NE Syrtis Major, a Record of the Noachian-Hesperian Environmental Transition: Clays, Carbonates, Sulfates, and Multiple Igneous Units in Stratigraphy

Mustard JF, Ehlmann BL, Skok JR, Quinn DP, Mangold N., Desmarais D, Wiseman S, Head JW, Edwards CS, Milliken RE, Parman S, Cannon K, Goudge T, Amador ES, Harvey RP

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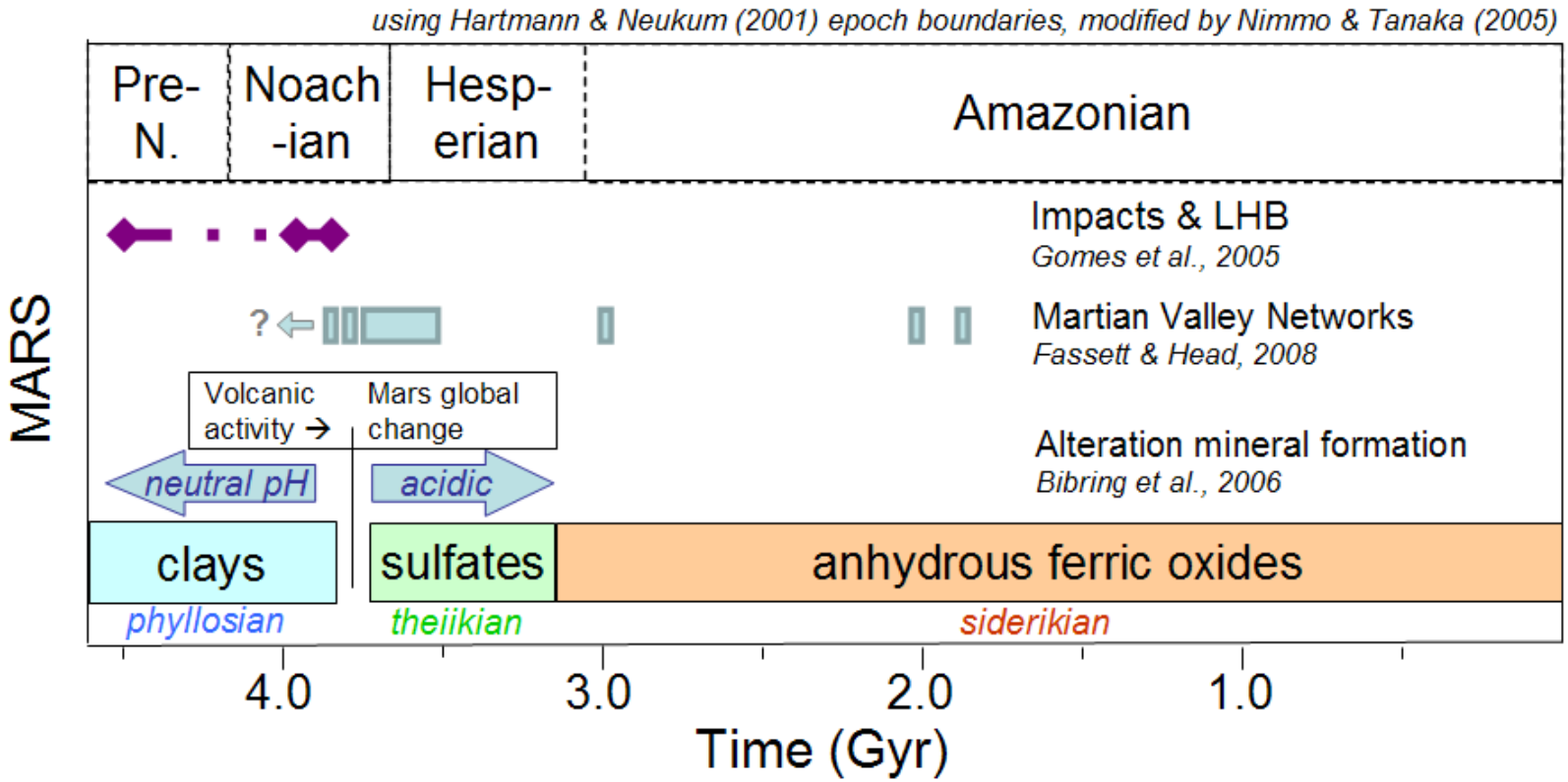
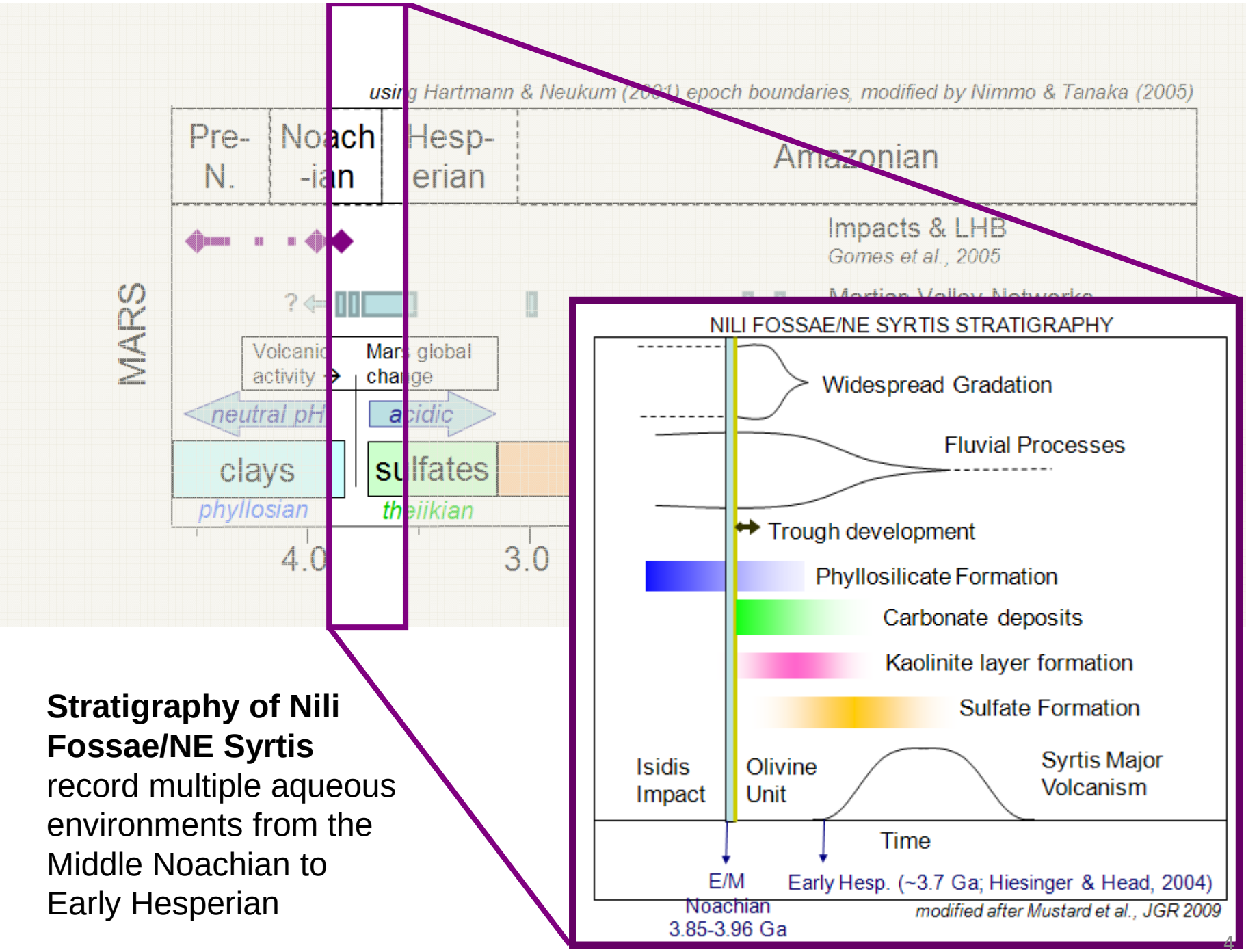
Compelling Mars and Astrobiology Science

- 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): 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 measurements and caching
- Key stratigraphies from Noachian and Hesperian eras: Does this capture Mars global environmental change?



Stratigraphy of Nili Fossae/NE Syrtis
record multiple aqueous environments from the Middle Noachian to Early Hesperian



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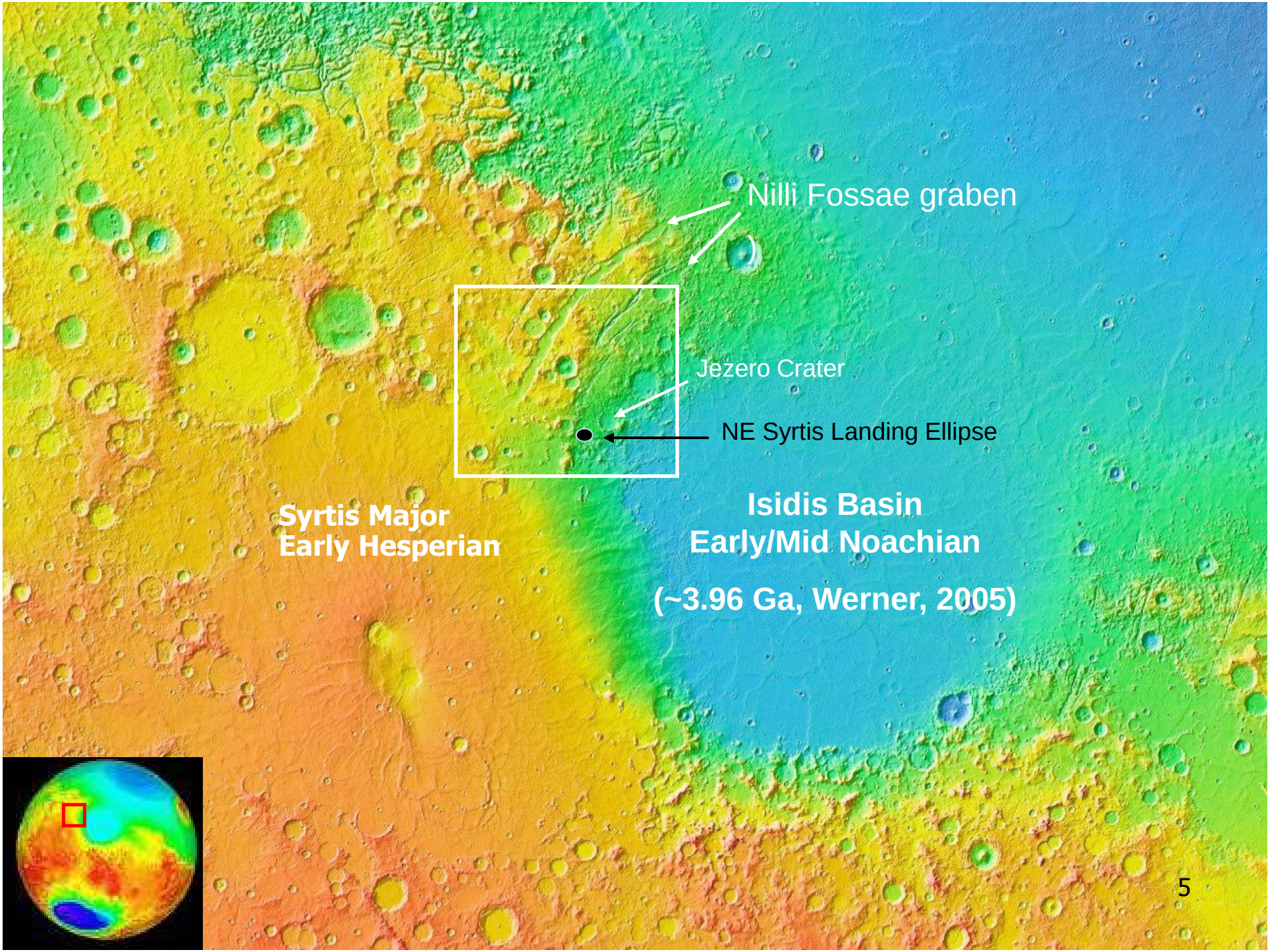
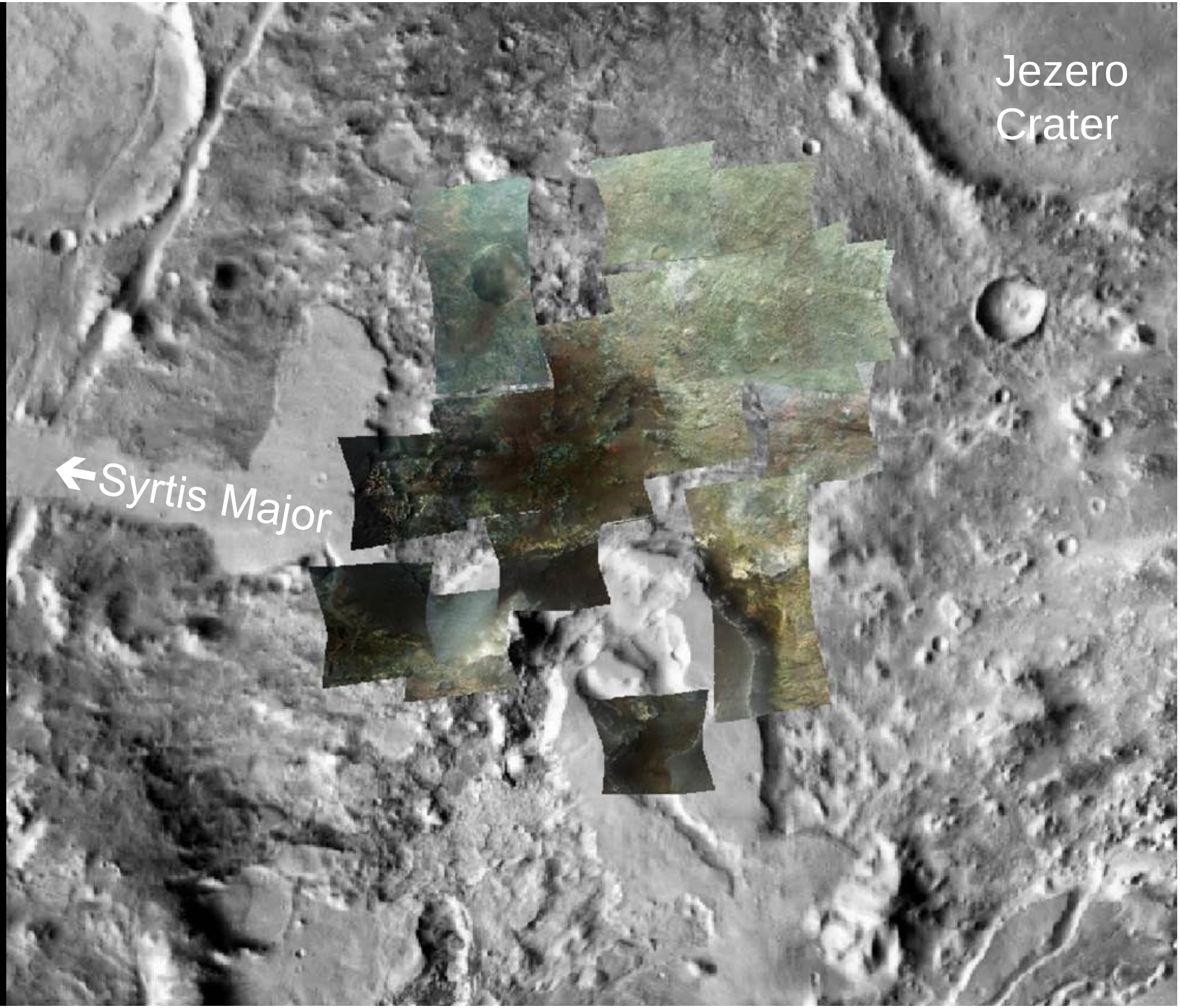

Nilli Fossae graben
Jezero Crater
NE Syrtis Landing Ellipse
Syrtis Major
Early Hesperian
Isidis Basin
Early/Mid Noachian
(~3.96 Ga, Werner, 2005)


Jezero
Crater
Syrtis Major

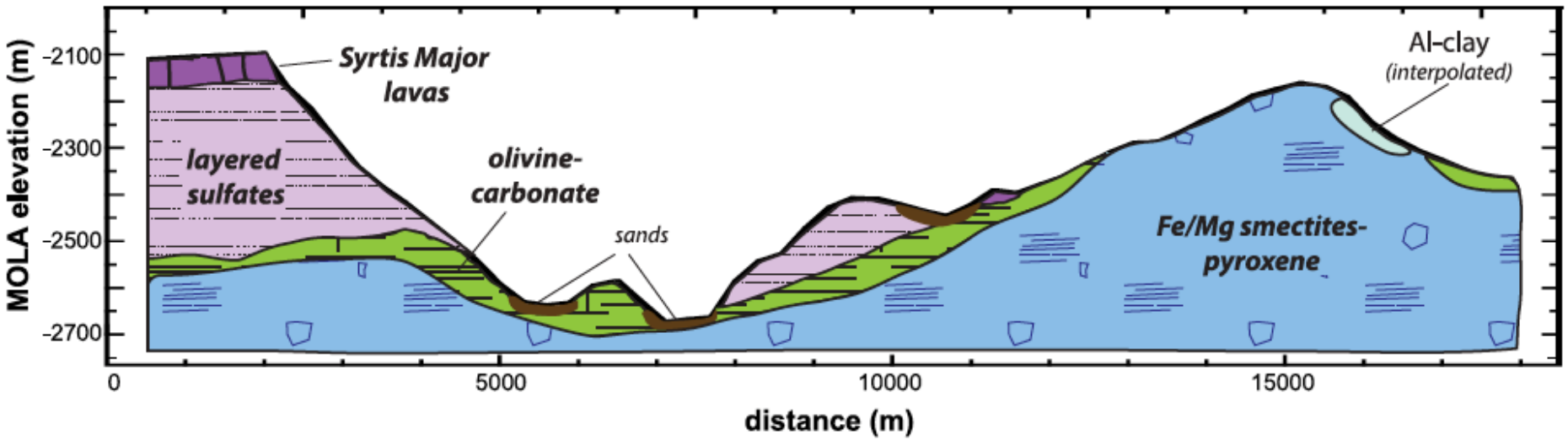
Major Hypotheses to be Tested

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

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

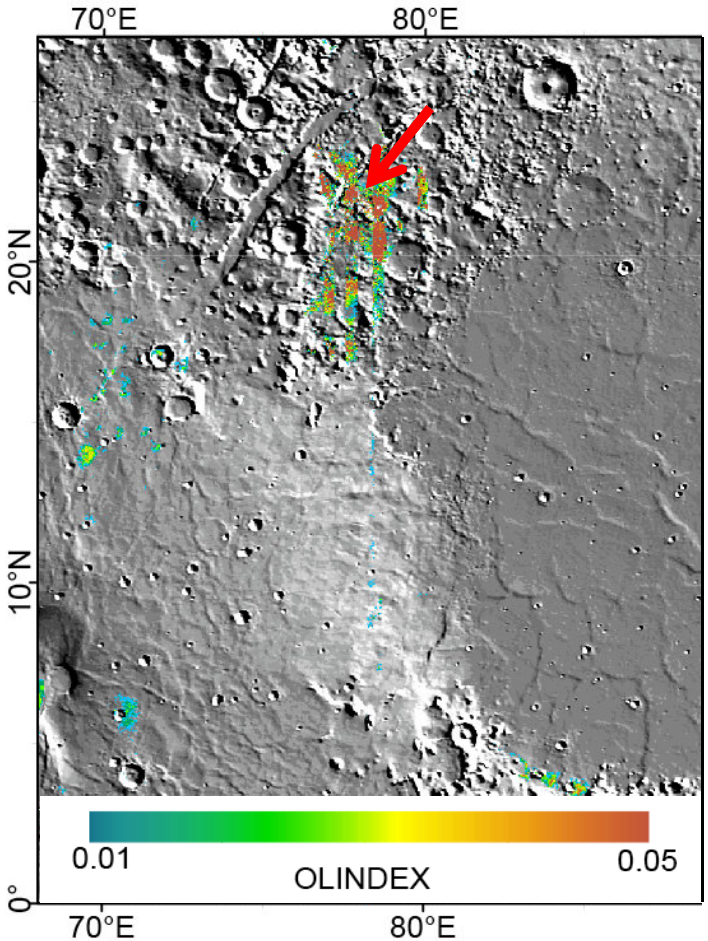
Layered kaolinite-bearing capping stratigraphy:	• Extensive leaching during a period of vertically integrated water cycle
Erosionally resistant ridges	• Fracture zones mineralized with hydrothermal sediments • Breccia Dikes
Hesperian-aged Sulfate stratigraphy	• Sedimentary deposition • Alteration of basalt • Box-work structures with jarosite: acidic geochemistry
Syrtis Major Hesperian volcanics	• Calibration of crater chronology, testing the formation mechanism (chemistry and mineralogy), validating remote sensing

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

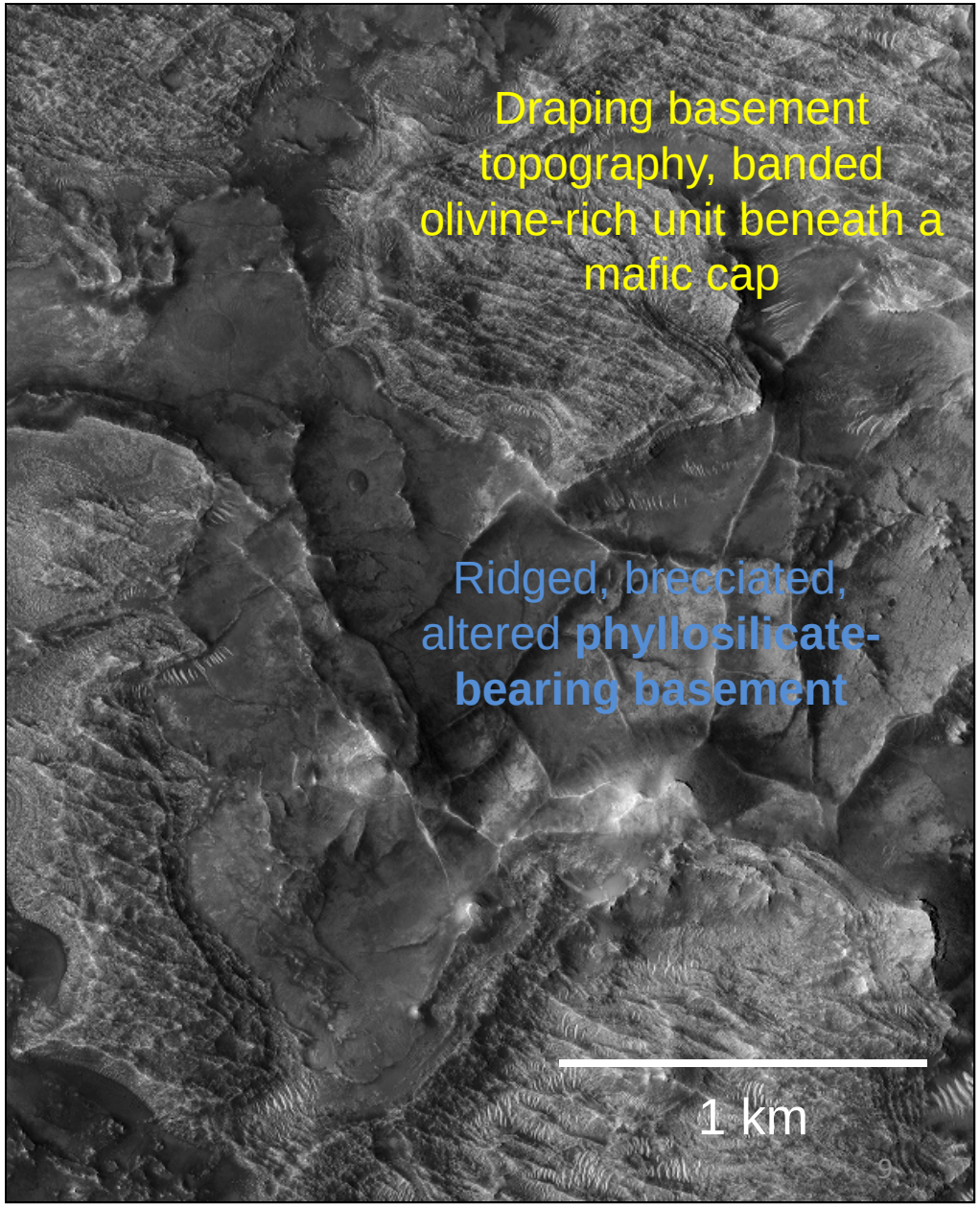


Ehlmann and Mustard GRL 2013

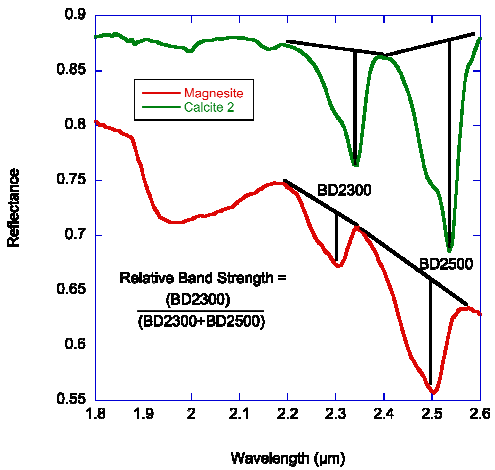
Widespread olivine-bearing unit is a distinctive stratigraphic marker
Shows the same texture, thickness, and composition across 1000s km^2



- Volcanic flows [Tornabene et al. 2007] vs impact melt [Mustard etal., 2007]
- Drapes topography and is cut by fossae
- Associated with carbonate and serpentine in the region near and north of Jezero Crater



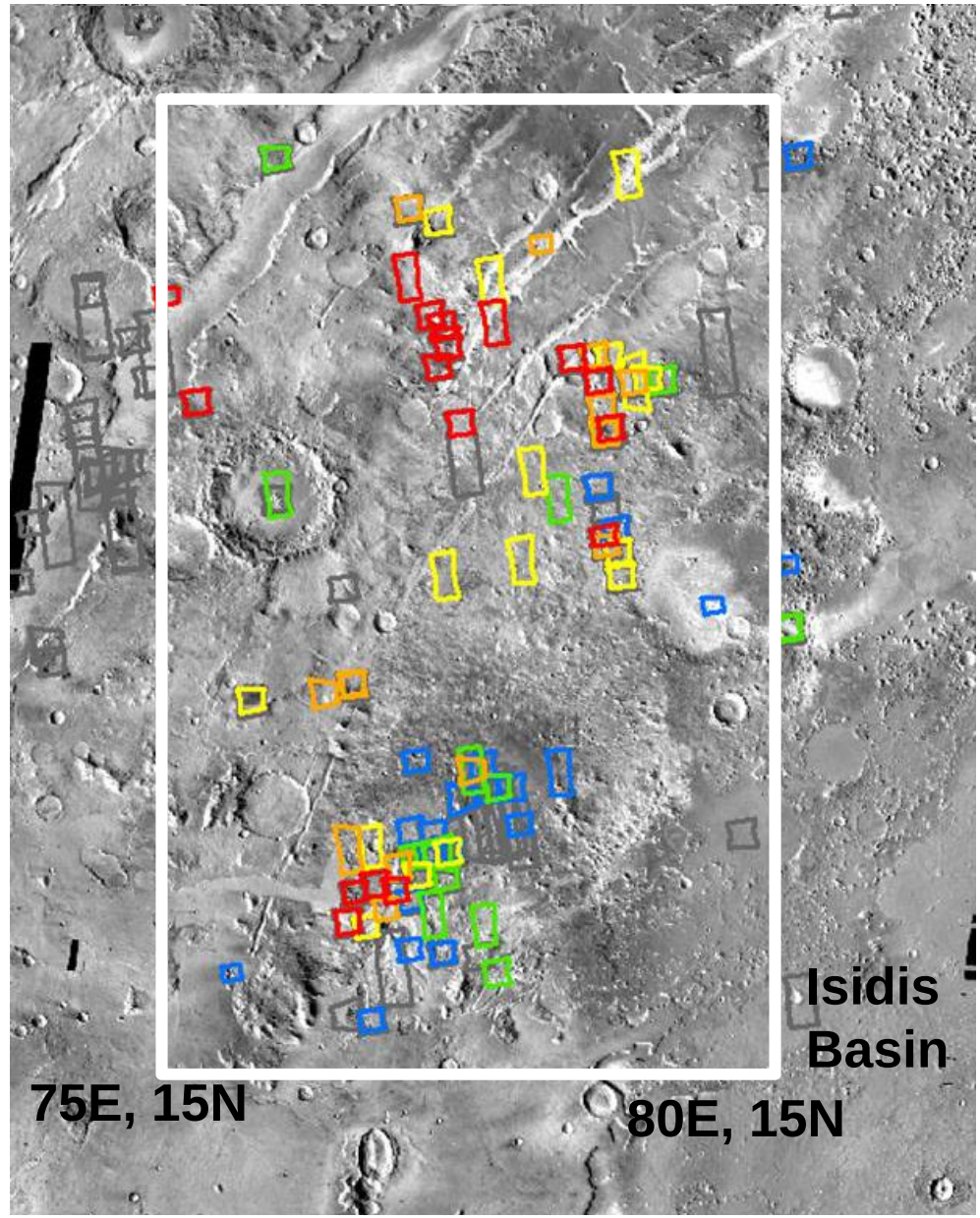
Regional Carbonate Signatures



$$\frac{BD2500}{(BD2300 + BD2500)}$$

Carbonate Clean ↓=↑ Mixed

- 0.30 – 0.35
- 0.35 – 0.40
- 0.40 – 0.45
- 0.45 – 0.50
- > 0.50

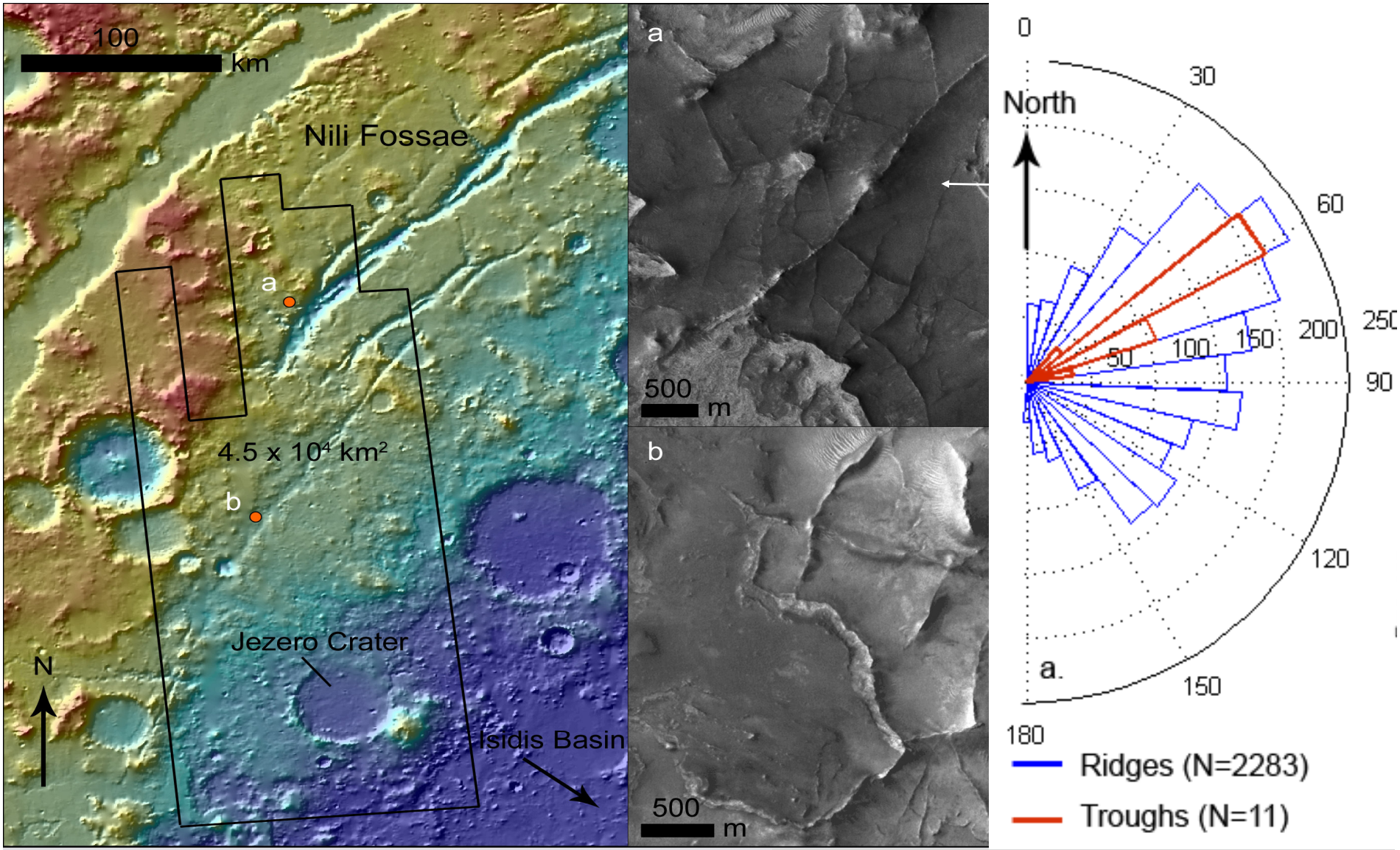


Carbonation of Olivine

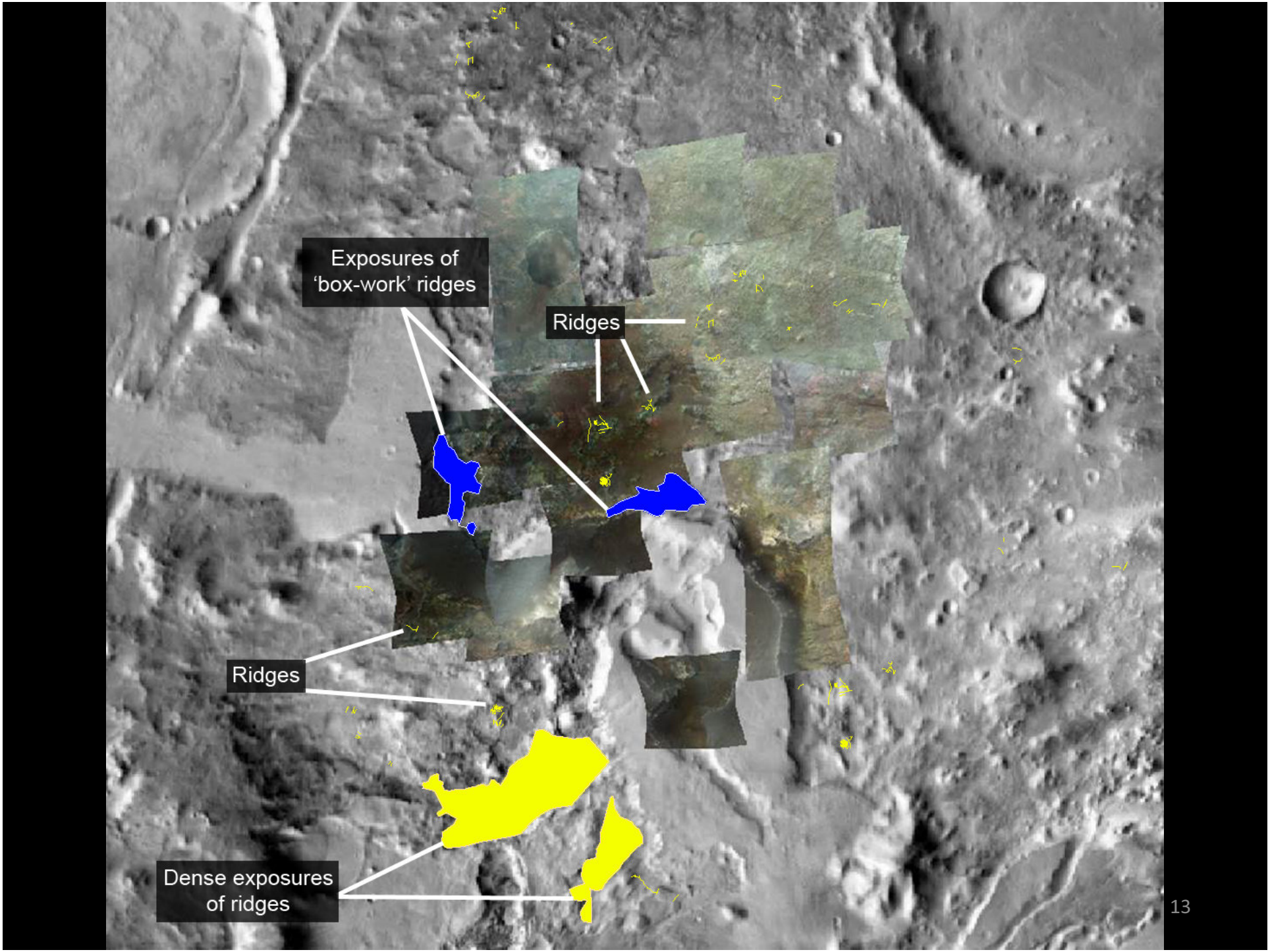
$$Mg_2SiO_4 + 2H_2O + 2CO_2 \rightarrow 2MgCO_3 + H_4SiO_4$$

- Multiple reaction pathways with different intermediate products (e.g. talc, serpentine): critical input to hypothesis testing
- Magnesite through a serpentine intermediate product is not thermodynamically favorable under near surface conditions
- This direct pathway is energetically favorable and consistent with the geologic observations
  - Magnesite always with olivine
  - Serpentine etc. is rare
- Significant liberation of SiO_2: what is its fate?

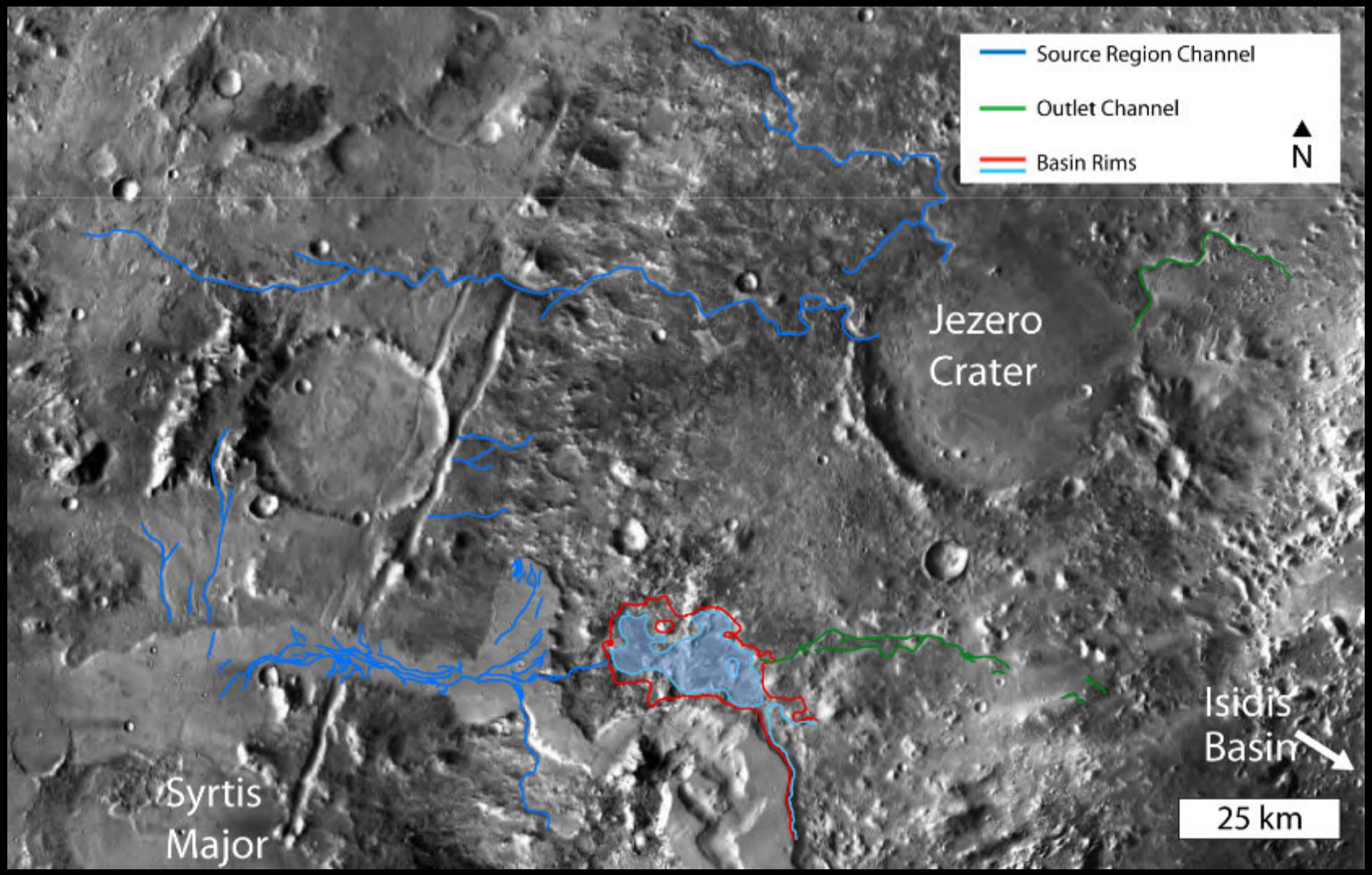
Morphology and Orientation of Ridges suggest mineralized fracture zones
Widespread ridges in the Noachian crustal unit, 10s m wide, 100s m long
Mapping of over 4000 ridges shows a NE-SW orientation: Response to Isidis Impact



Saper and Mustard (GRL, 2013)

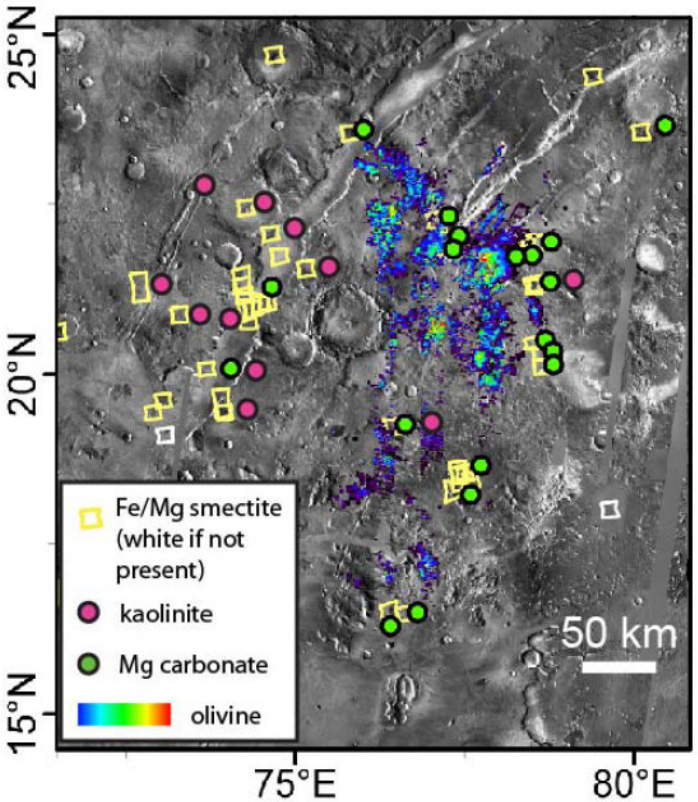

Exposures of
'box-work' ridges
Ridges
Ridges
Dense exposures
of ridges

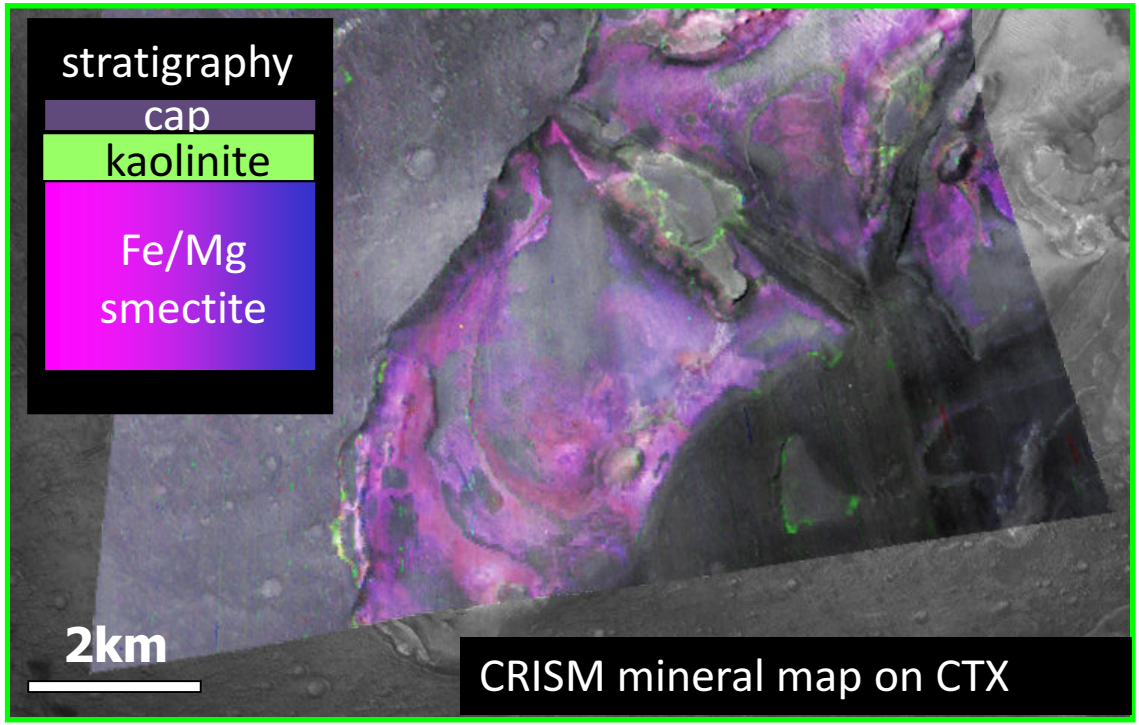
Channels and Basins



basalt $\xrightarrow[\text{alteration}]{\text{partial}}$ Fe/Mg smectite $\xrightarrow[\text{loss of } Ca^{2+}, Mg^{2+}, Fe^{2+} \text{ ions}]{\text{enhanced leaching}}$ Kaolin group mineral $Al_2Si_2O_5(OH)_4$

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

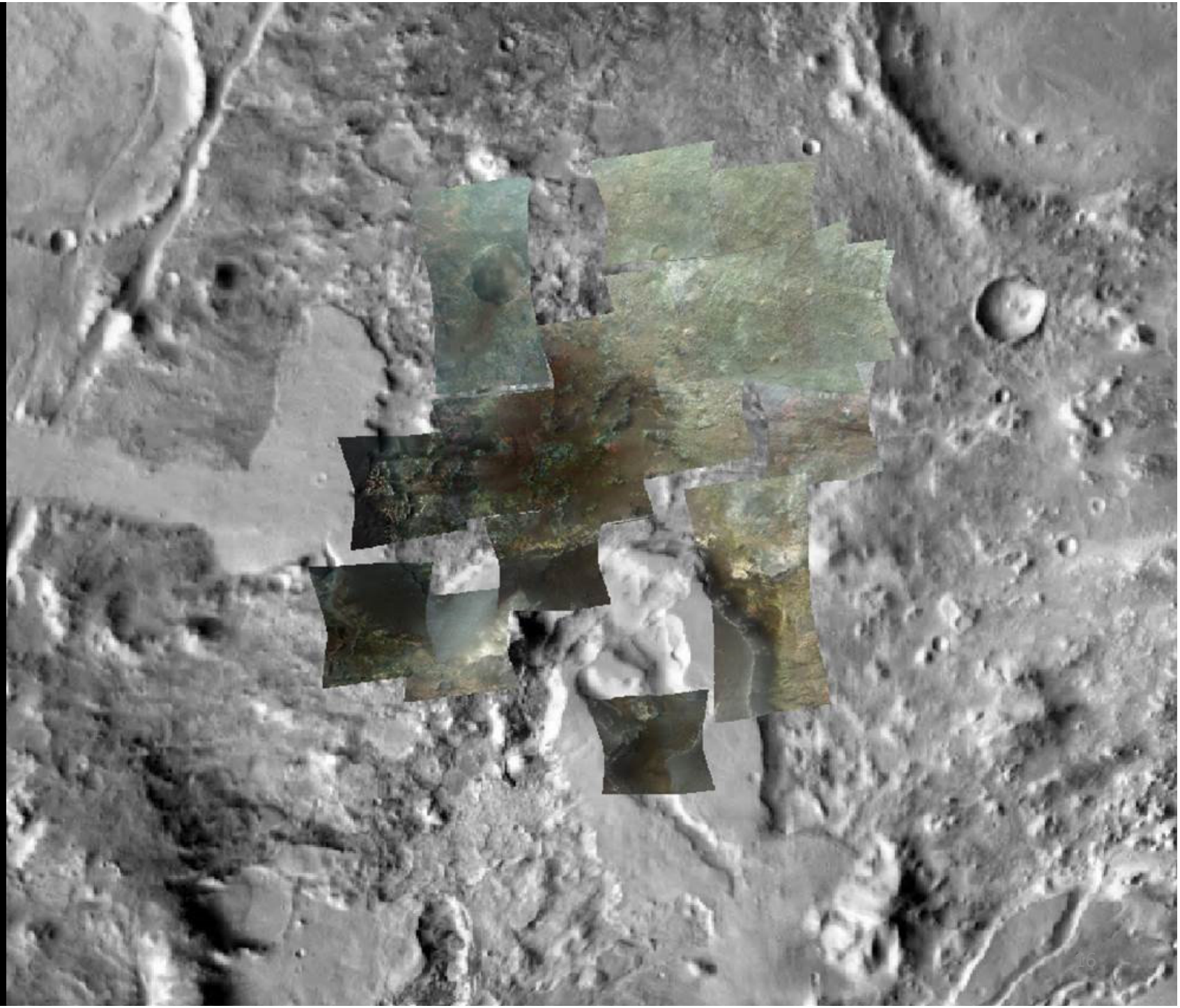


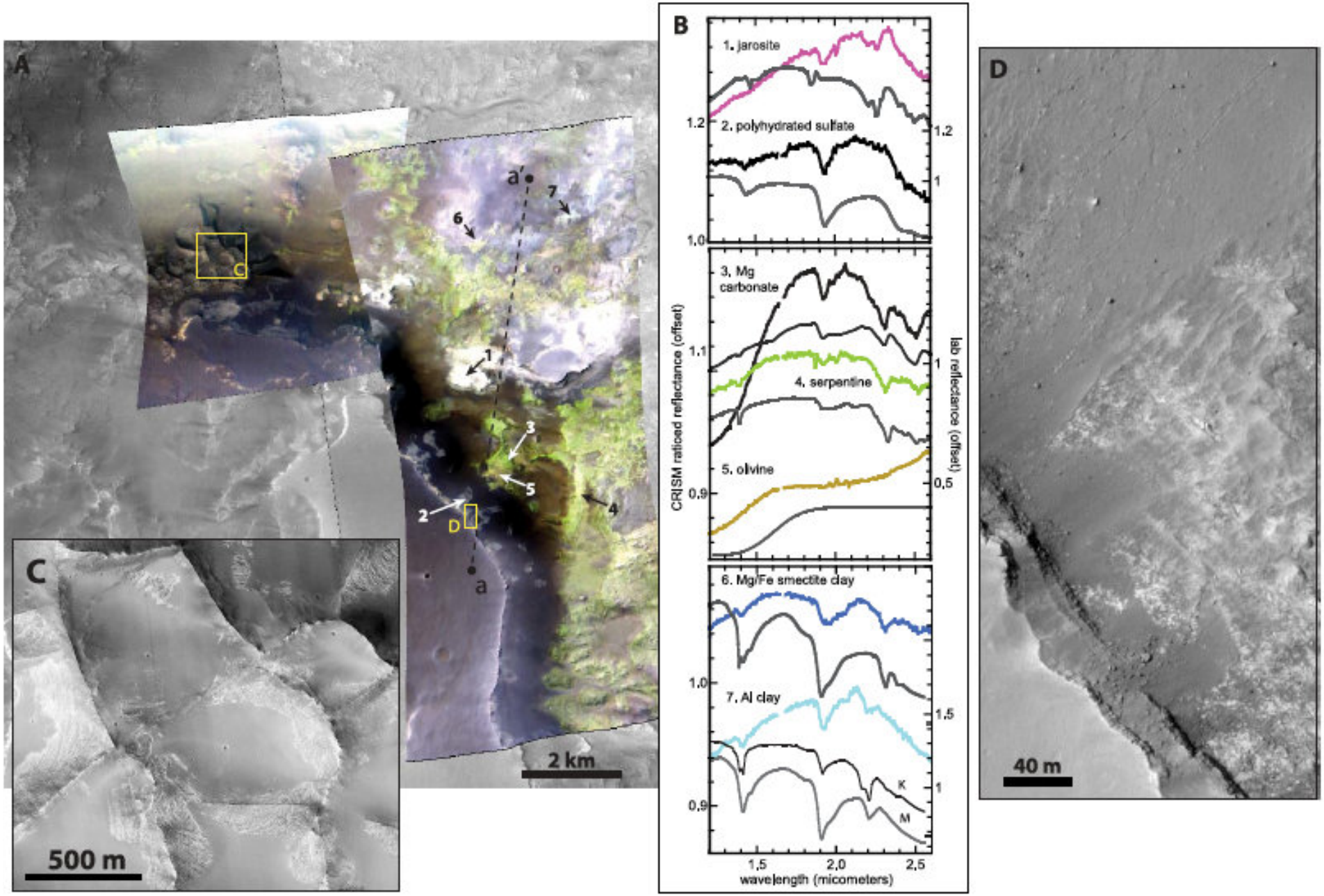


Ehlmann et al., Science 2008;
Ehlmann et al., *JGR*, 2009

Kaolinite-smectite alteration

occurs where precursor rock is not olivine-rich (pyx, Fe/Mg smectite)



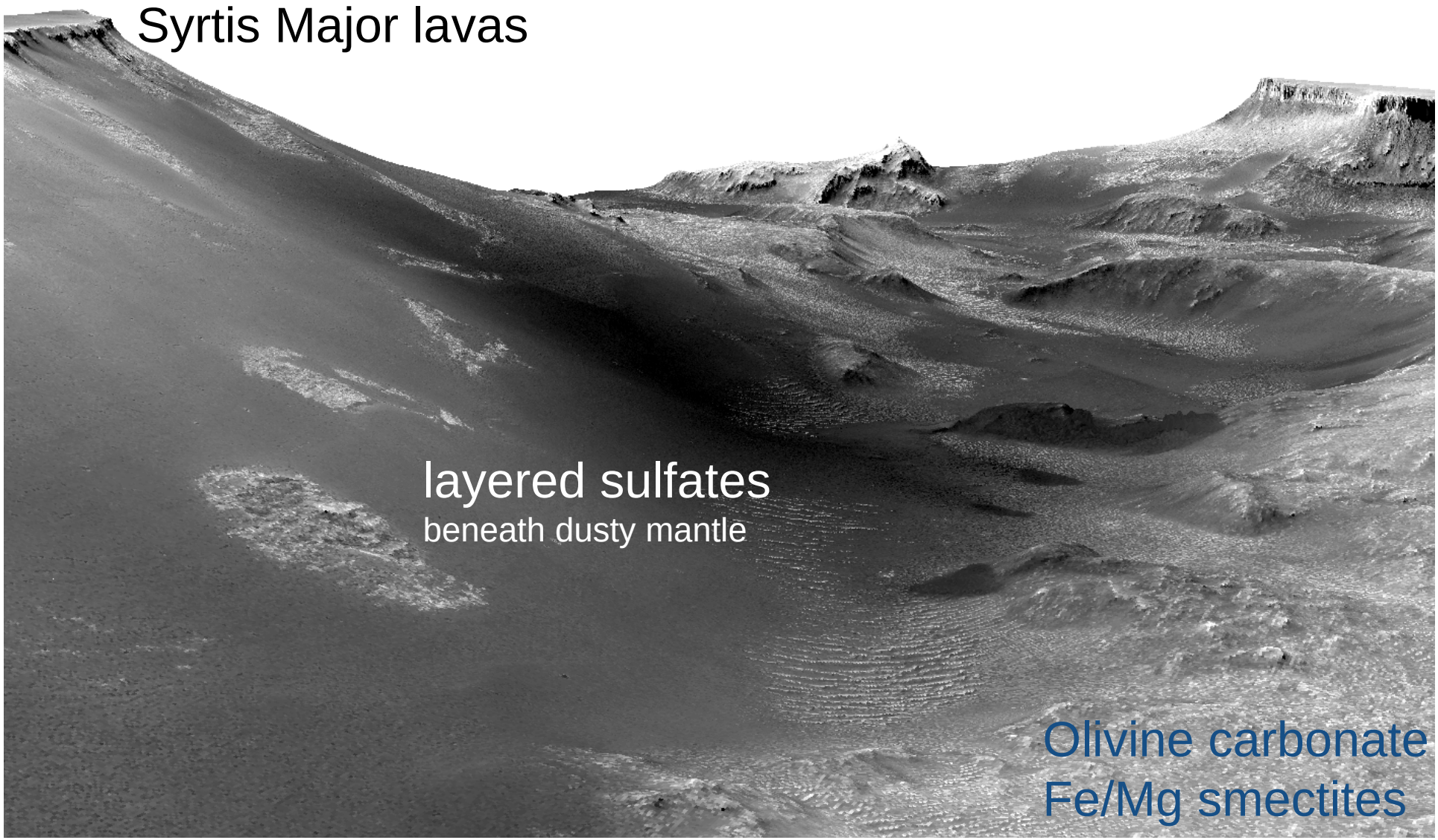

A
B
C
D
a
a'
1
2
3
4
5
6
7
2 km
500 m
40 m
1. jarosite
2. polyhydrated sulfate
3. Mg carbonate
4. serpentine
5. olivine
6. Mg/Fe smectite clay
7. Al clay
K
M
CRISM ratioed reflectance (offset)
lab reflectance (offset)
wavelength (micometers)
1,5
2,0
2,5

HiRISE Stereo DEMs

PSP_009217_1975 - ESP_027625_1975

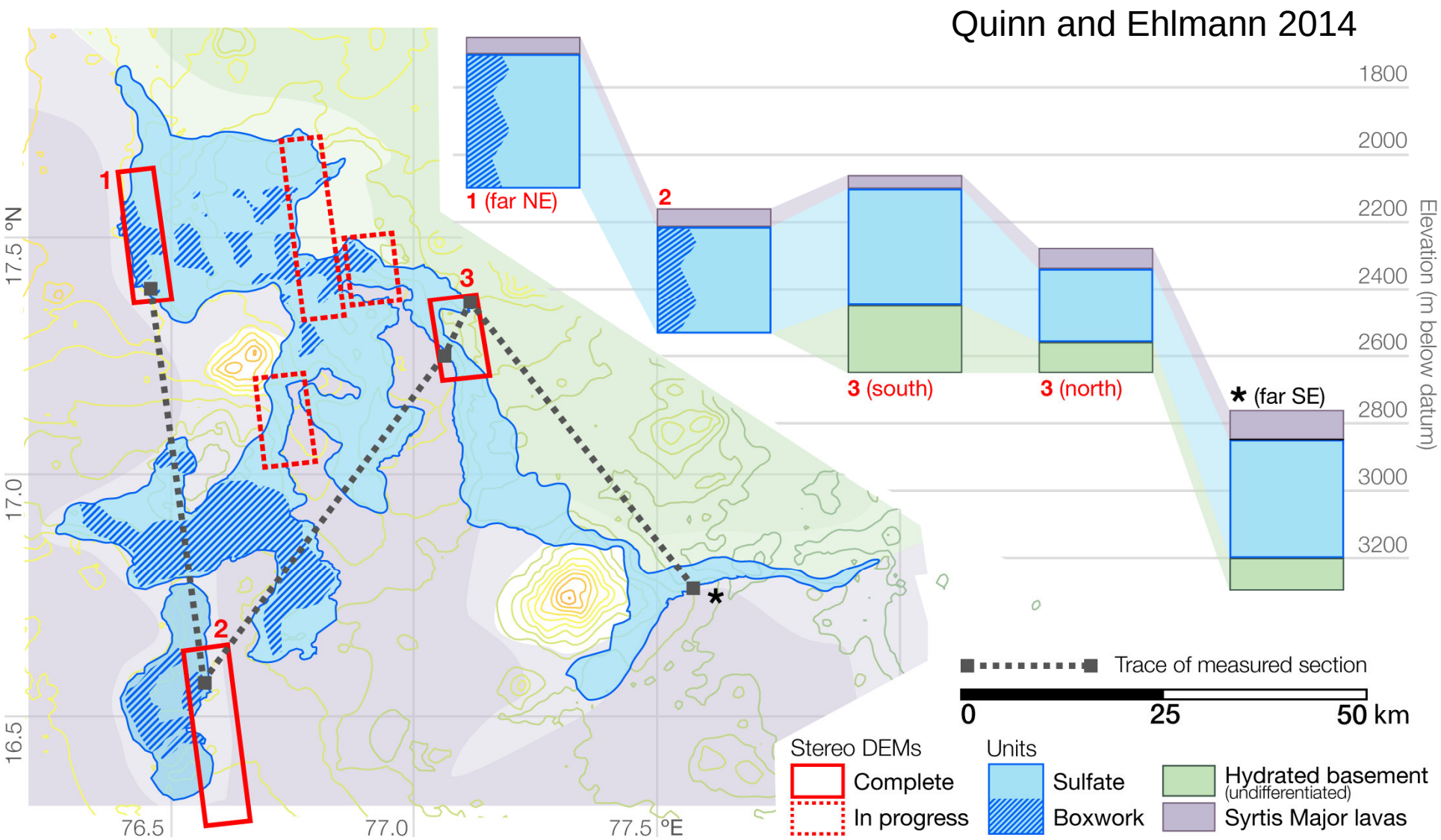
View to the northwest

2x vertical exaggeration



Correlated stratigraphic column

Elevation of layered sulfate unit decreases to the east



Possible mechanisms for layered sulfate formation

Implications for environment

Init

Av

Bedding

Equipotent

thic

VOLCANIC

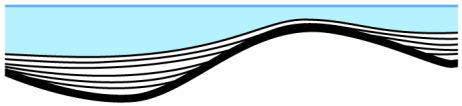
Lava flow
Effusive volcanism over large area [2,4]

Ash fall
Airborne volcanic ash from explosive eruptions [3]

Ash flow
Pyroclastic flow deposits

SEDIMENTARY

Lacustrine (deep)
Lake covering the entire region



Lacustrine (shallow)
Lakes in localized craters or valleys

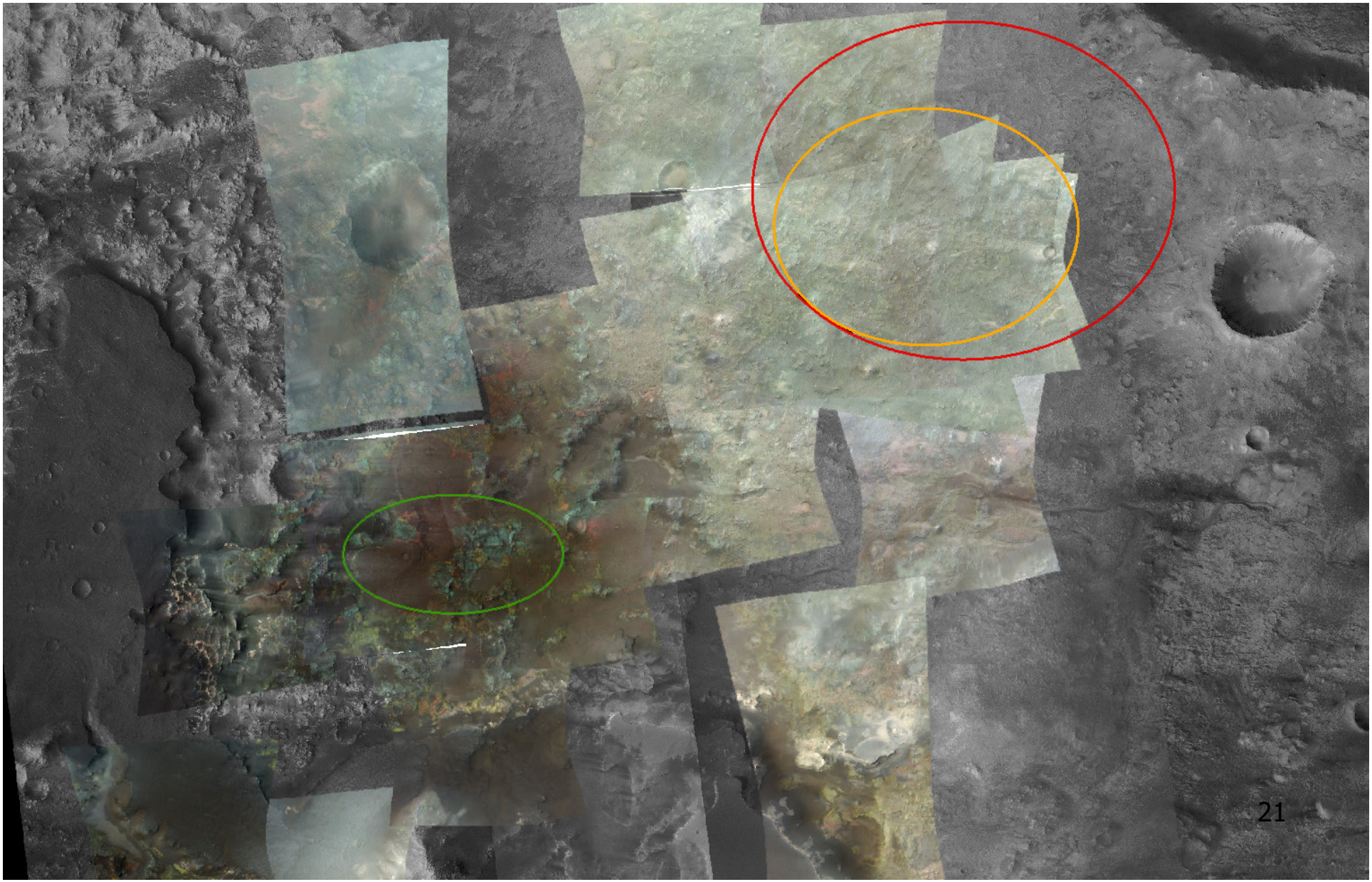
Alluvial/ fluvial
River or upstream sedimentary system

Evaporite
Playas/ephemeral lakes, deposition by drying [10]

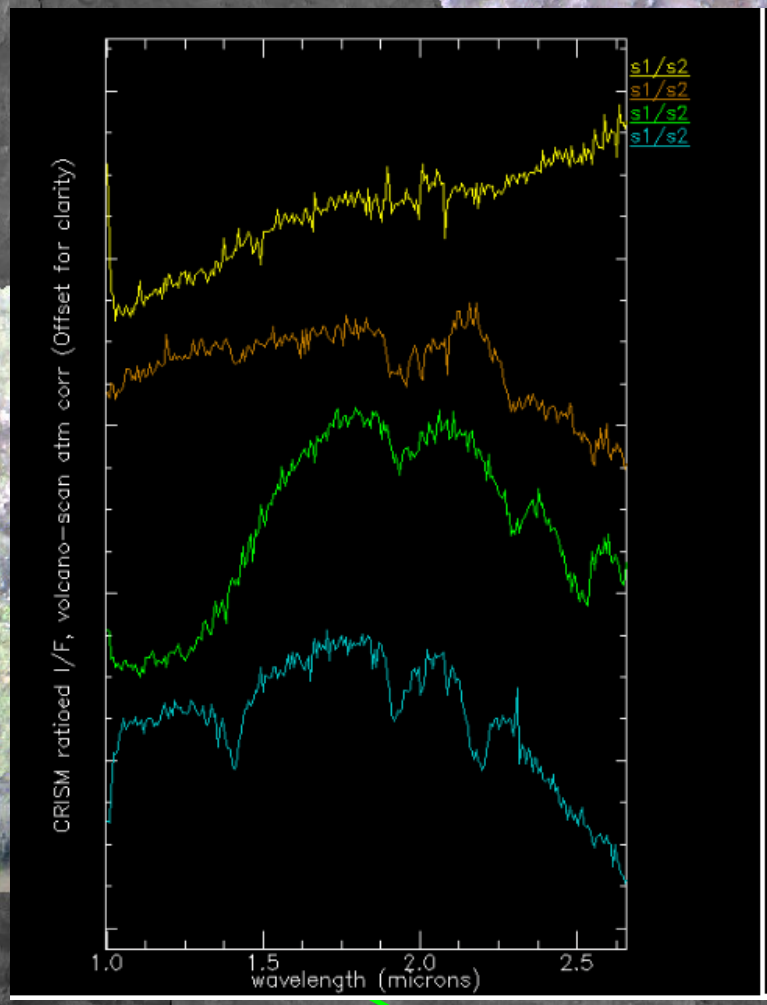
Aeolian
Wind-blown dust and sand

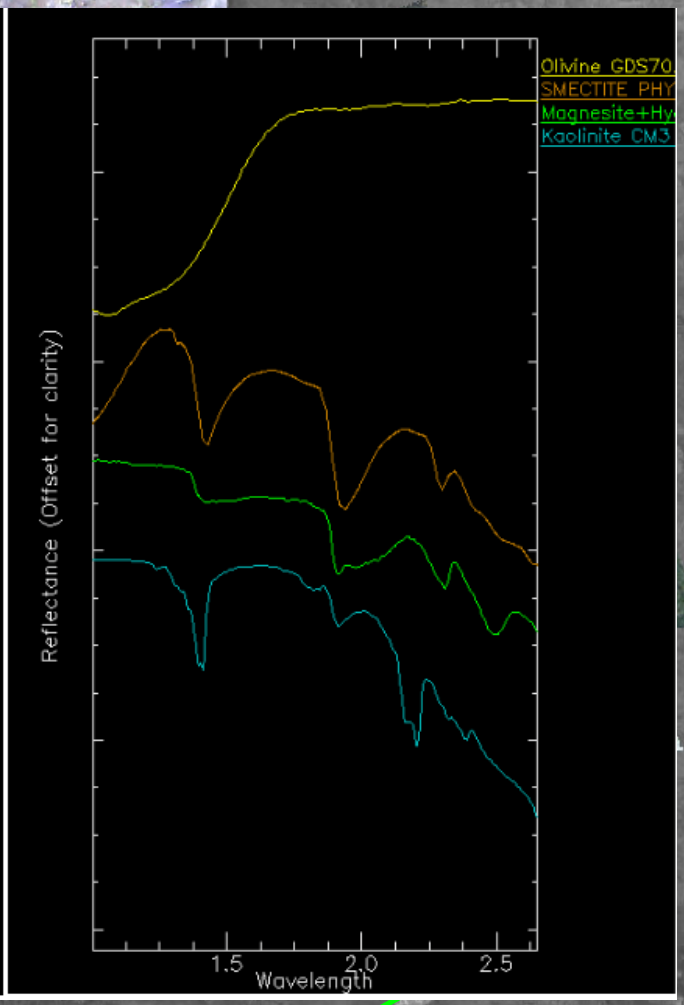
Glacial/ snowfall
Dust residue from precipitation and sublimation [5]

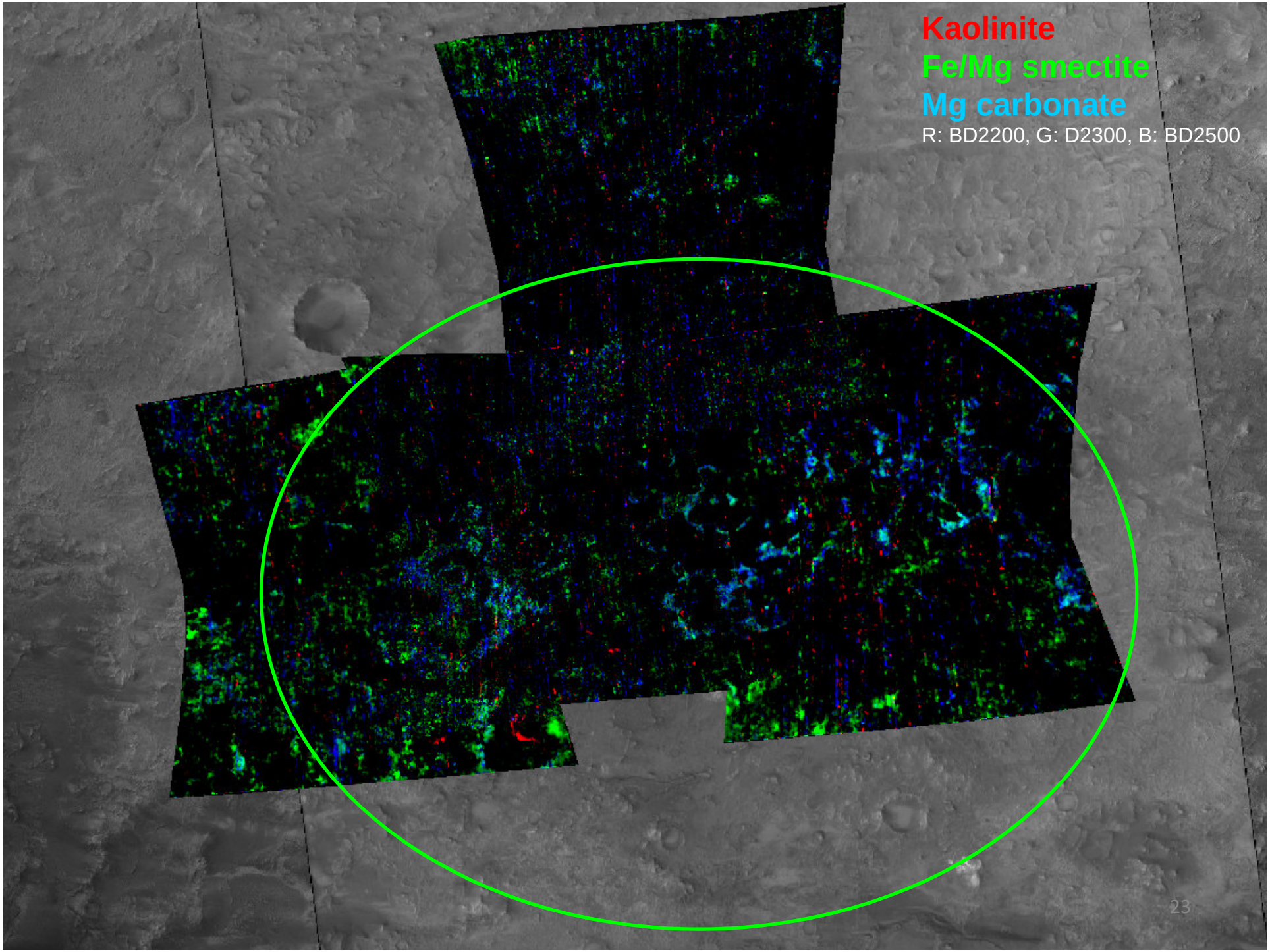
Quinn and Ehlmann 2014

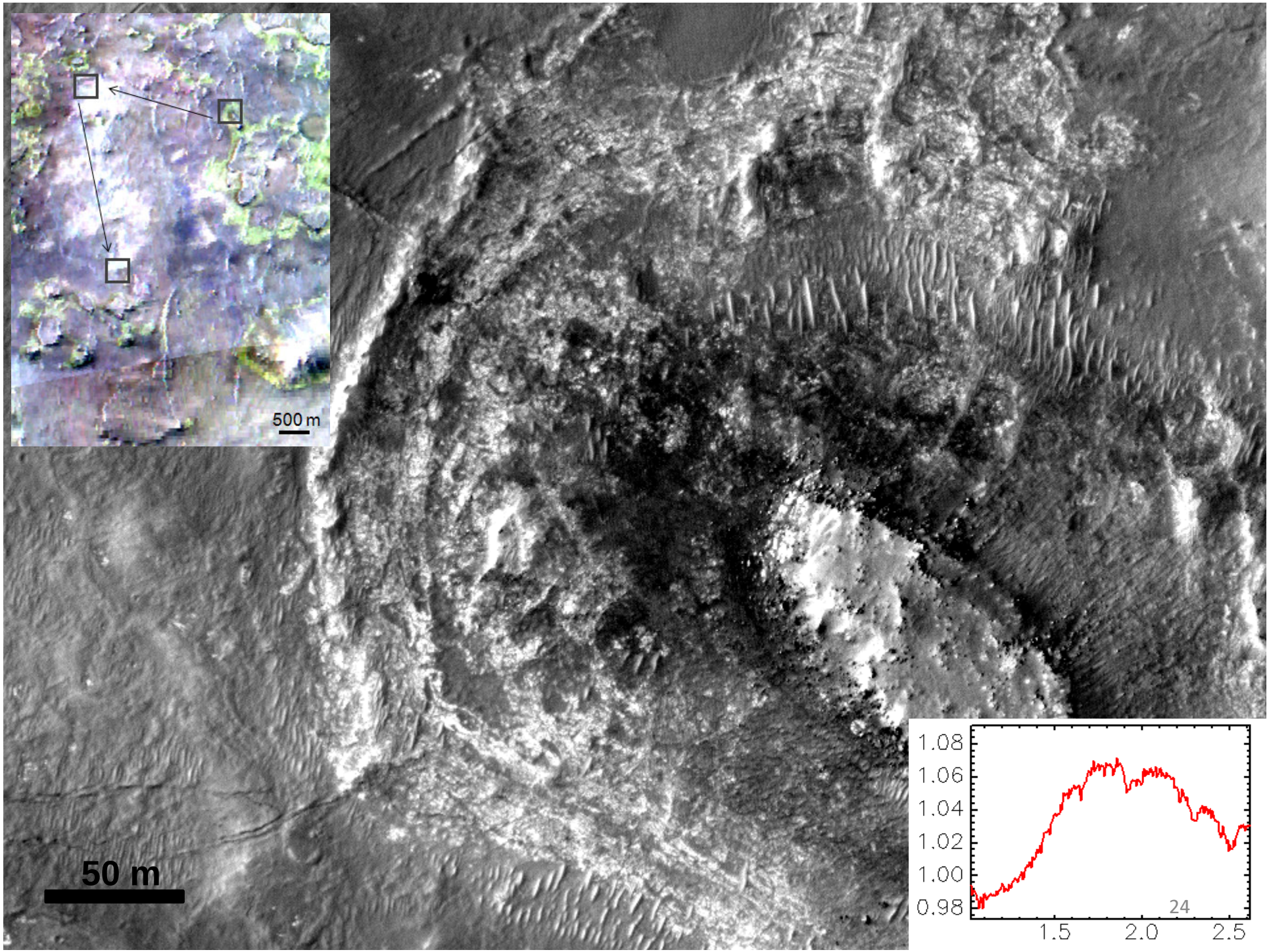


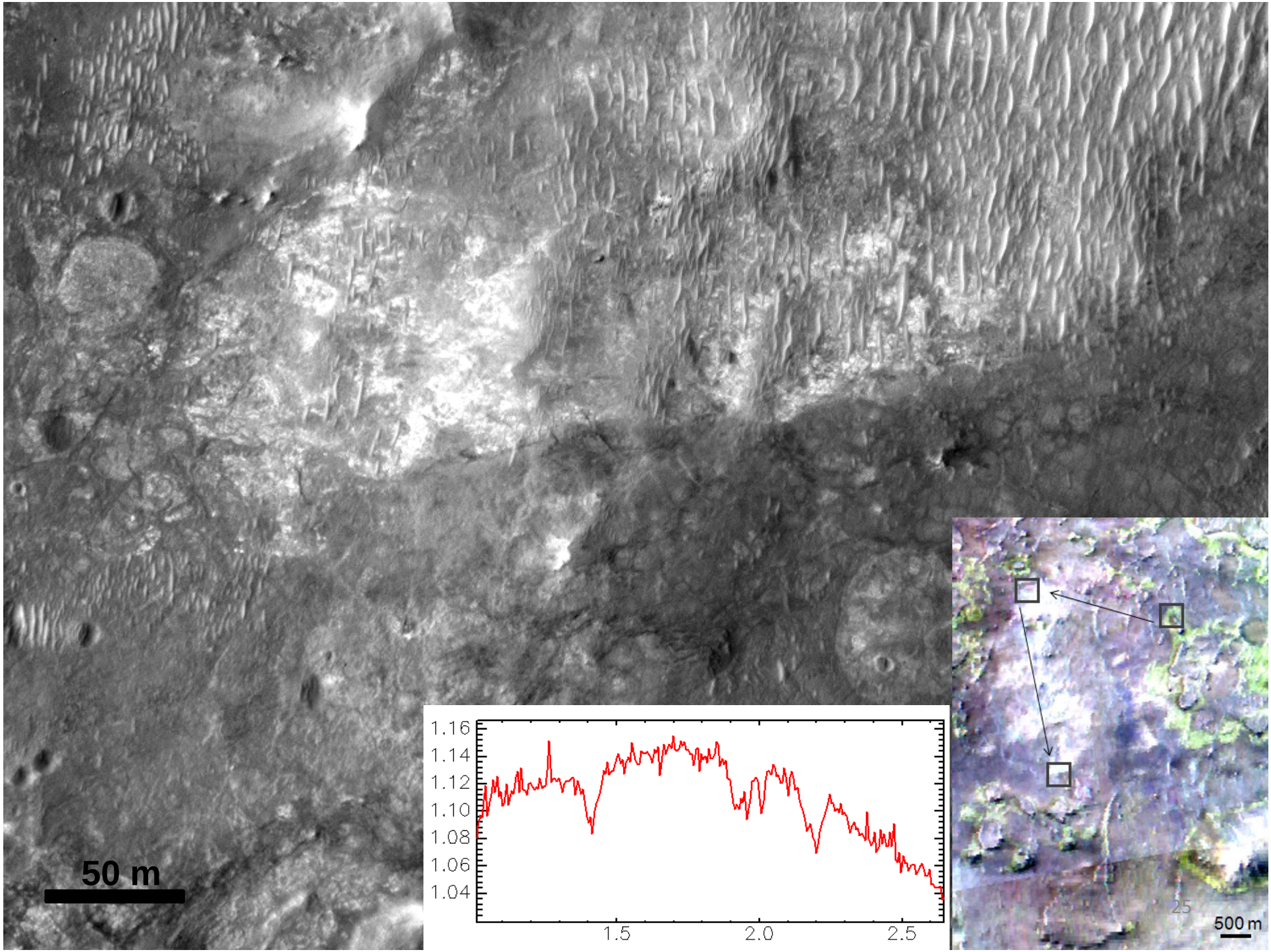
In Ellipse Science and Notional Traverses

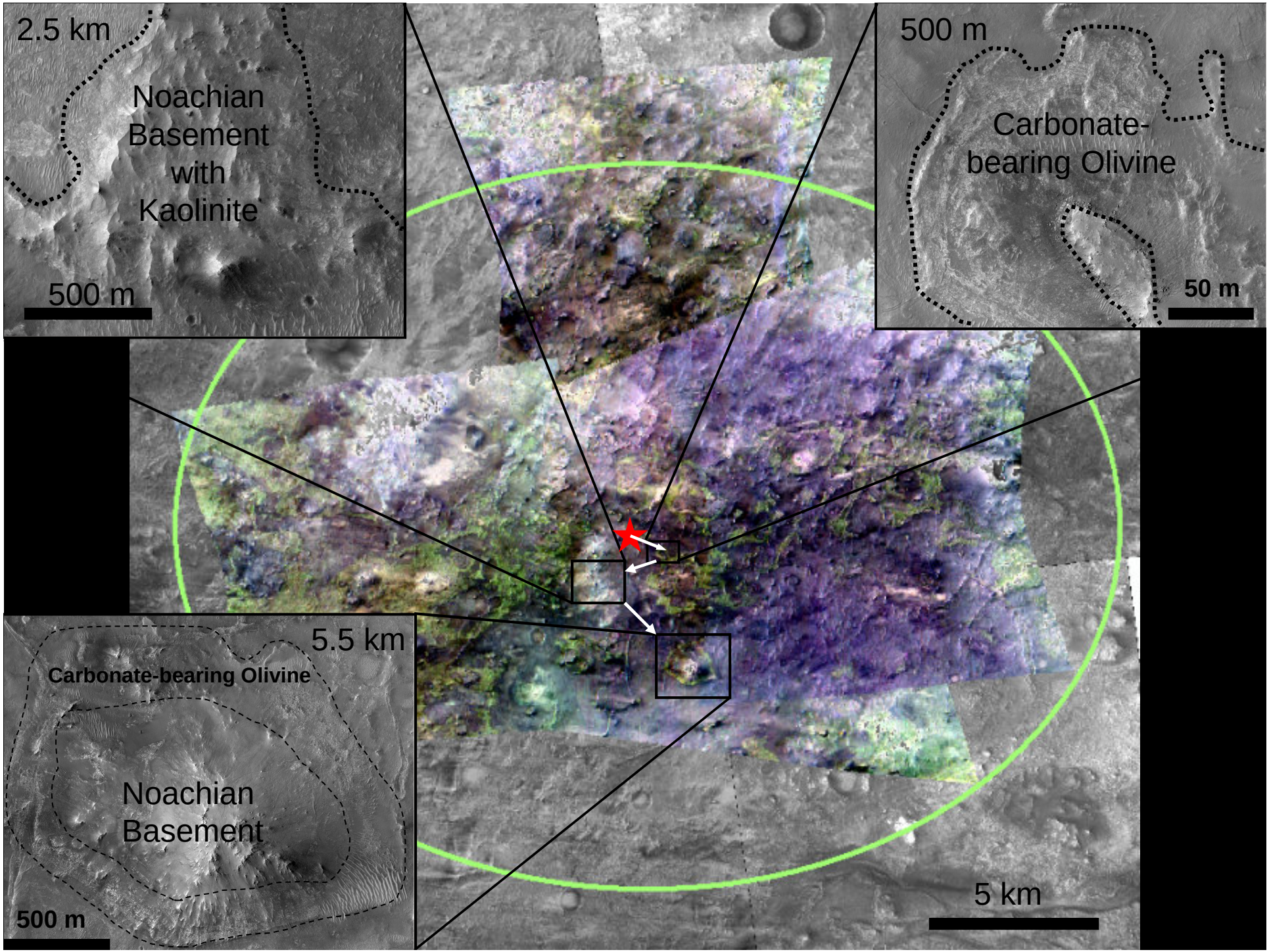


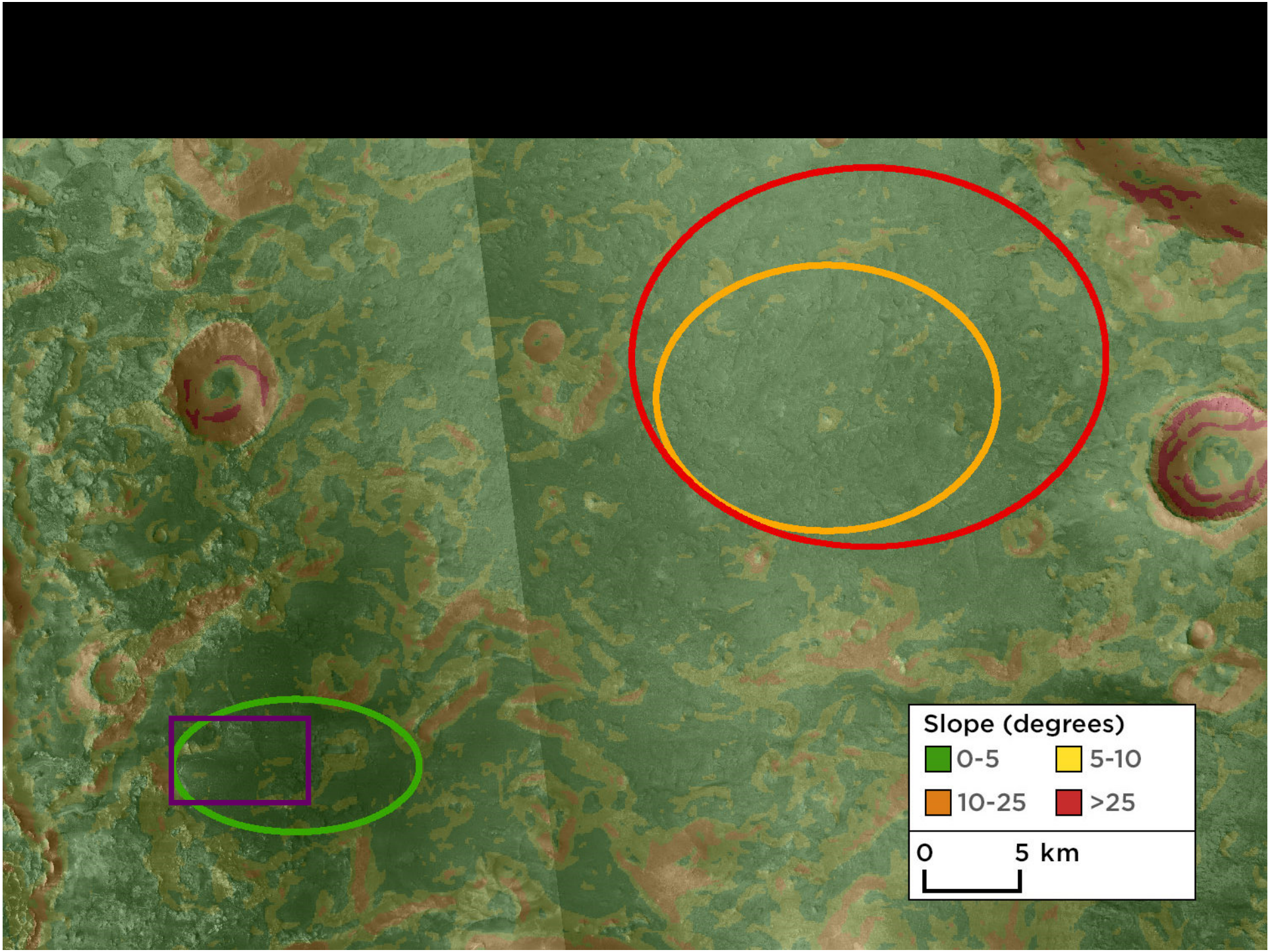


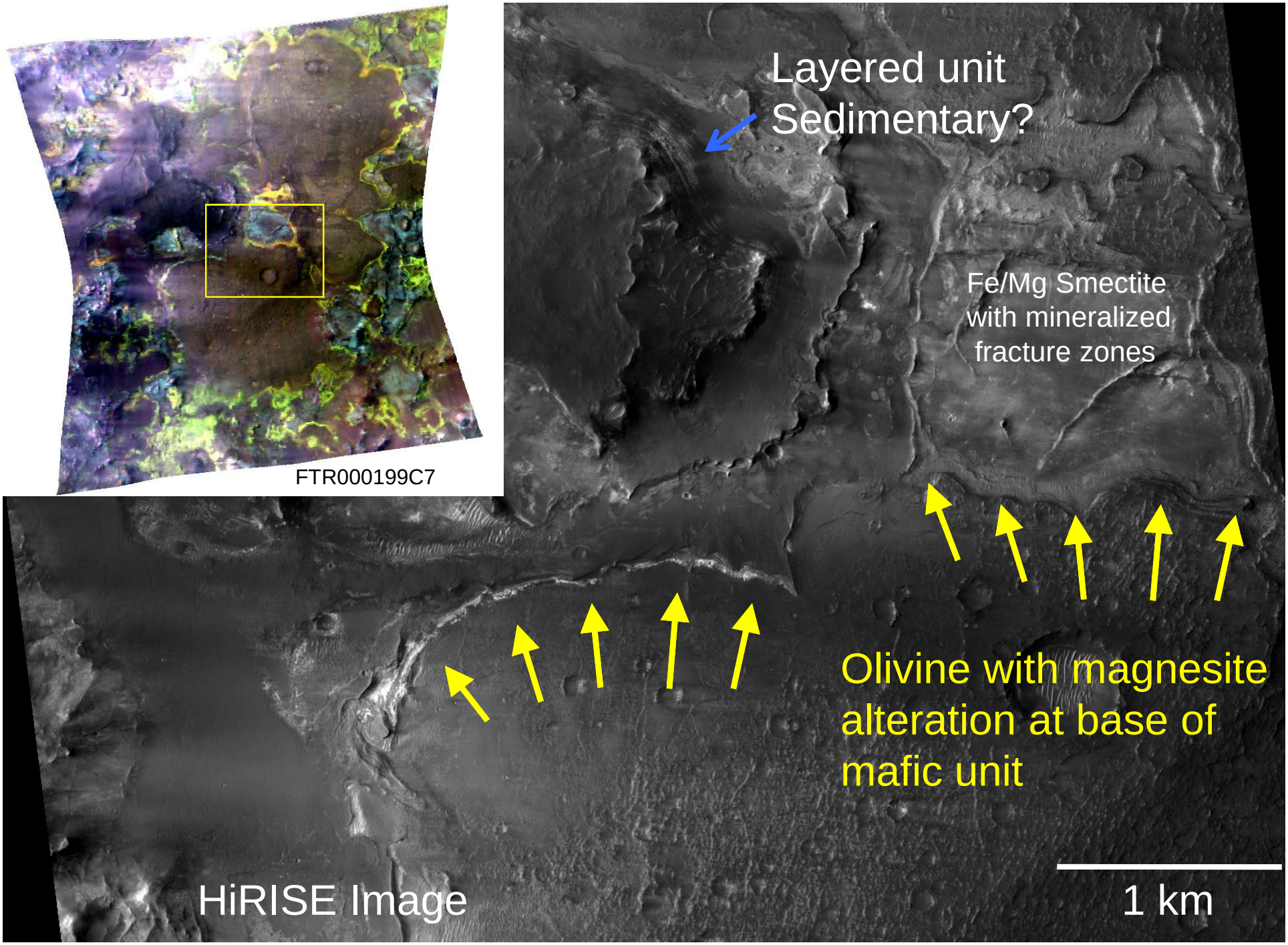

Kaolinite
Fe/Mg smectite
Mg carbonate
R: BD2200, G: D2300, B: BD2500


500 m
50 m
1.08
1.06
1.04
1.02
1.00
0.98
1.5
2.0
2.5
24


50 m
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.5
2.0
2.5
500 m


2.5 km
Noachian
Basement
with
Kaolinite
500 m
500 m
Carbonate-
bearing Olivine
50 m
5.5 km
Carbonate-bearing Olivine
Noachian
Basement
500 m
5 km


Slope (degrees)
0-5
5-10
10-25
>25
0
5 km


FTR000199C7
Layered unit
Sedimentary?
Fe/Mg Smectite
with mineralized
fracture zones
Olivine with magnesite
alteration at base of
mafic unit
HiRISE Image
1 km

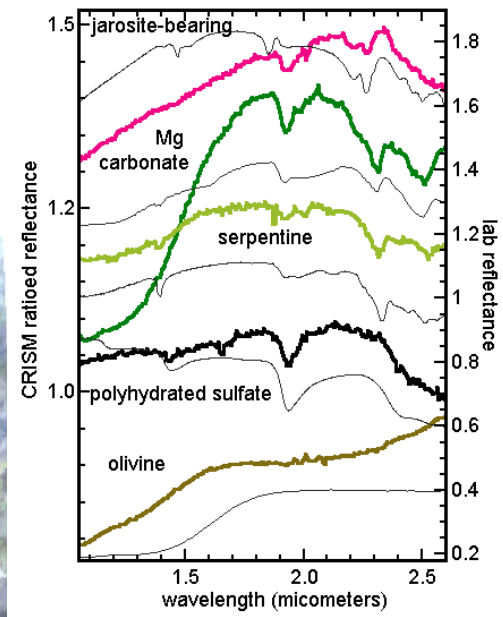
NE Syrtis Acid-Alkaline Transition

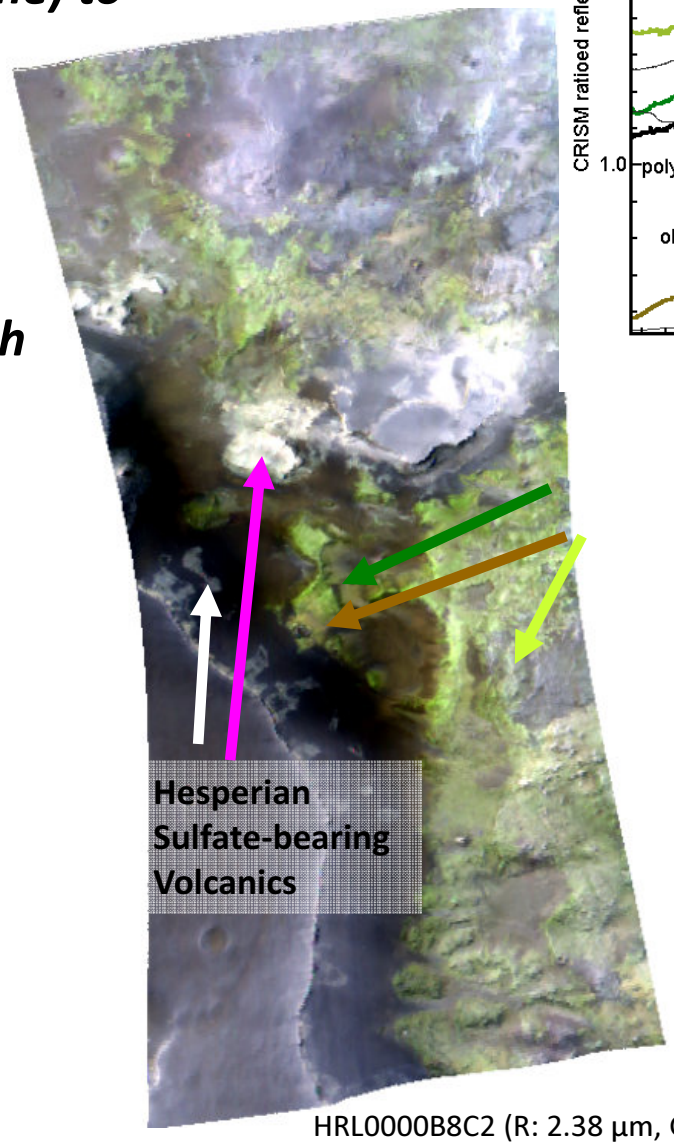
Cross the Noachian-Hesperian boundary and the transition from phyllosilicate/carbonate (alkaline) to sulfate (acidic)

Emplacement of lava into a volatile-rich environment and onto the olivine-bearing units and Fe/Mg phyllo-silicate-bearing basement with serpentine formation

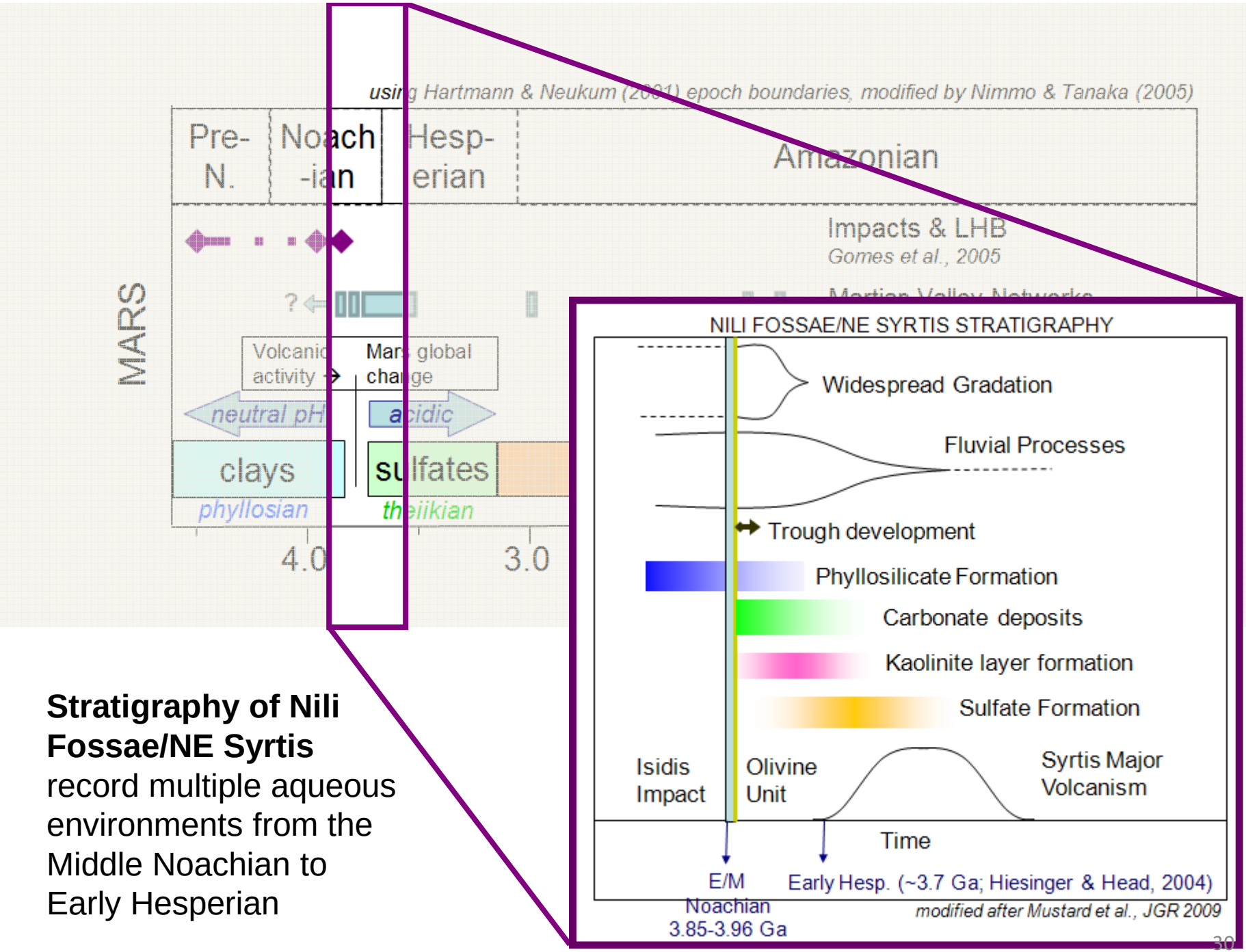
Sulfate deposits include jarosite and polyhydrated sulfate, largely with volcanic units

Evidence for circulation of fluids by heat of lava source





HRL0000B8C2 (R: 2.38 µm, G: 1.80 µm, B: 1.15 µm)



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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 MSL instrument suite
- Key stratigraphies, dateable (?) from Noachian to Hesperian eras: does this capture Mars global environmental change?

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

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

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Erosionally resistant ridges	• Fracture zones mineralized with hydrothermal sediments
Hesperian-aged Sulfate stratigraphy	• Four hypotheses by devan
Hesperian Syrtis Major volcanics	• Calibration of crater chronology, testing the formation mechanism (chemistry and mineralogy), validating remote sensing