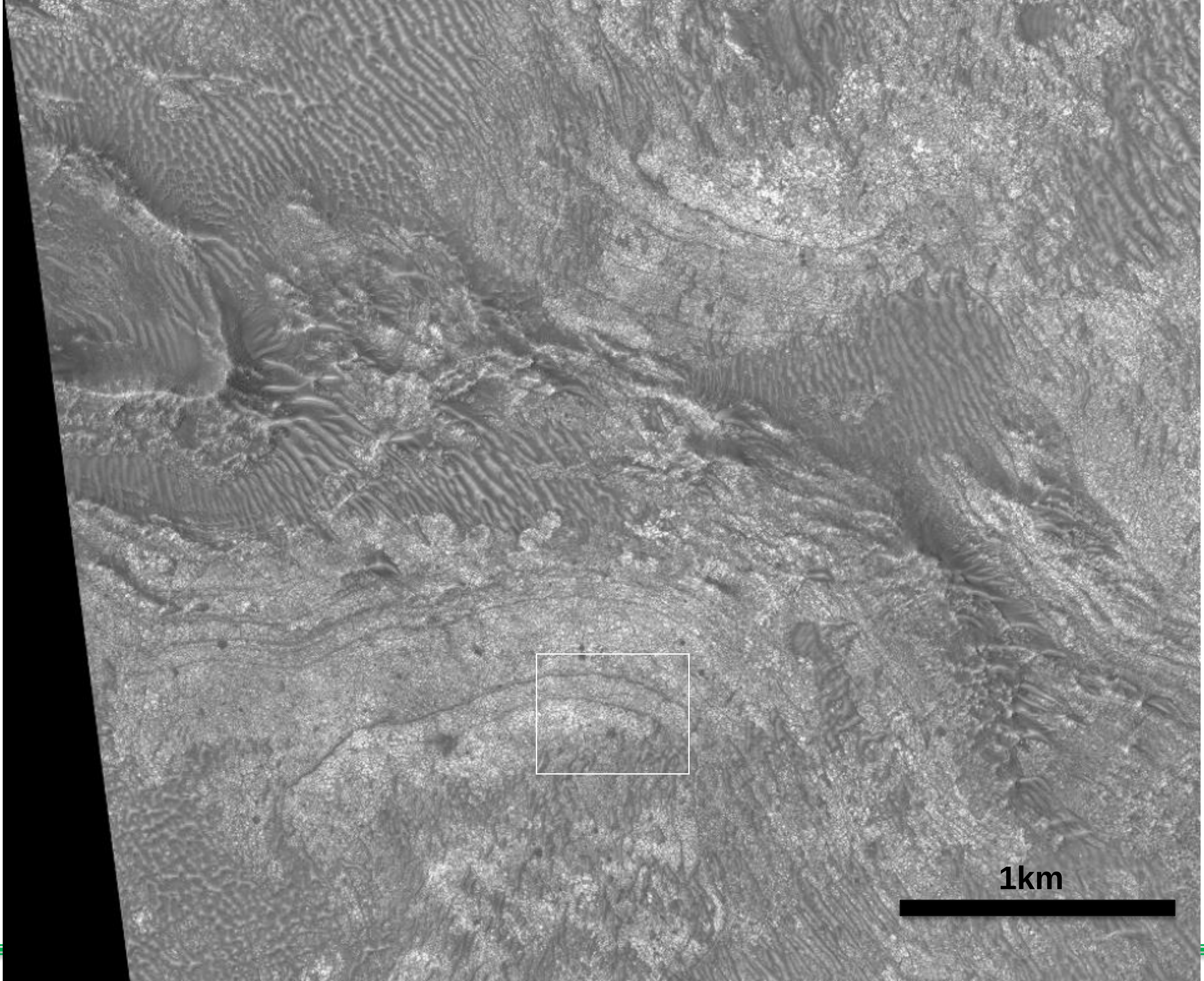

500 m
stratigraphy
cap
olivine carb
Fe/Mg smectite

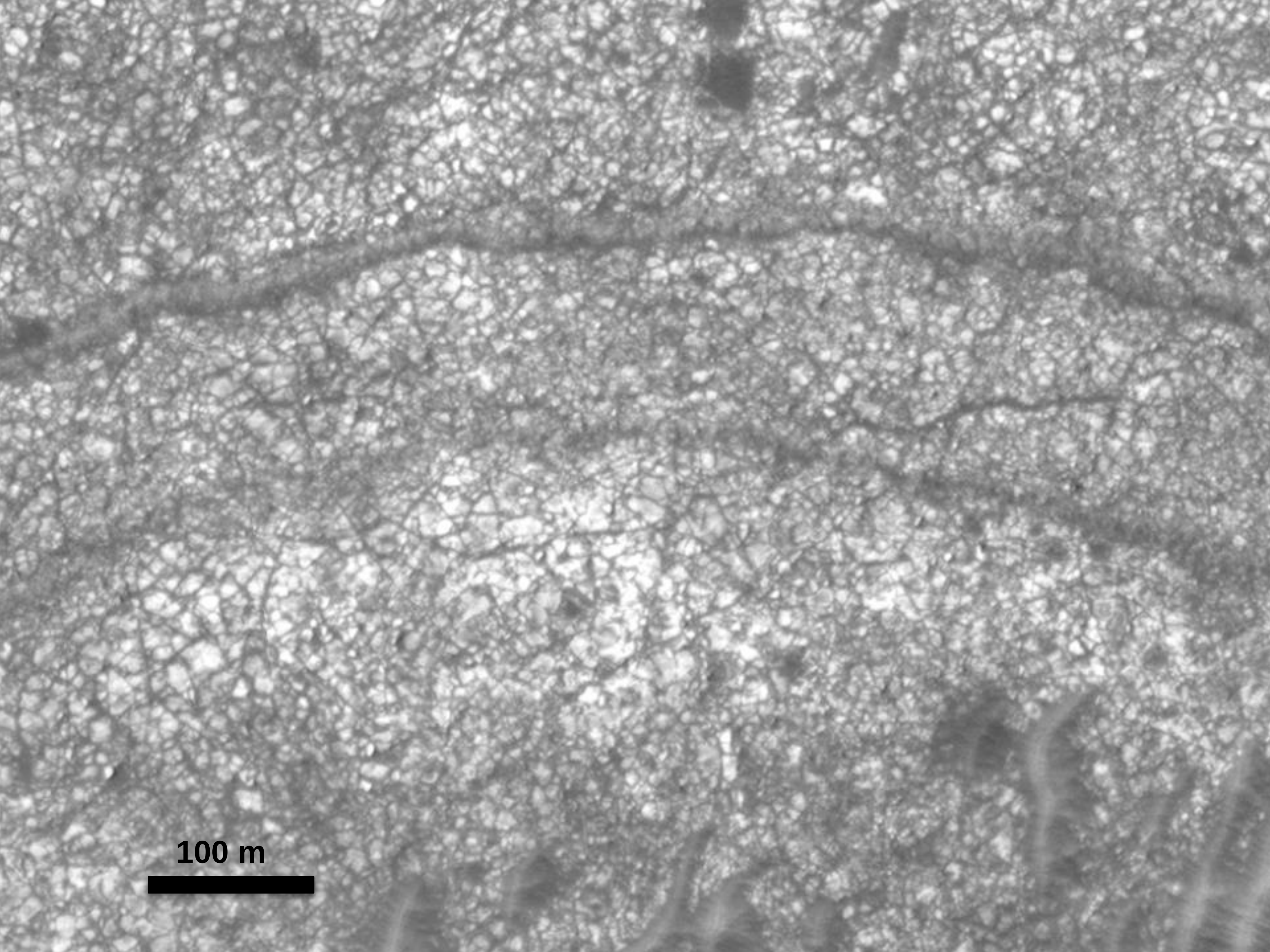

500 m


100 m
500 m


100 m


Carbonate plains/knobs
Mafic cap unit
10 km


1km


100 m

Top-Down Weathering: May explain top of section

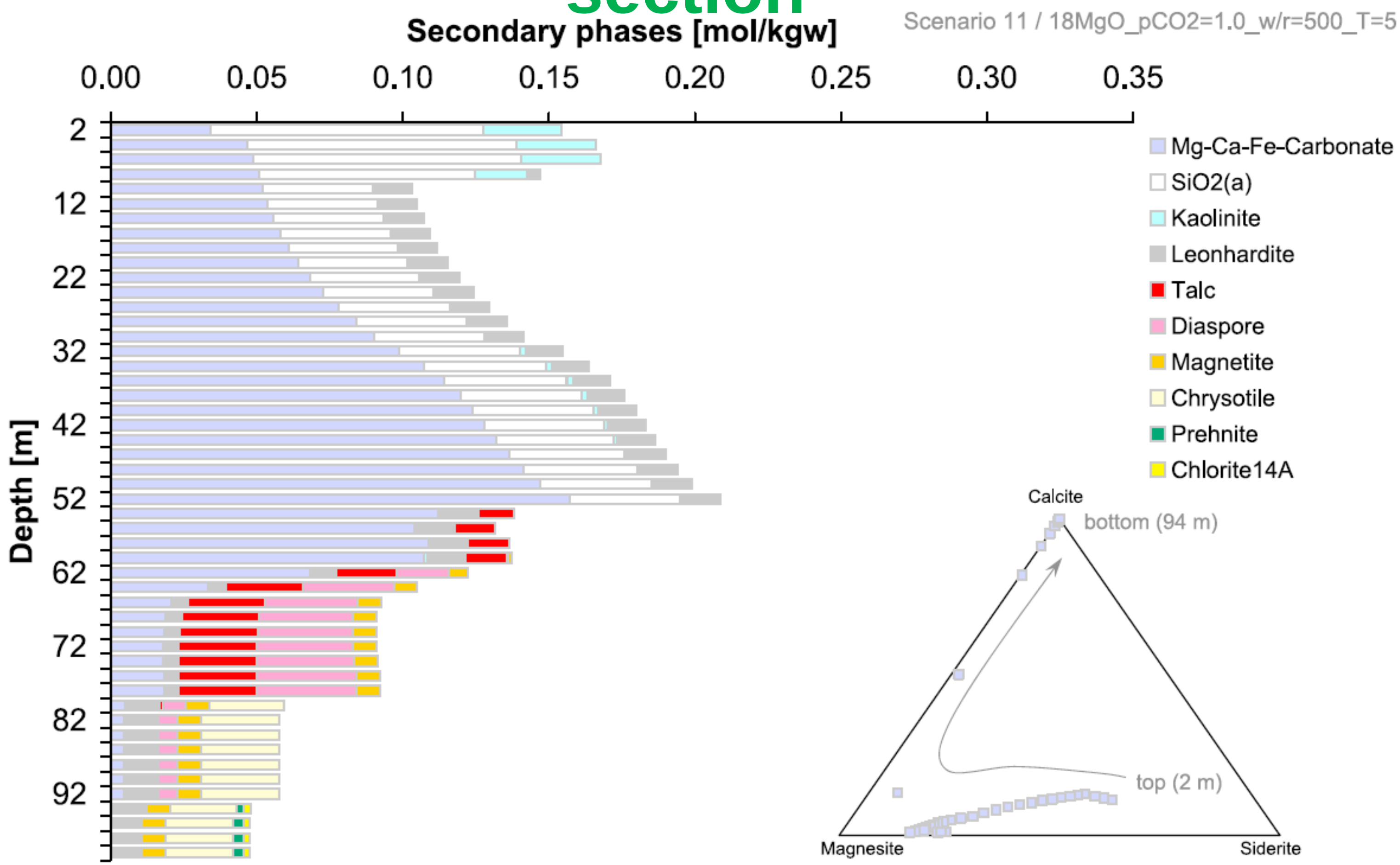


Figure 11. Scenario 11: Modeled depth distribution and composition of alteration mineral assemblages at 278 K and a water-to-rock ratio of 500 mol mol^{-1} for constant pCO_2 of 1 bar after 100,000 years of one-dimensional diffusive transport. The rock type is an olivine-rich ultramafite containing 18 wt% MgO. Inset displays Mg-Fe-Ca carbonate composition.

Van Berk & Fu, 2011, JGR