Mars Analogs: Water, Rocks, and Life in Iceland, Oman, and Hawaii: lessons for Mars from terrestrial alteration of mafic and ultramafic rocks

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(from Sept. 2011 @ Caltech; ehlmann@caltech.edu)

June 30, 2011


A


8/1/2002

What is a Mars analogue?

There is no perfect analogue of Mars on Earth

(1) **Need good assessment of the relevance of a site for the hypotheses/questions under investigation with rigorous attention to its Earth-based limitations**

- Earth: abundant water, high biomass, tectonics etc
- limitations will have different impact depending on the question under study
- Its cold and relatively dry ≠ Mars..
- phyllosilicates ≠ Mars
- Acid sulfate ≠ Mars

(2) **Scientific investigations at analogue sites should be designed to understand specific <u>processes</u> and <u>features</u> or their evidence as detectable by planetary exploration missions.**

Role of Terrestrial Analog Studies

- Understand geomorphic, geochemical, and biological processes relevant to Mars environments
- Evaluate instrumentation (or payloads) and their synergies in ways not possible in laboratory settings
- Train and condition scientists and engineers on what is possible for remote robotic operations (instrument measurement capabilities, mobility, time, bits, power)


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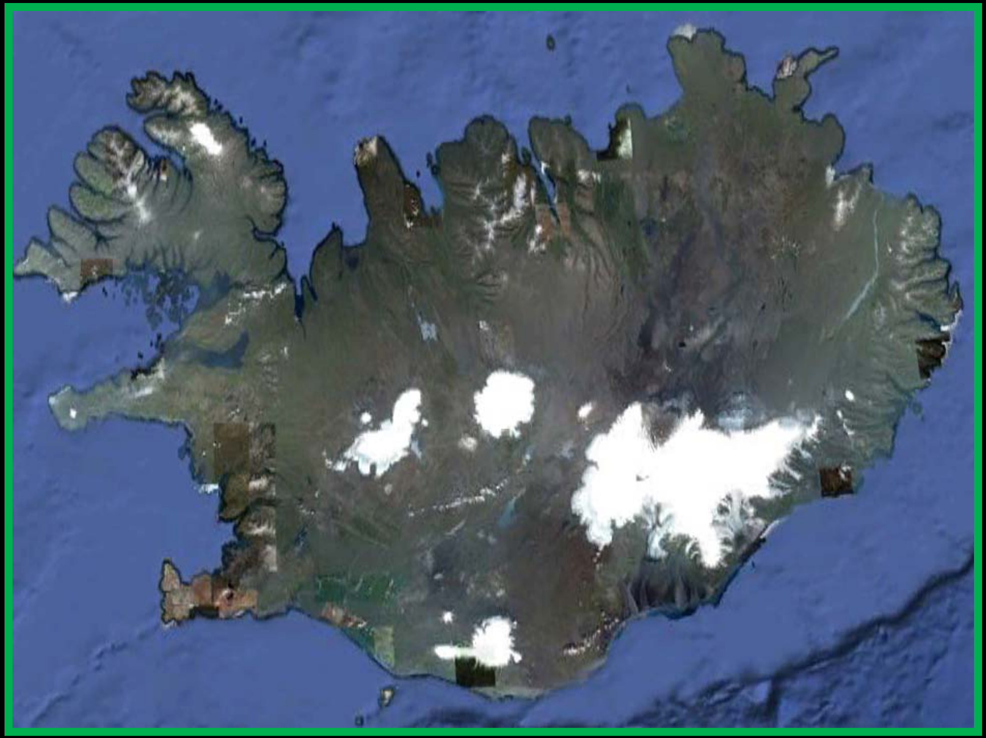
8/1/2002

Outline

I. Aqueous Alteration of Basaltic Lavas in Iceland: An Analogue for Noachian Mars
II. Terrestrial Serpentinizing Systems as Mineralogical, Geochemical (and Biological?) Analogues for Mars: Oman
III. Sulfurous Volcanic Gases and their Role in Basalt Weathering at Kilauea, Hawaii

I. Alteration of Basalt in Iceland: linking orbital and landed datasets

Iceland as a Mars Analog



- Basaltic island constructed by shield volcano eruptions
- Aqueous alteration by precipitation and groundwaters
- Volcanic vapors and gases affect atmosphere and fluids
- Recent lava flows have little vegetation that would inhibit studies


VÍKING
Mars

Hydrated/altered mineral phases on Mars, found from orbit

white = new since 2006

Phyllosilicates
- Fe/Mg smectite
- Montmorillonite
- Kaolinite
- Chlorite
- Serpentine
- Al, K mica (muscovite or illite)

Other hydrated silicates
- Prehnite
- Zeolite (analcime)
- Opaline silica
- Hydrated basaltic glass

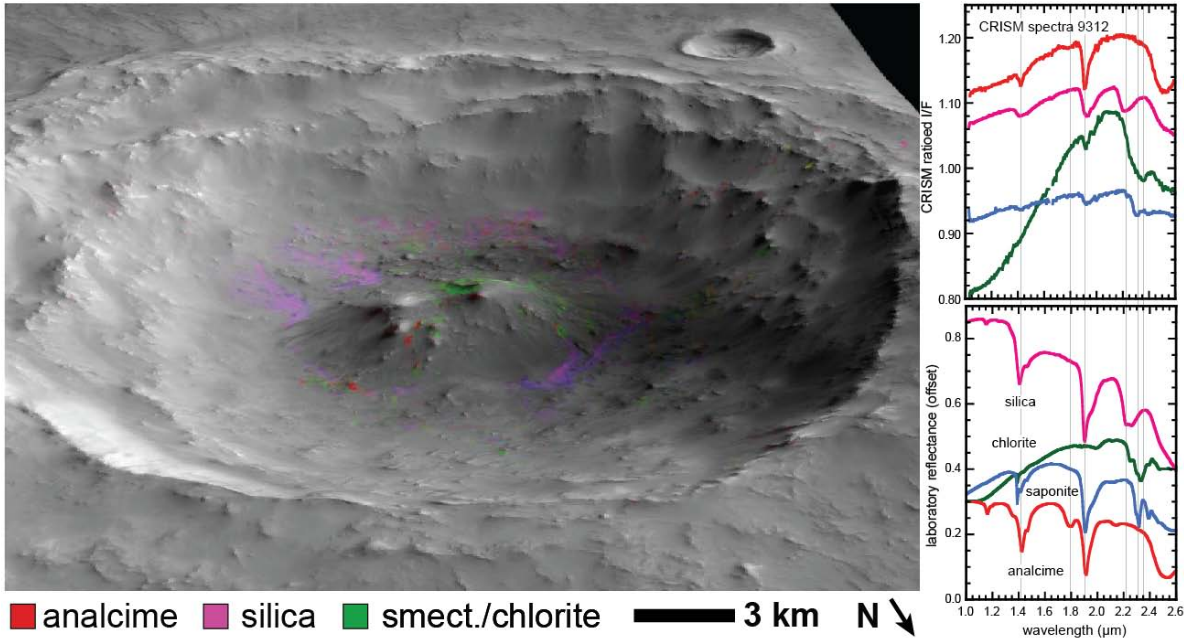
Carbonates
- Mg carbonate

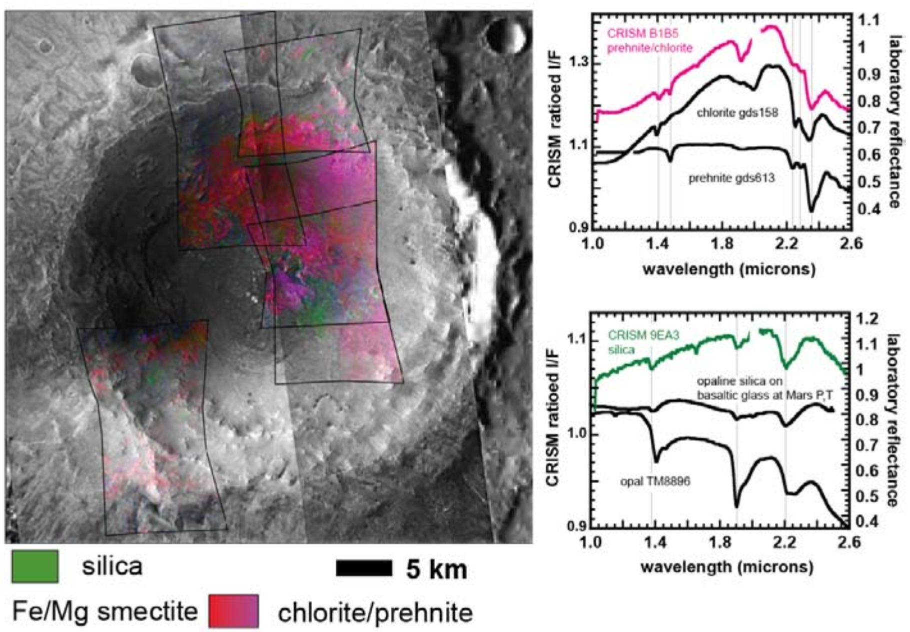
Sulfates
- Fe, Mg mono- and poly- hydrated sulfates
- Gypsum
- Jarosite
- Alunite
- $FeSO_4(OH)$

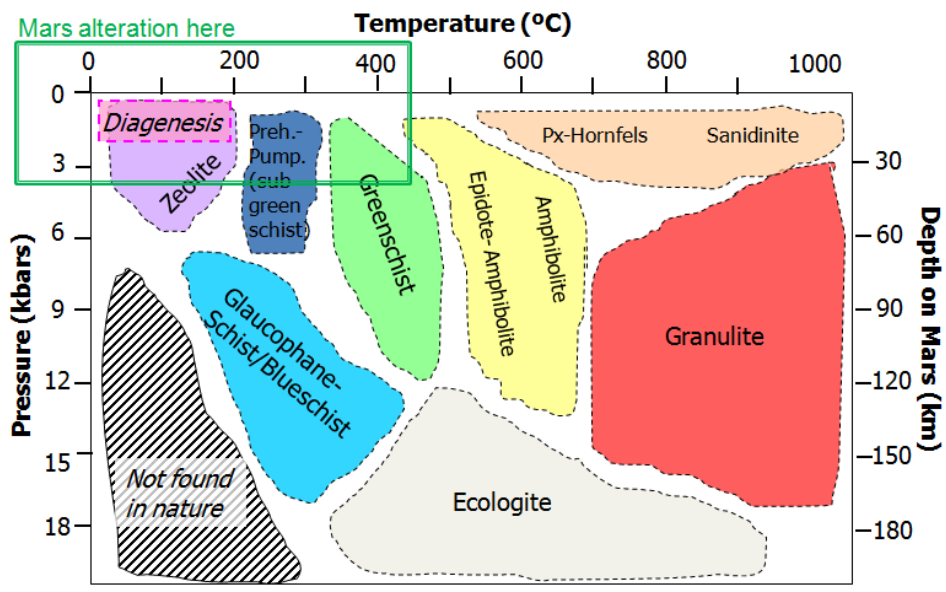
Fe oxides
- Hematite
- Goethite

[Mustard et al., *Nature*, 2008; Bishop et al., *Science*, 2008; Milliken et al., *Geology* 2008; Ehlmann et al., *Science,* 2008; Ehlmann et al., *J. Geophys R.,* 2009; Murchie et al., *J. Geophys. Res*., 2009;. Swayze et al., in prep.]

Mars Mineral Assemblages: Low-grade hydrothermal

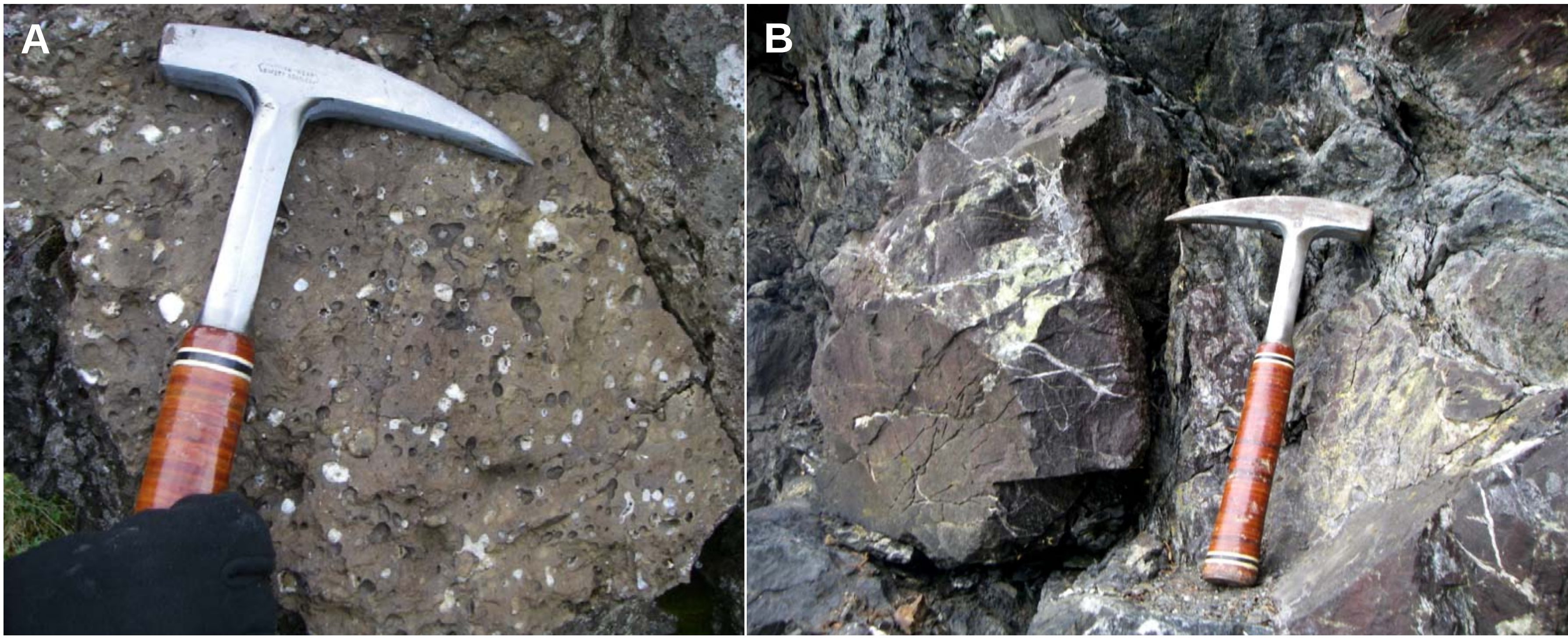






Ehlmann et al., 2009, *JGR*

Are we seeing hydrothermally altered basalts on Mars?
What would they look like?



zeolitized basalts, Iceland

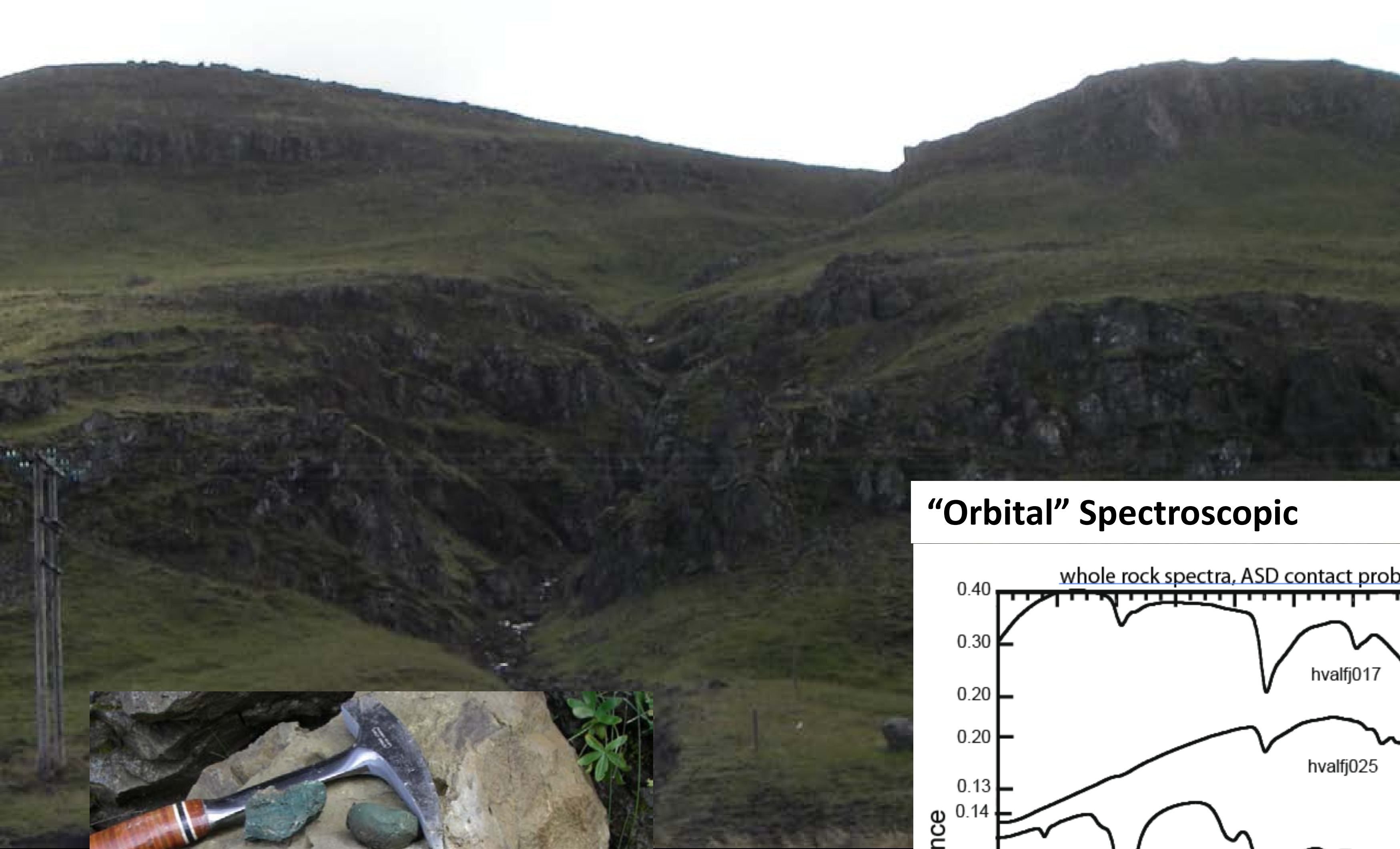
prehnite-pumpellyite facies basalts, New Foundland

Key motivating questions

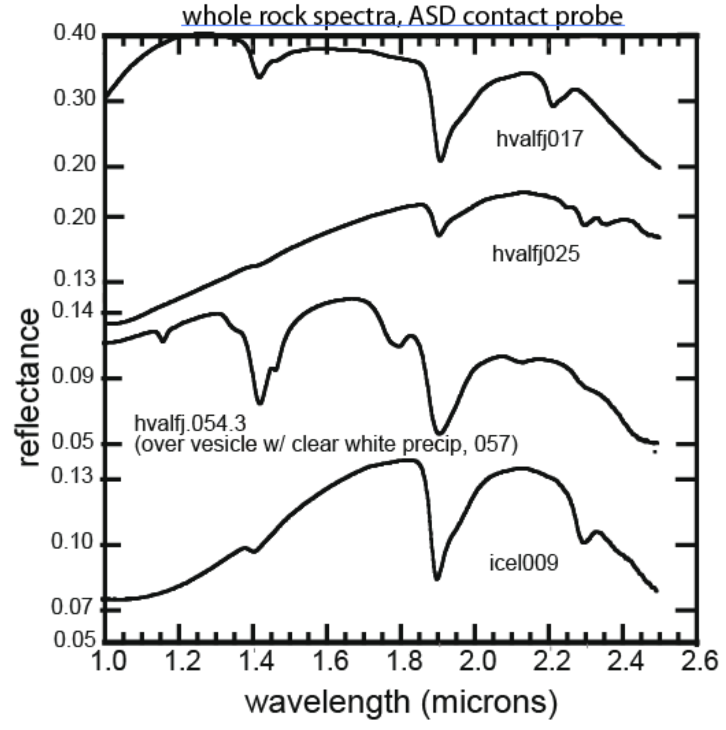
- What is the nature of alteration in non-volcanic, basaltic hydrothermal systems?
  - Need to measure minerals present and abundances
  - Variation in spectra/mineralogy: what environmental factors control?

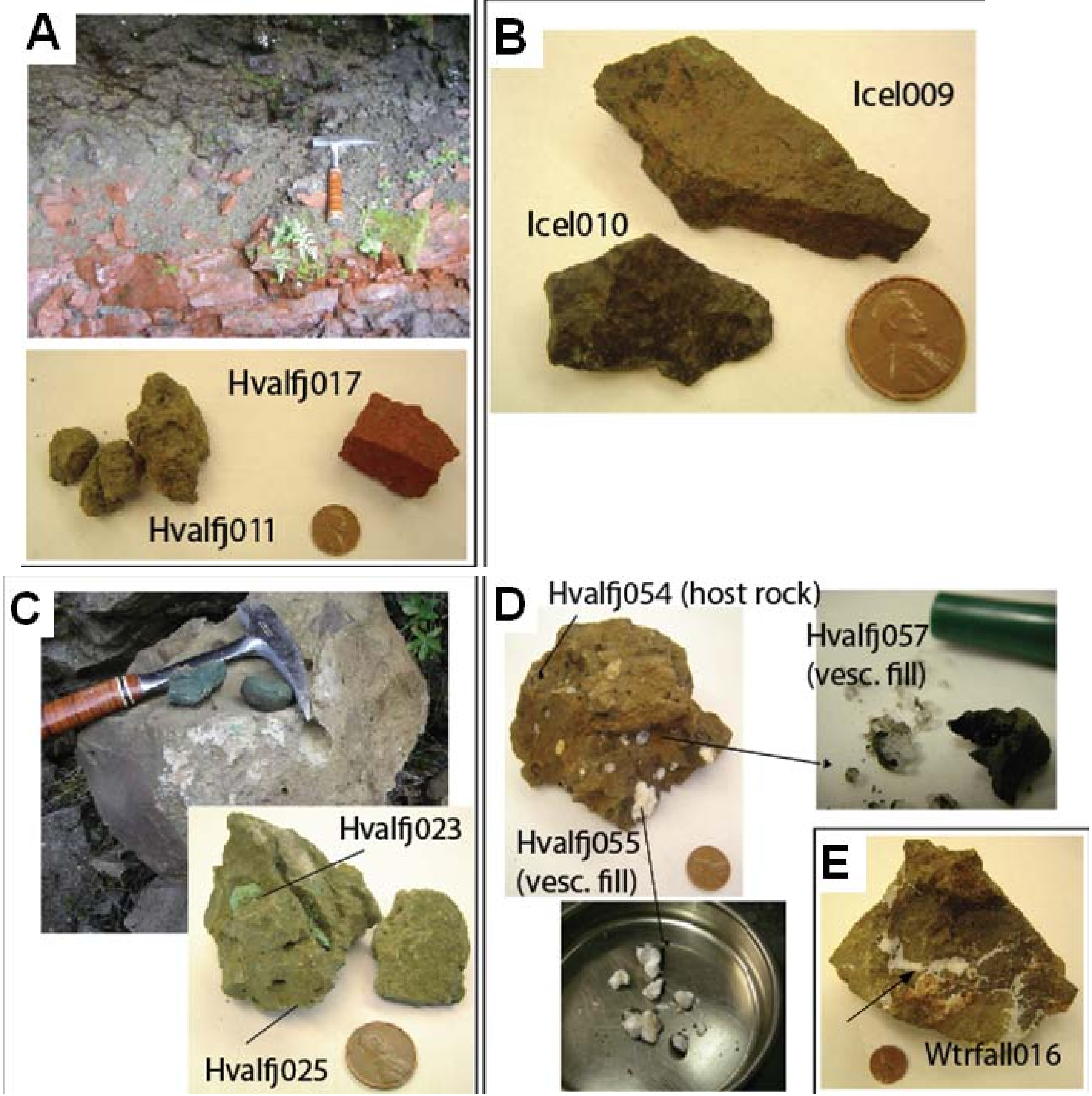
- Could evidence for these systems be found from orbit?
  - Which phases are apparent in the VNIR? Which are not?
  - Is there evidence of alteration in the TIR?
  - How much alteration needs to occur before it is VNIR/TIR-detectable? Variation by mineral assemblage? Spatial scale?
- Are VNIR/TIR data from Iceland and the mineral assemblages they represent consistent with spectra from Mars?
- How well does data from VNIR analysis corroborate XRD results? (ChemMin/CRISM comparison)


0 50 100 km
Berufjordur
Hvalfjordur



“Orbital” Spectroscopic




A
Hvalfj017
Hvalfj011
B
Icel009
Icel010
C
Hvalfj023
Hvalfj025
D
Hvalfj054 (host rock)
Hvalfj057
(vesc. fill)
Hvalfj055
(vesc. fill)
E
Wtrfall016

Methods

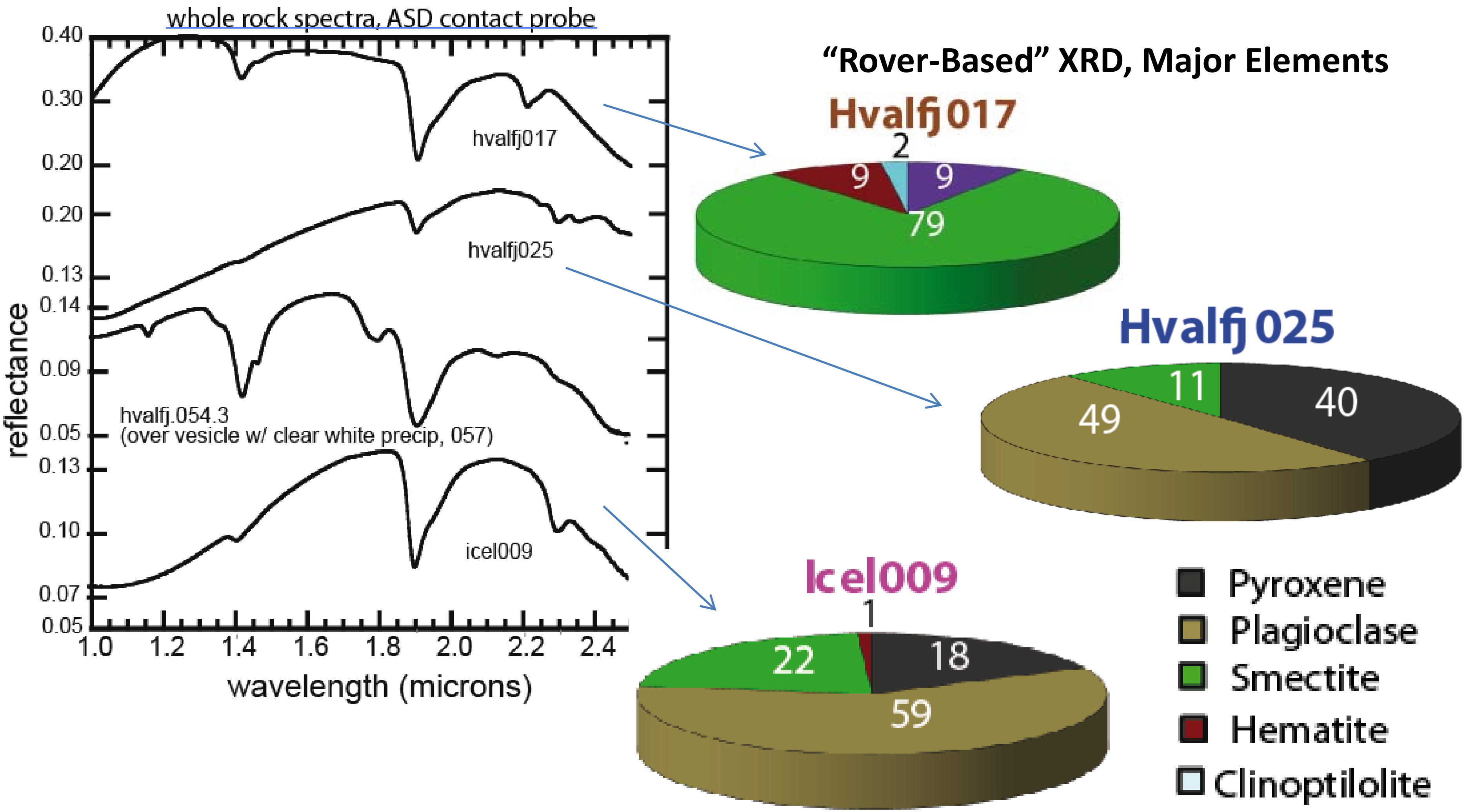
- VNIR spectroscopy
  - whole rock, bulk rock, and fracture/vesicle fill
- TIR spectroscopy

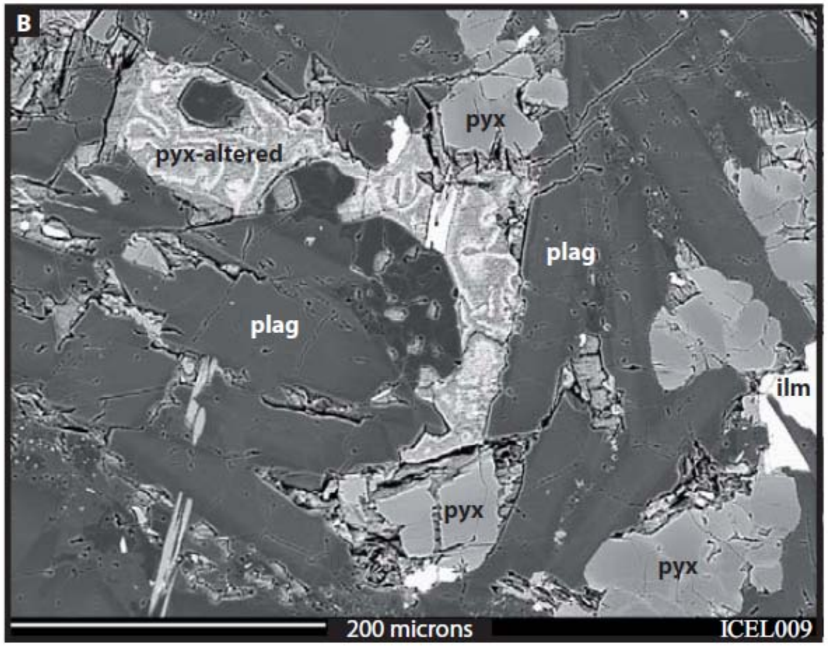
Mars orbit:
OMEGA,
CRISM,
TES

- XRD
- Elemental analysis
  - flux fusion

Mars rover:
ChemMin
XRD/XRF on
MSL (2011)

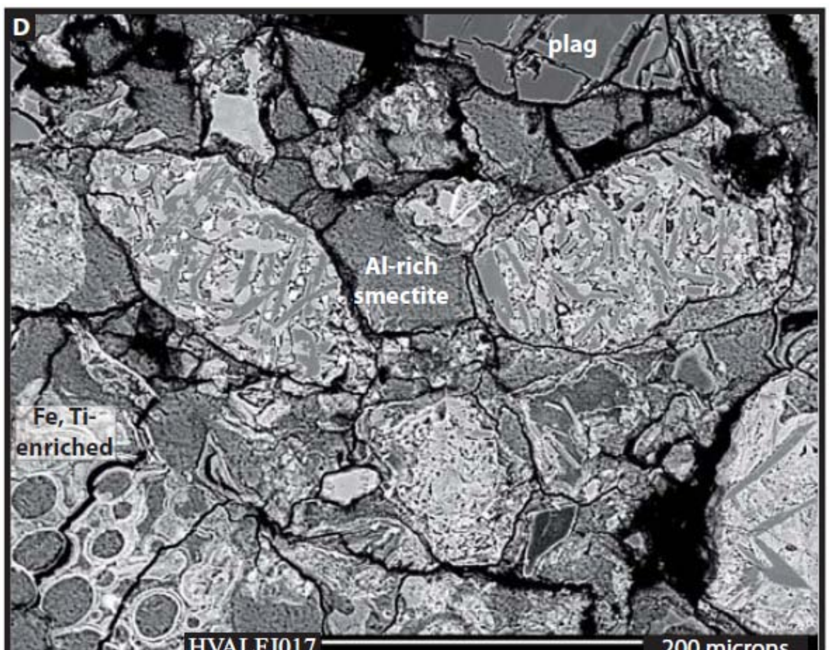
Groundtruthing Spectral Identifications

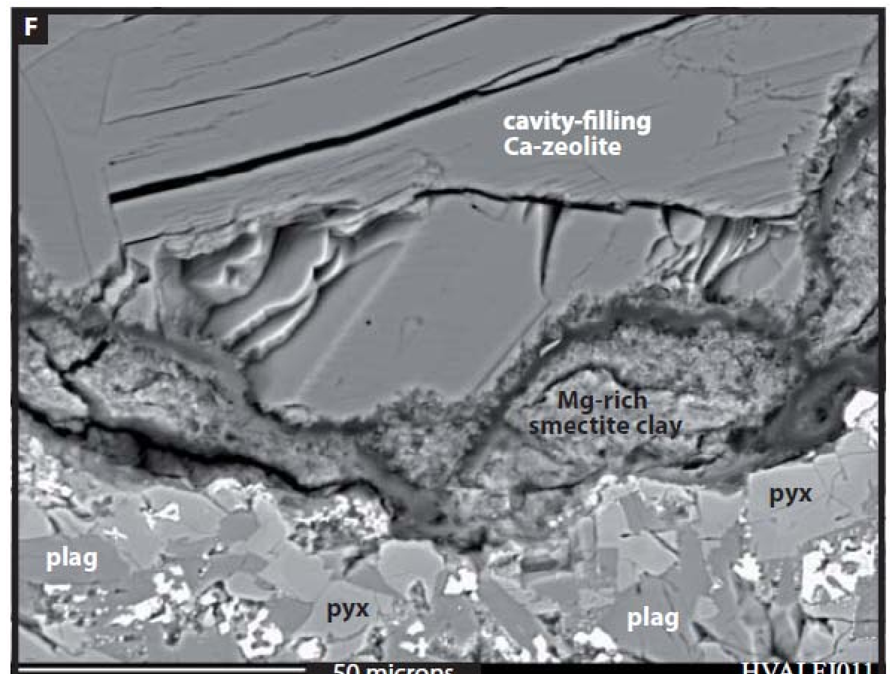




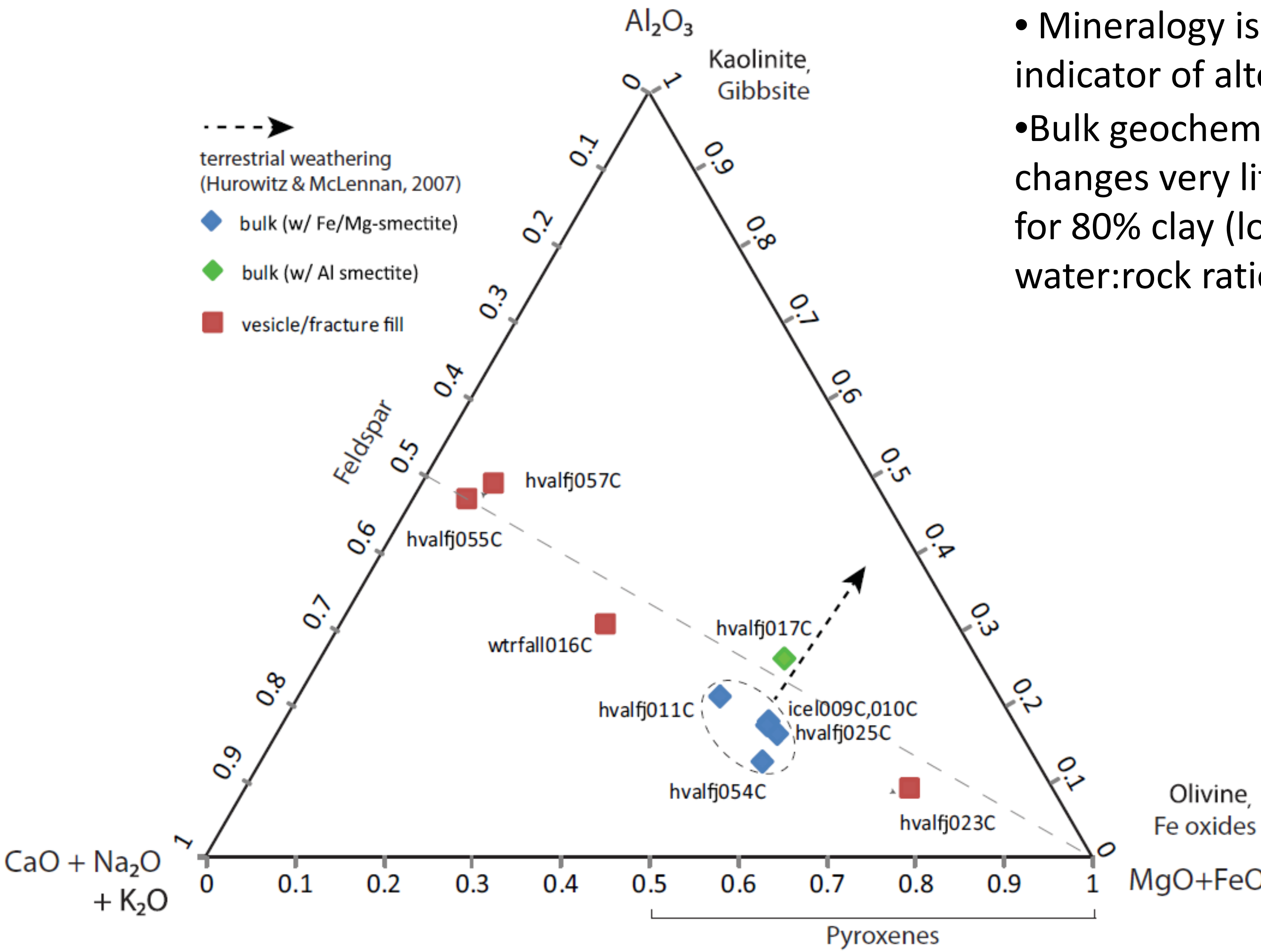
Nature of Alteration

- Not coatings
- Bulk rock is altered to clay (20%-80%)
- Zeolites, silica occupy the vesicles
- Both phases seen in bulk rock





Nature of Alteration



- Mineralogy is the key indicator of alteration
- Bulk geochemistry changes very little, even for 80% clay (low water:rock ratio)

Implications for Biology/Habitability?

- Points to the fact that subsurface groundwater-driven alteration may have been important in forming similar assemblages in Mars clays
- Low W:R zeolitization of basalt: not well-studied. Need for future work
- Higher W:R Icelandic springs are rich abodes for microbial life

Korarchaeota , 70–97 °C with pH 2.5–6.5, *Reigstad et al., ISME, 2009*

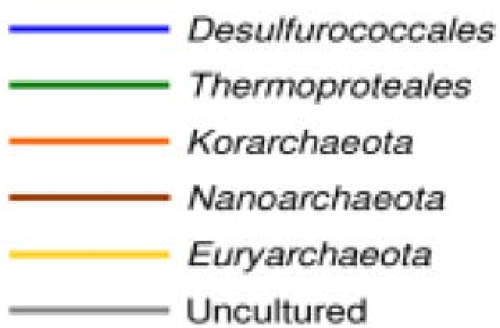
Hvergaadi

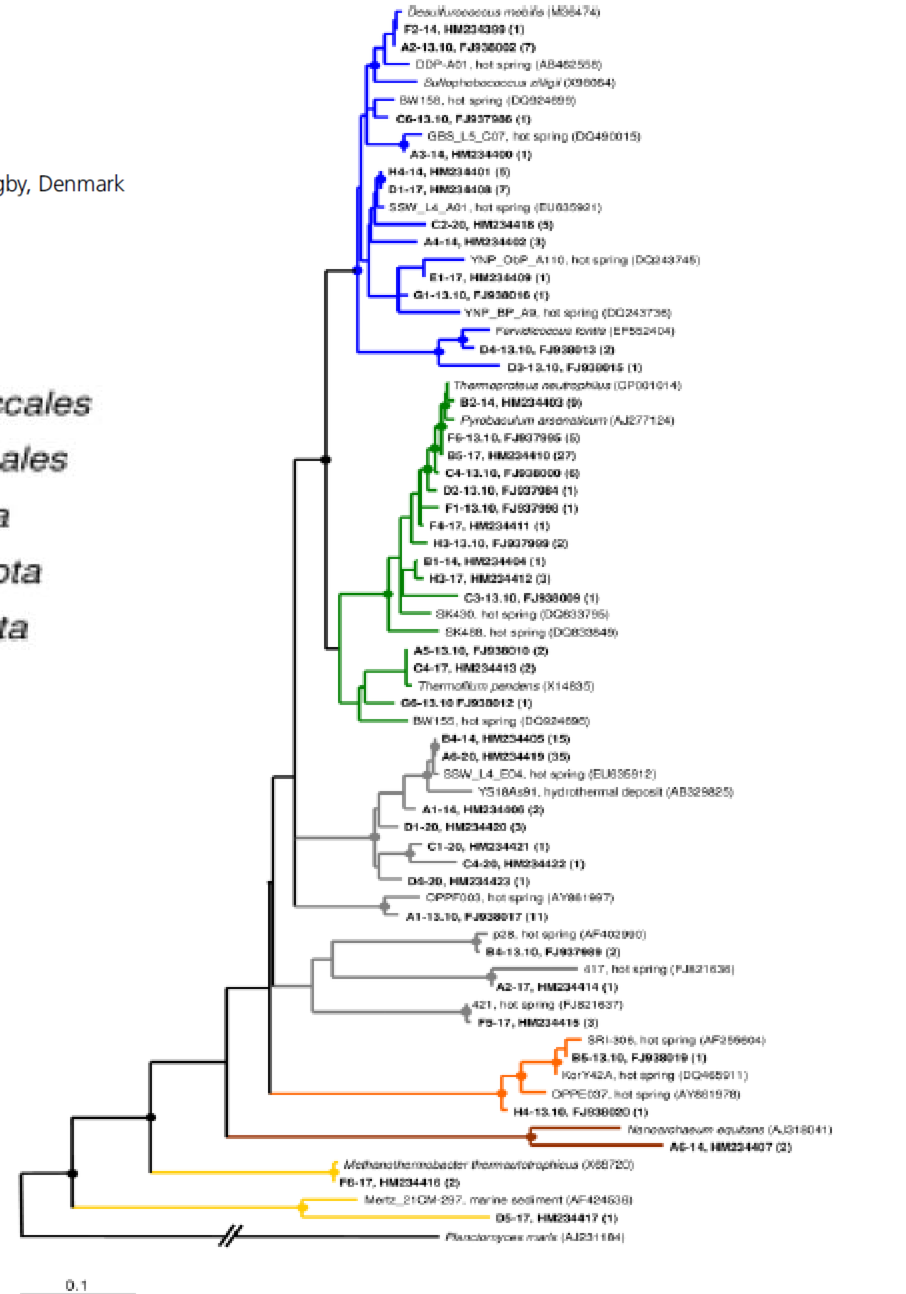
FEMS Microbiol Ecol **59** (2007) 71–80

Archaeal diversity in Icelandic hot springs

Thomas Kvist, Birgitte K. Ahring & Peter Westermann

Bioprocess Science and Technology Group, Biocentrum-DTU Technical University of Denmark, Lyngby, Denmark





- Icelandic spring biodiversity among the highest in the world, and still being characterized

II. Weathering of Ultramafic Rocks in Oman: understanding carbonate and serpentine formation on Mars

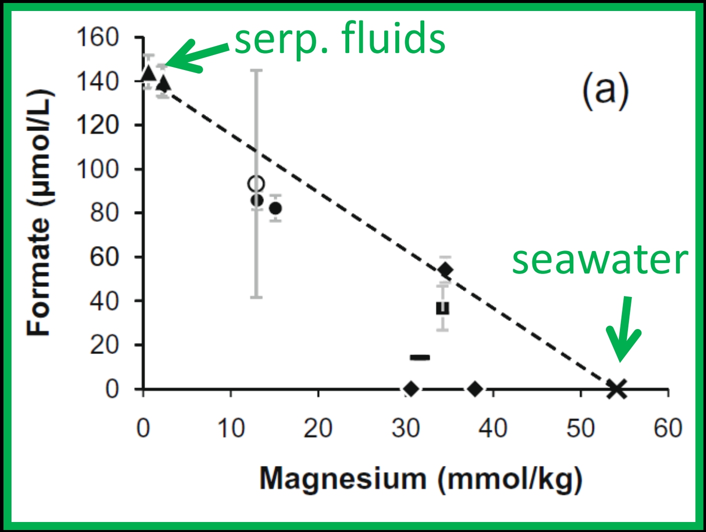
Seafloor Serpentinizing Systems

- Seawater reacts with hot ultramafic rock at depth → serpentinization reactions
- T~90C, pH 11 fluids venting from carbonate chimneys
- System is self-sustaining and fractures propagate (30% volume expansion)
- Rich array of organics, microbial (and macro) life

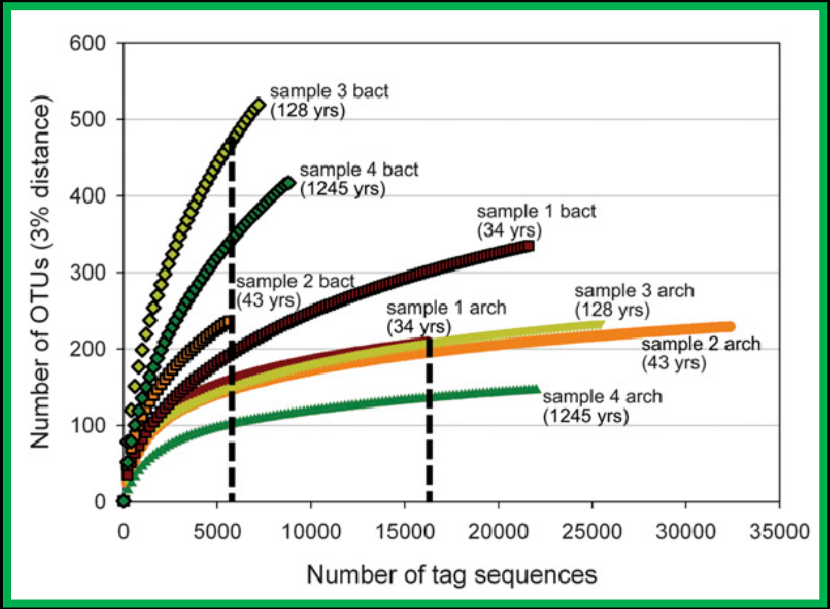
Kelly et al., 2001, Nature

Seafloor Serpentinizing Systems

- Organic compounds and methane are produced by Fischer-Tropsch synthesis from reaction of CO2 with serpentinization-produced hydrogen
- Diverse microbial communities reflect age (temperature, water chemistry)
- Methanogenic archaea, *Methanosarcinales* dominate at young chimneys

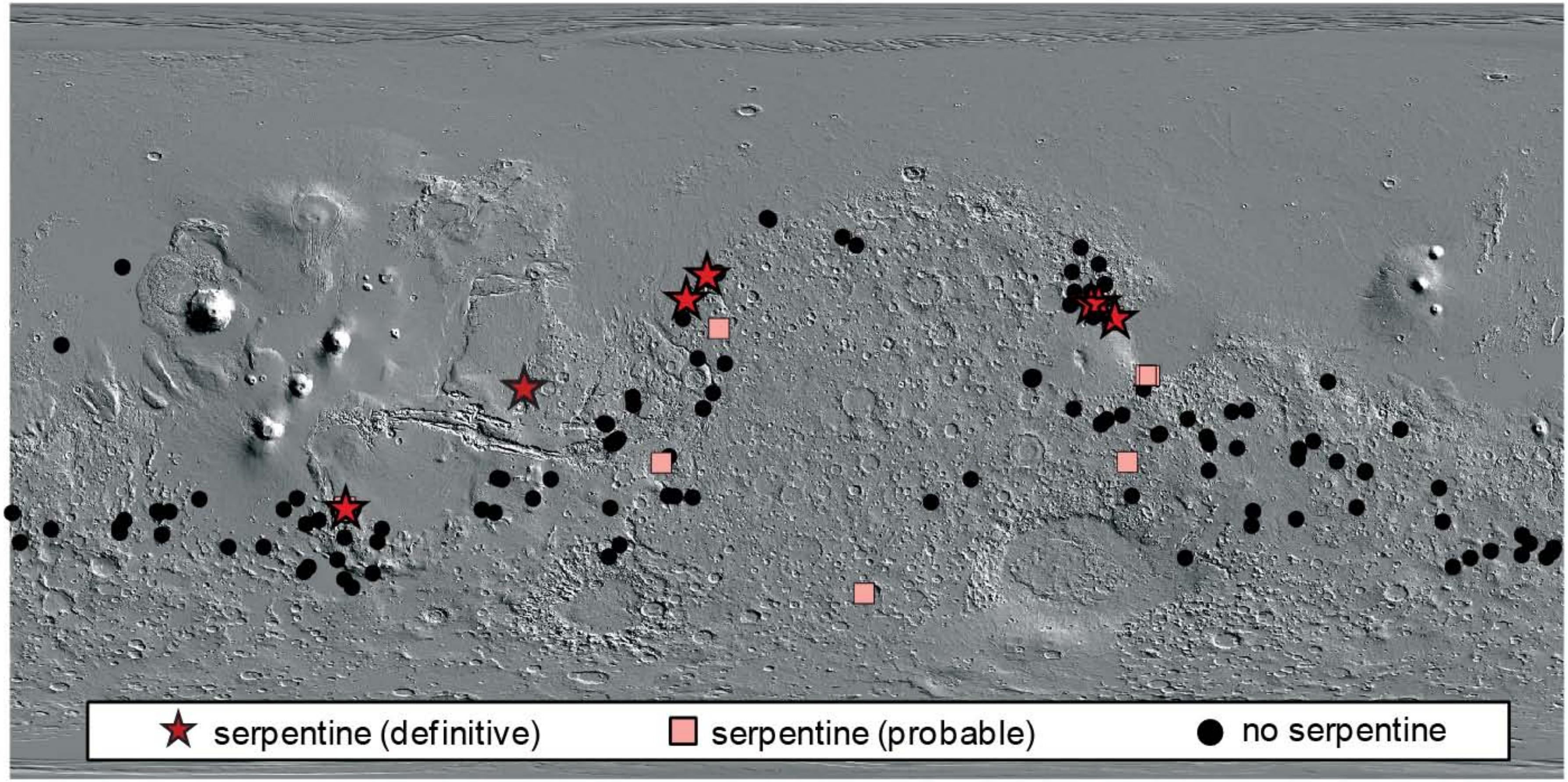


Lang et al., GCA, 2010



Brazelton et al., 2010, PNAS

Serpentine: Global Distribution on Mars



Importance of serpentine $(Fe, Mg)_3Si_2O_5(OH)_4$ on Mars

- **Indicator of hydrothermal alteration (25-500°C)** of ultramafic rocks (aqueous conditions: low $aSiO_2$, high pH, usually highly reducing)

- **Serpentinization-produced magnetite** has been suggested as a **possible cause of Martian highly magnetized regions** [Nazarova & Harrison, 2000; Lillis et al., 2008; Quesnel et al., 2009; Hood et al., 2009]

$$\underset{\text{(olivine)}}{(Fe,Mg)_2SiO_4} + H_2O \dashrightarrow \underset{\text{(serpentine)}}{(Fe, Mg)_3Si_2O_5(OH)_4} + \underset{\text{(brucite)}}{(Mg, Fe)(OH)_2} + \underset{\text{(magnetite)}}{Fe_3O_4} + H_{2(g)}$$

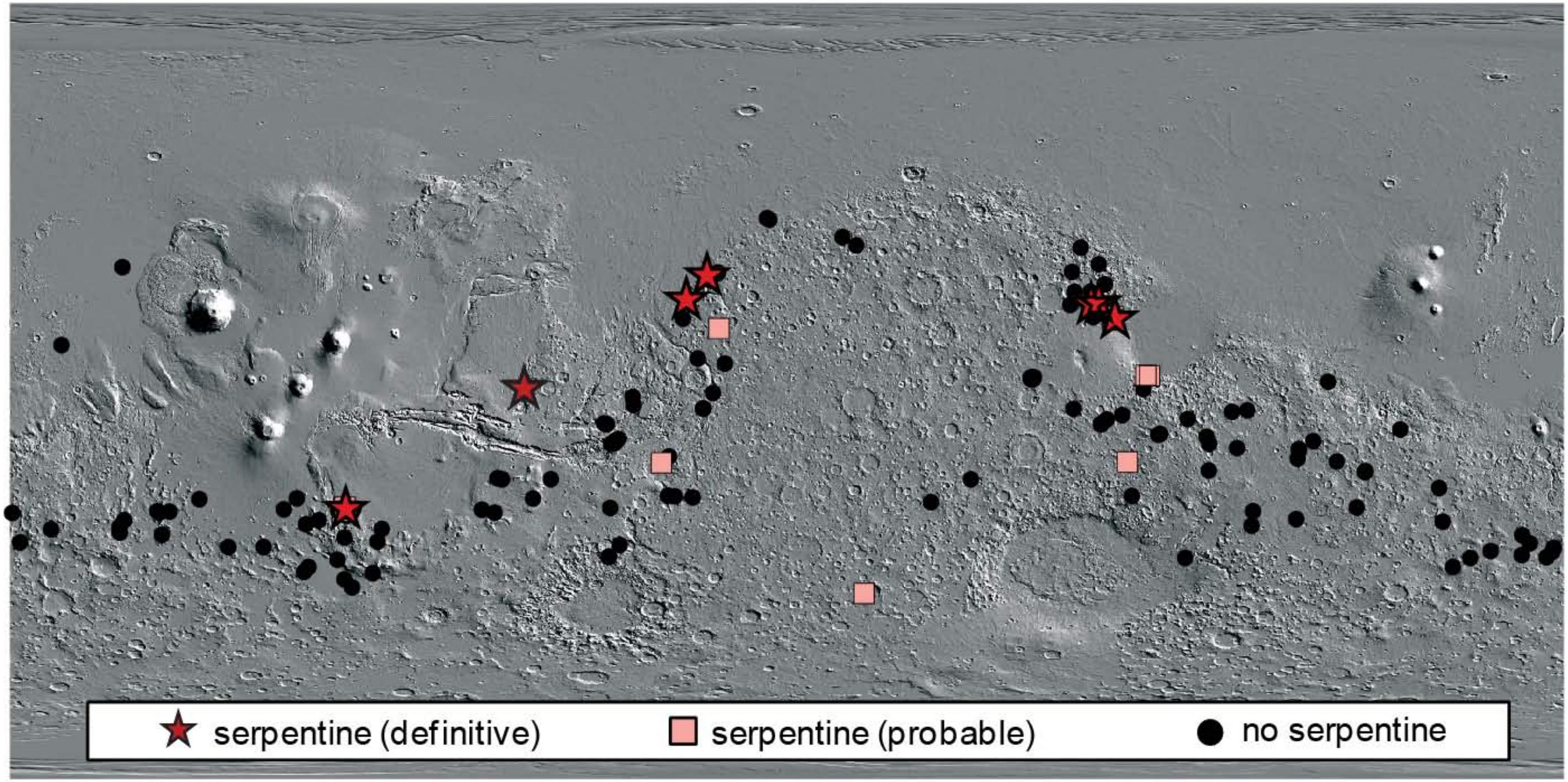
- **Serpentinization releases H_2,** an **energy source for microbes** [Sleep et al., 2004; Schulte et al., 2006]

- **Serpentinization can produce methane (CH_4)** [Oze and Sharma, 2005]
  - abiotically, via reaction with CO_2
  - biotically-mediated, during reduction of H_2

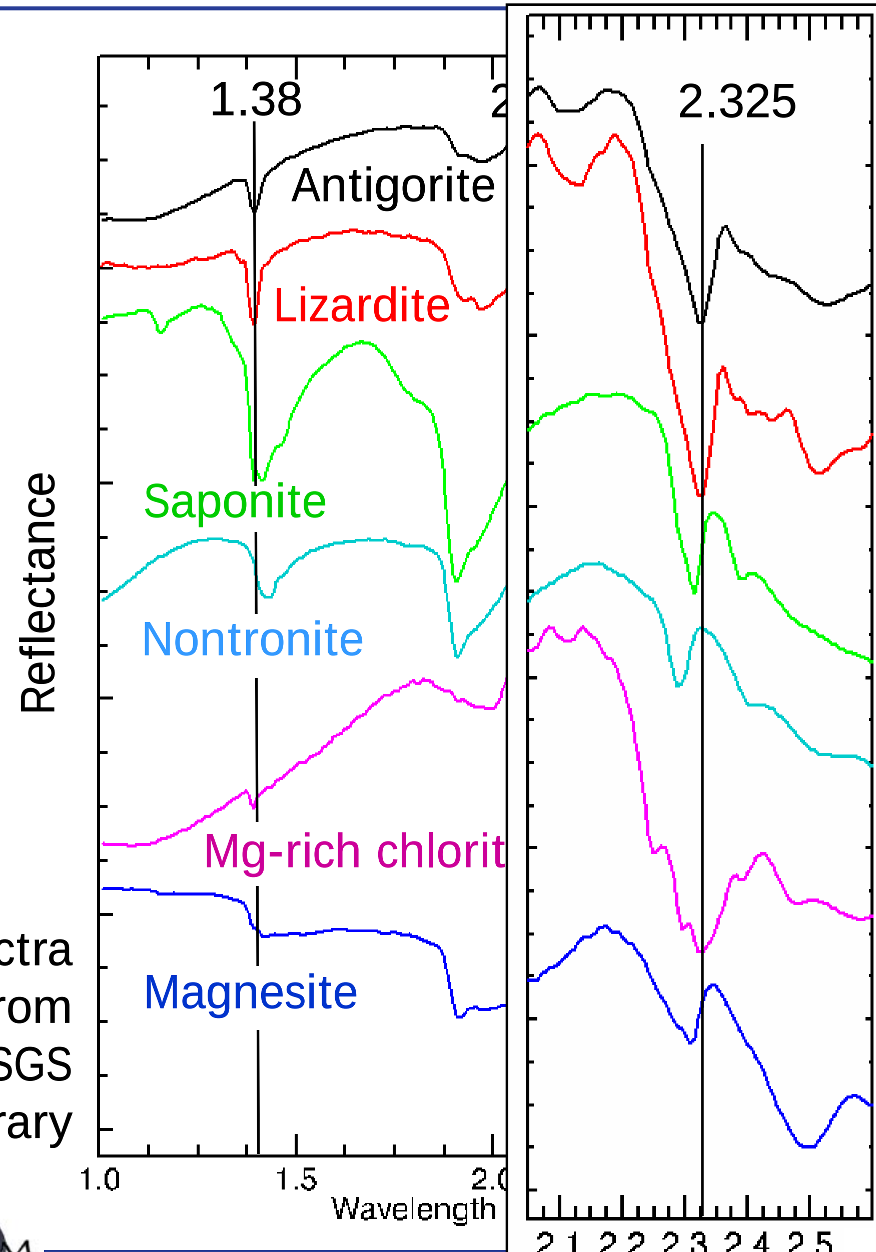
$$H_2(g) + CO_2(aq, g) \dashrightarrow CH_4(g)$$

CRISM

Serpentine: Global Distribution



Methods: identifying Mg serpentines



spectra from USGS library

- Serpentine is hard to identify uniquely
- Overtone and combination bands of (Fe, Mg)-OH in the 1.0-2.6 µm range

  [King & Clark, 1989, Calvin & King, 1997, Post & Borer, 2000, Bishop et al., 2008]
  - Asymmetric, narrow 2.32 µm Mg-OH combination band
  - Sharp 1.39 µm absorption (Mg-OH)
  - Weaker 2.12 and 2.51 µm bands
  - Distinctive spectral shape, 1.4-2.6 µm region
- ALL these bands are necessary to UNIQUELY and DEFINITIVELY distinguish Mg serpentine from, e.g., Mg-rich chlorites, Mg-rich smectites, and carbonates

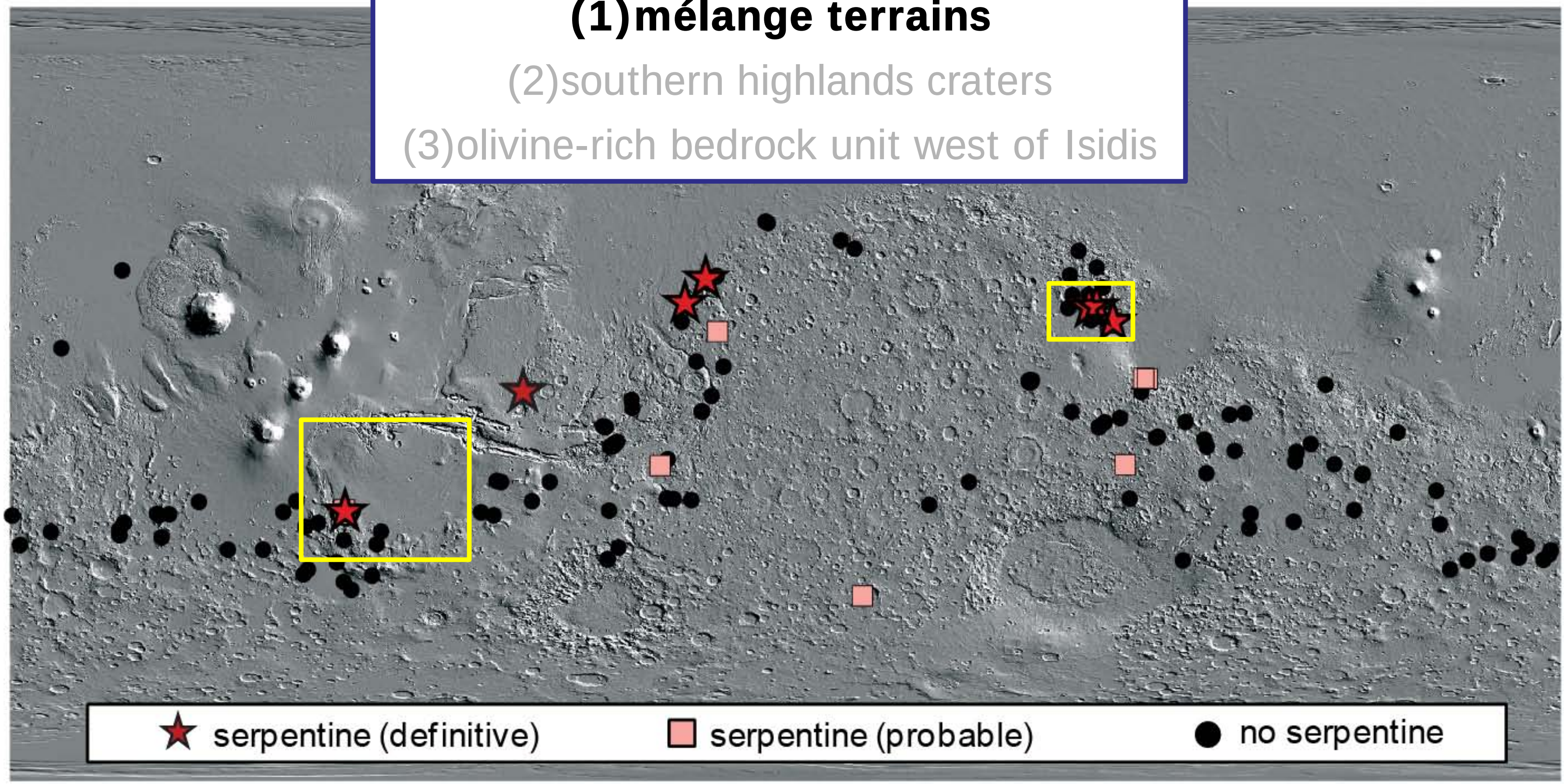
Serpentine: C

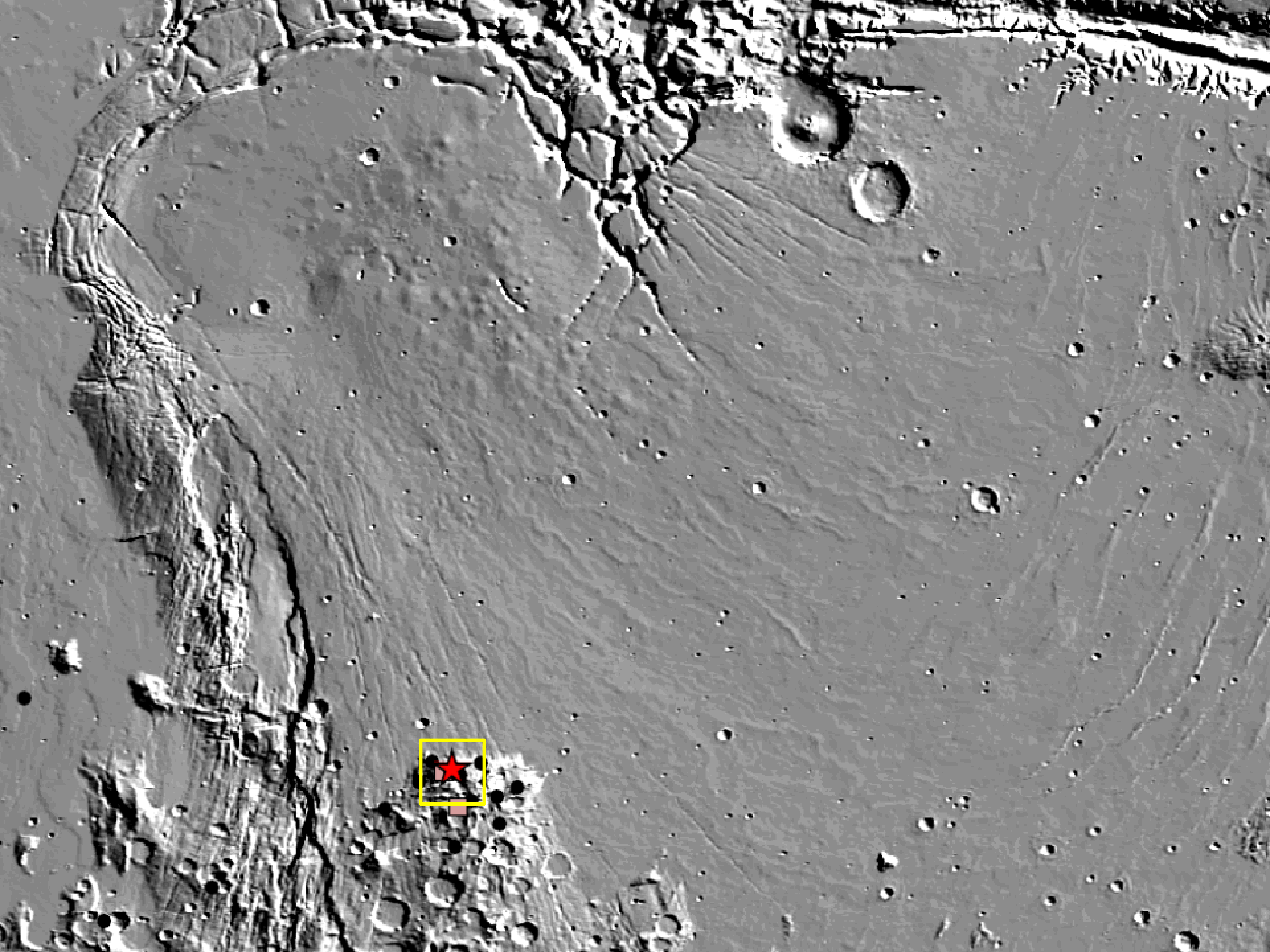
Three geologic settings:

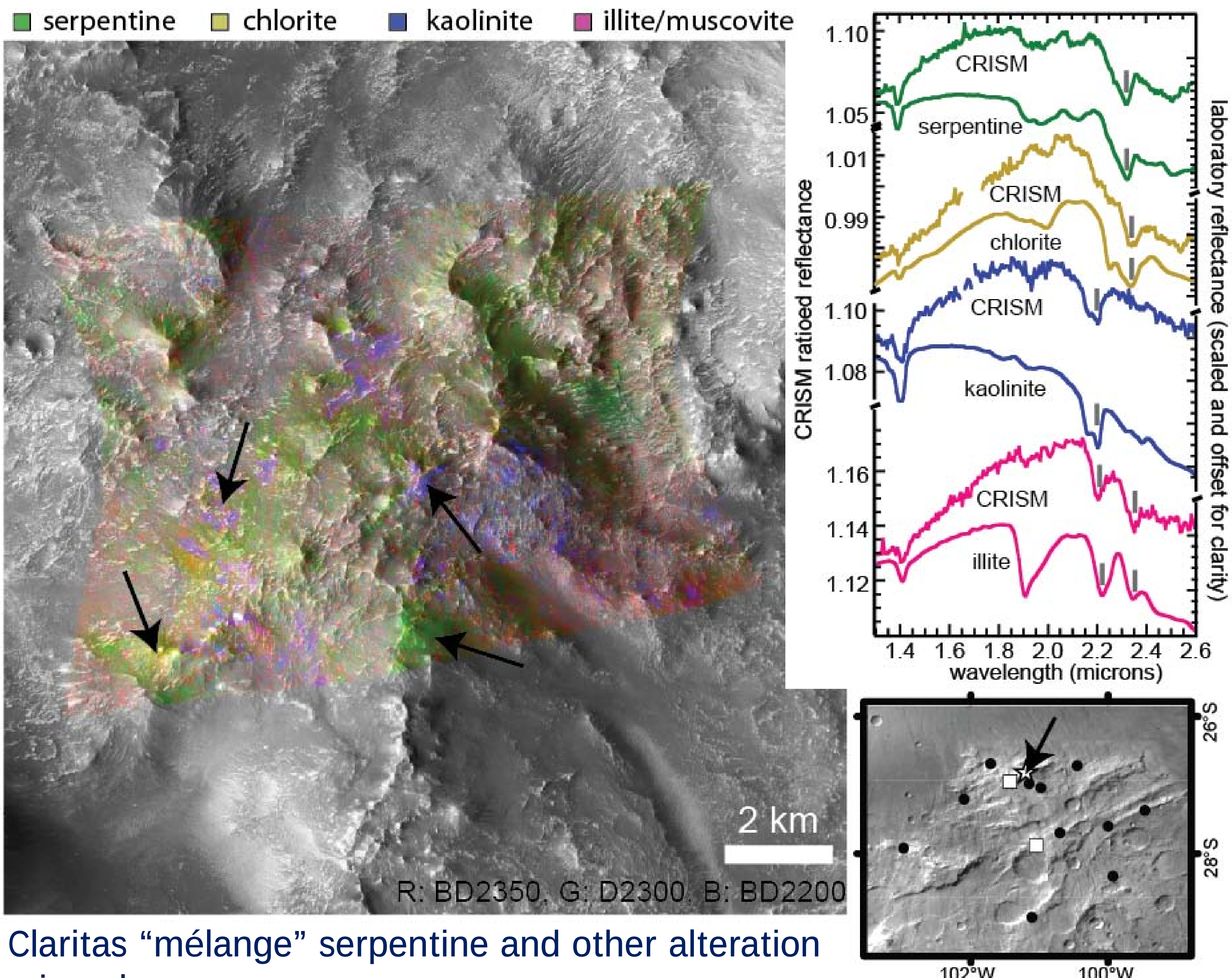
(1)mélange terrains

(2)southern highlands craters

(3)olivine-rich bedrock unit west of Isidis







Claritas "mélange" serpentine and other alteration minerals

Serpentine: C

Three geologic settings:

(1)mélange terrains

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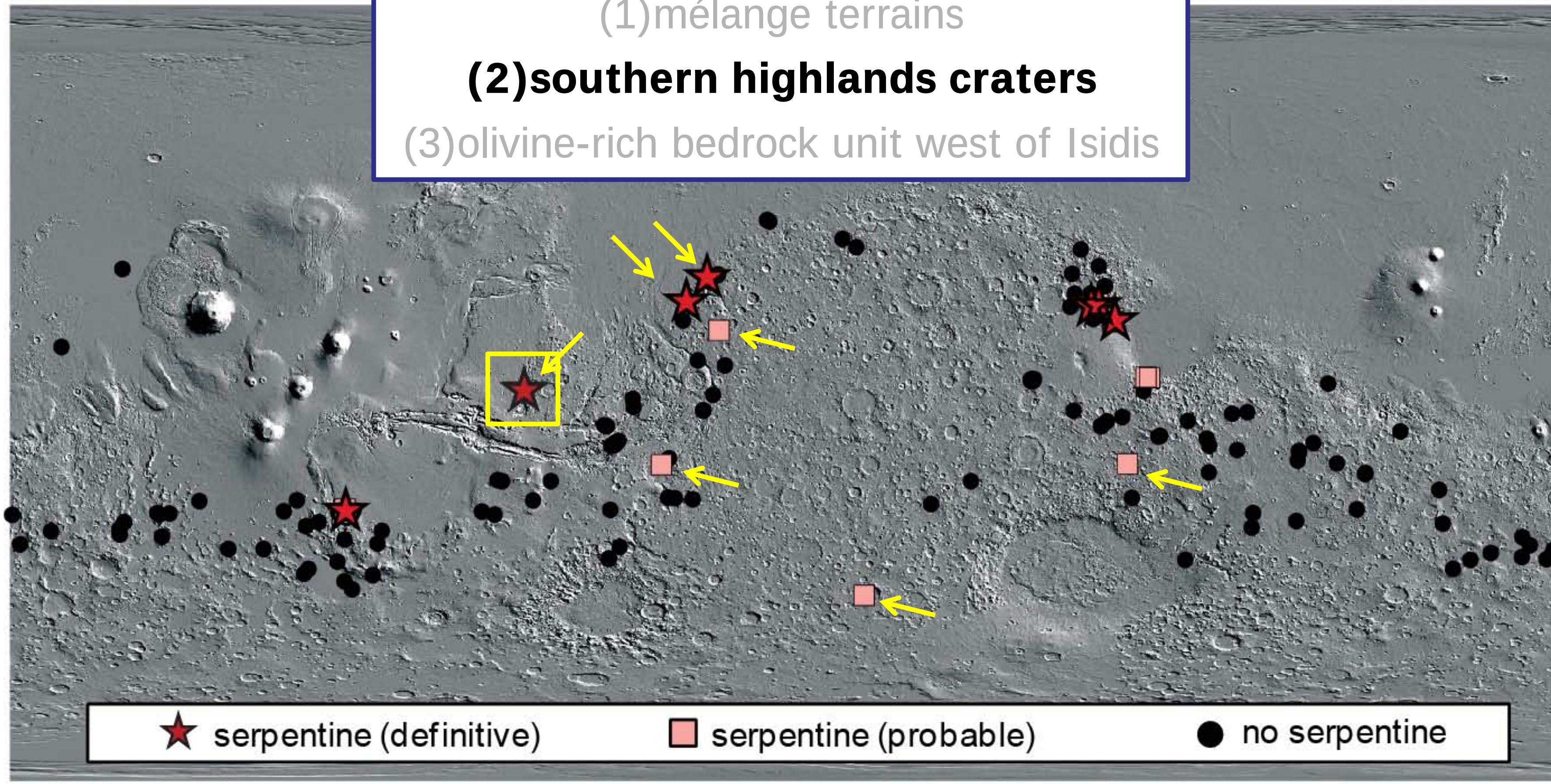
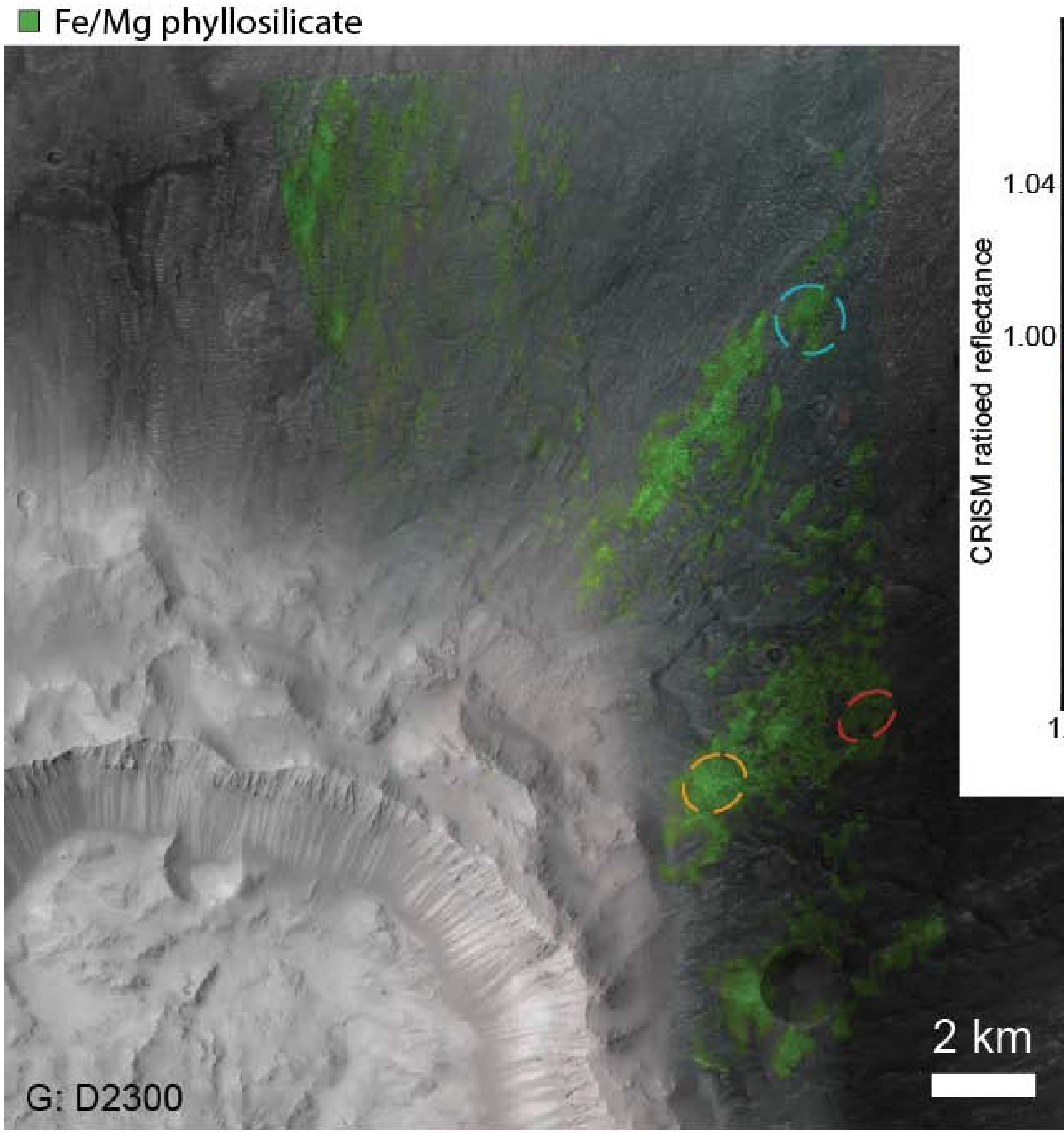
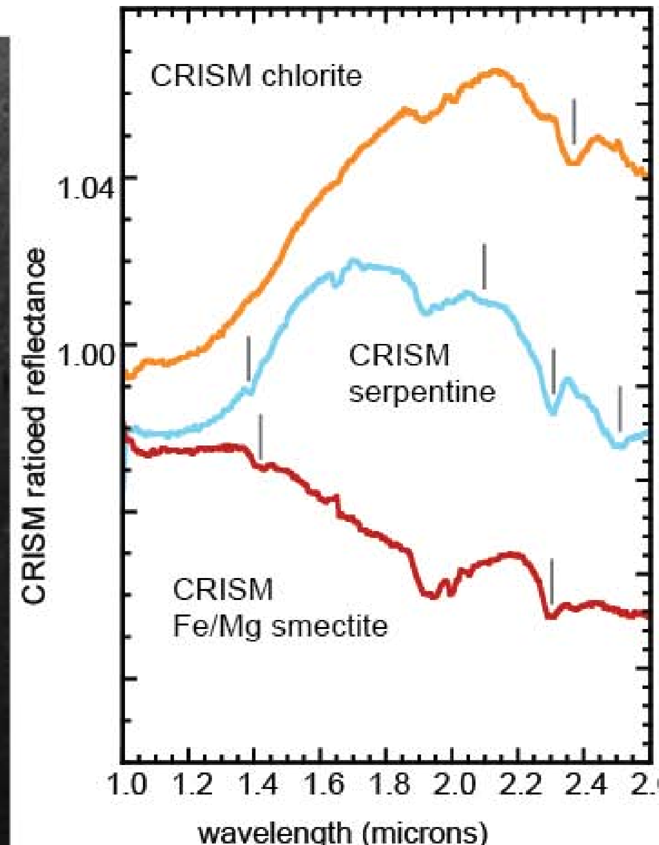
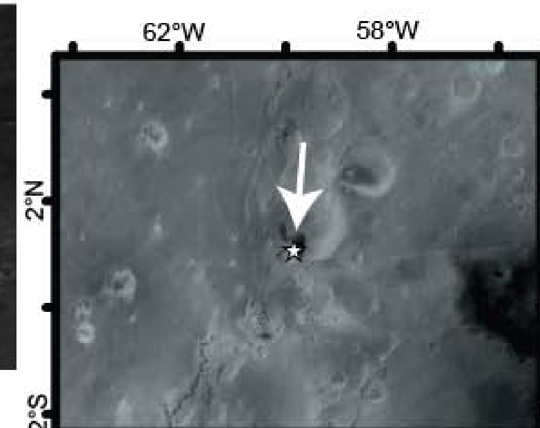




Fe/Mg phyllosilicate
G: D2300
2 km



CRISM chlorite
CRISM serpentine
CRISM Fe/Mg smectite
CRISM ratioed reflectance
1.04
1.00
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
wavelength (microns)



62°W
58°W
2°N
2°S

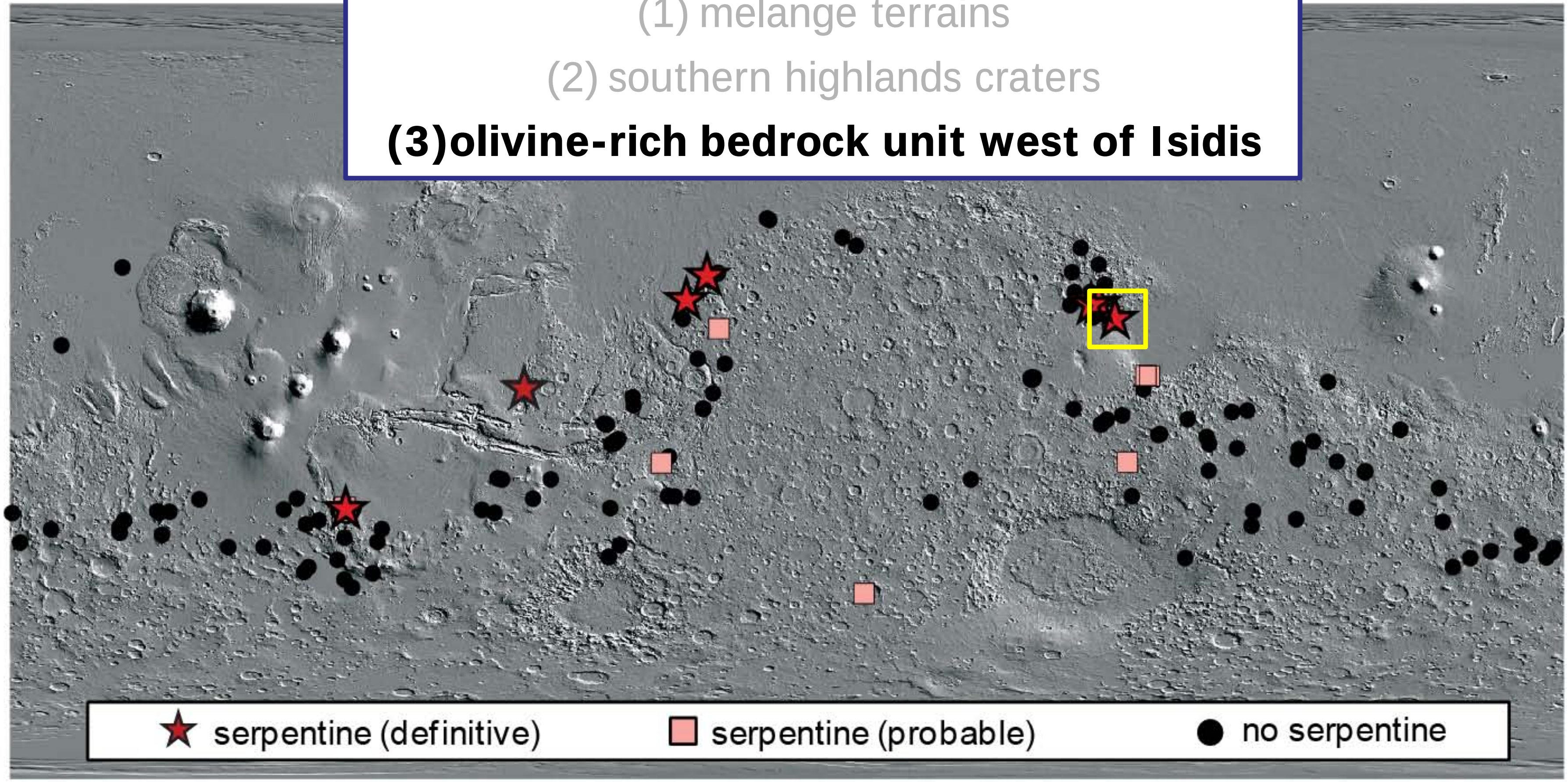
Serpentine:

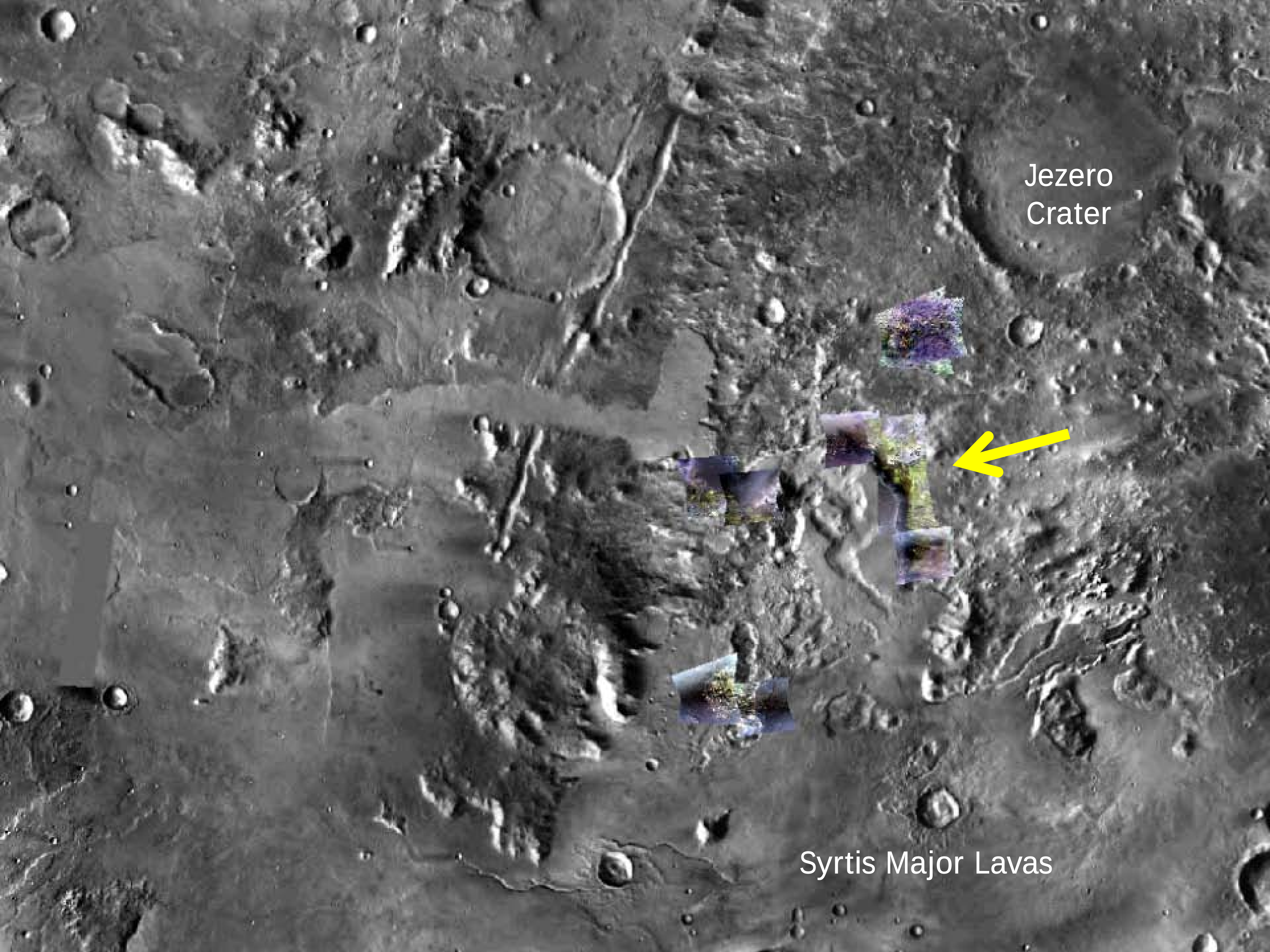
Three geologic settings:

(1) melange terrains

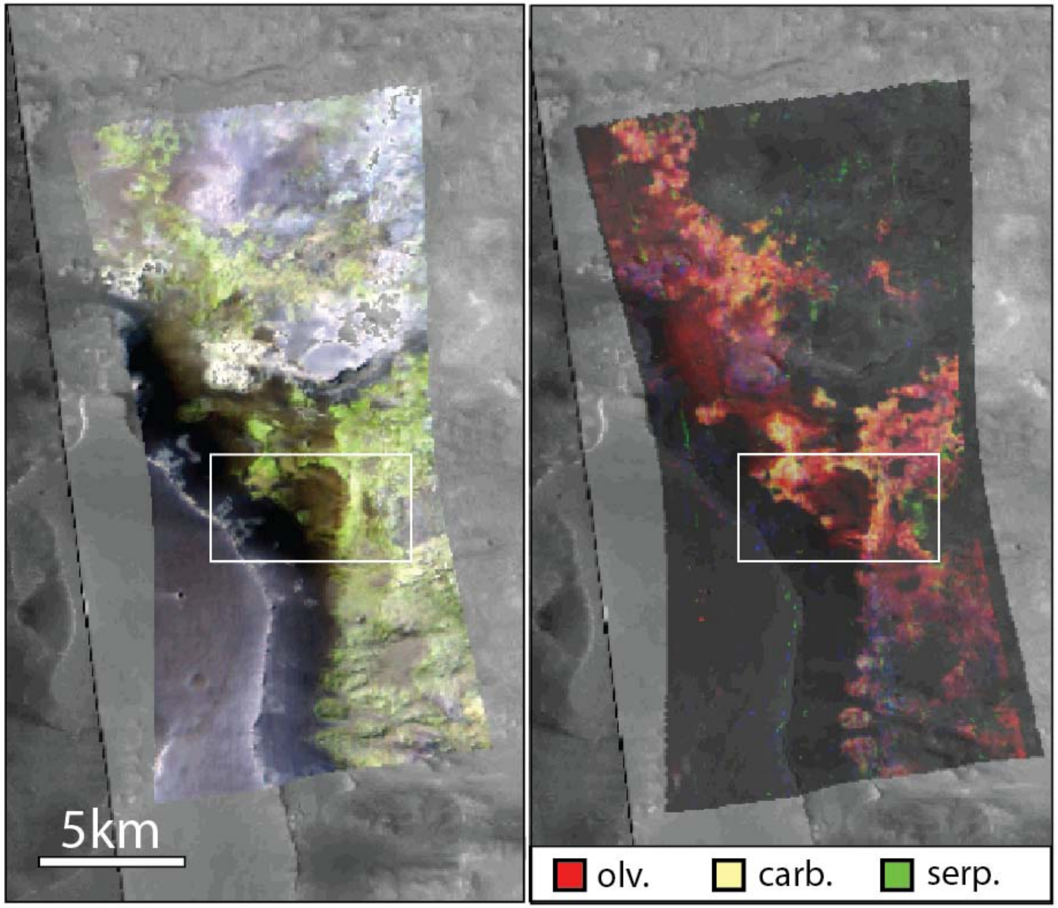
(2) southern highlands craters

(3)olivine-rich bedrock unit west of Isidis

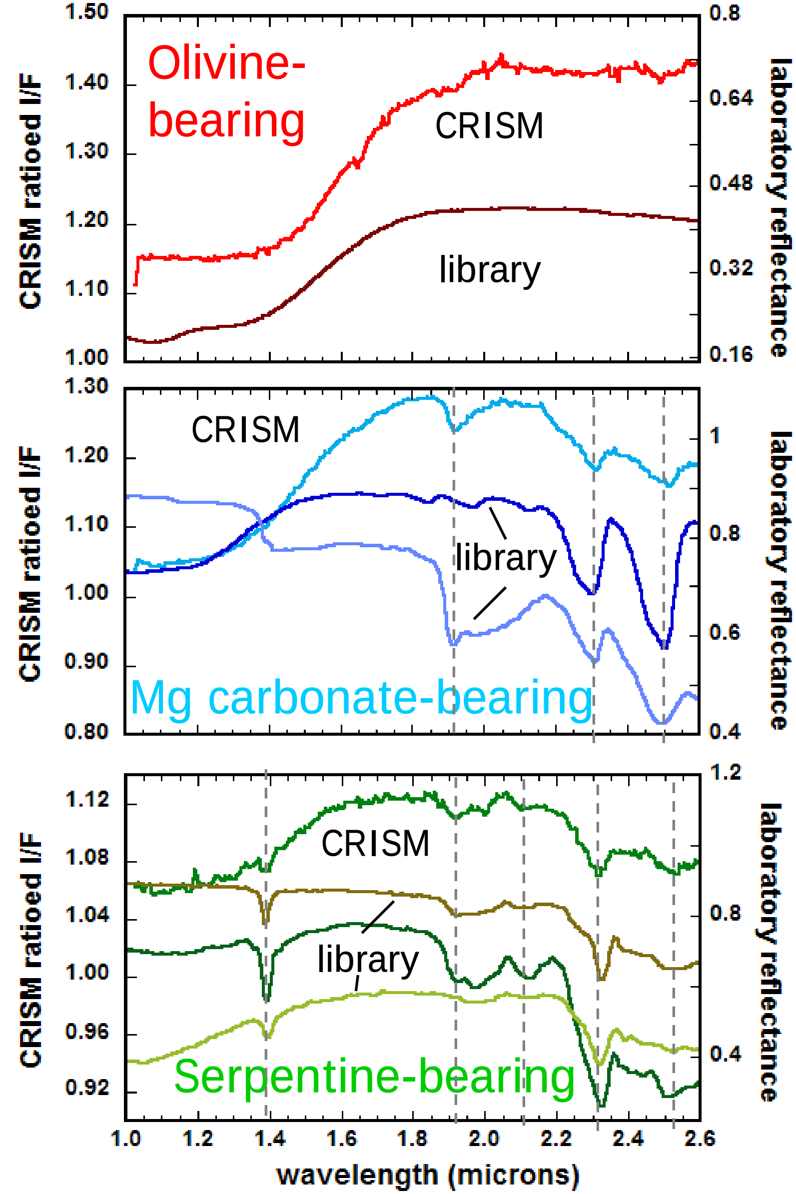



Jezero
Crater
Syrtis Major Lavas

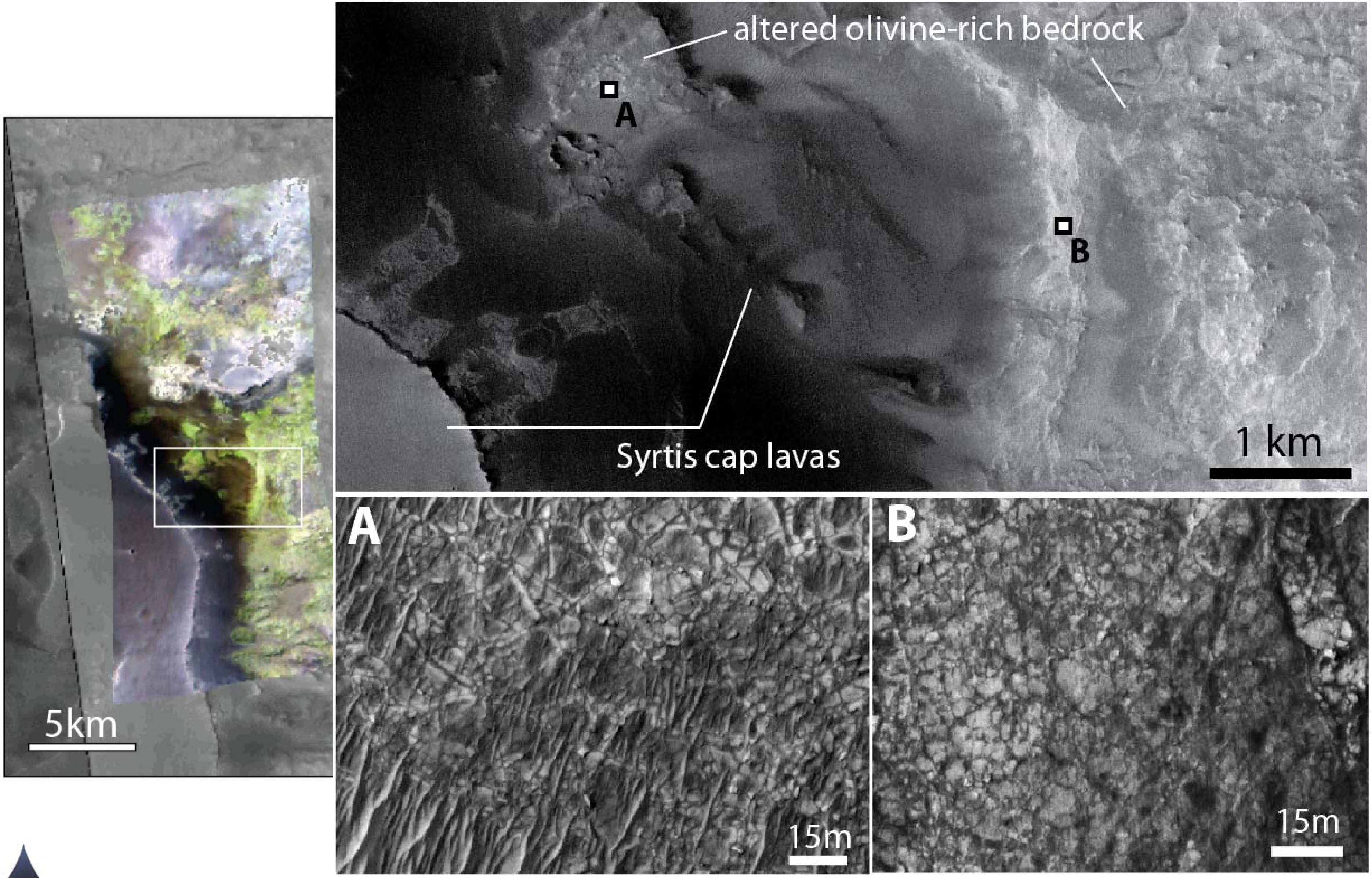
Serpentine in olivine-rich bedrock



False color CRISM RGB



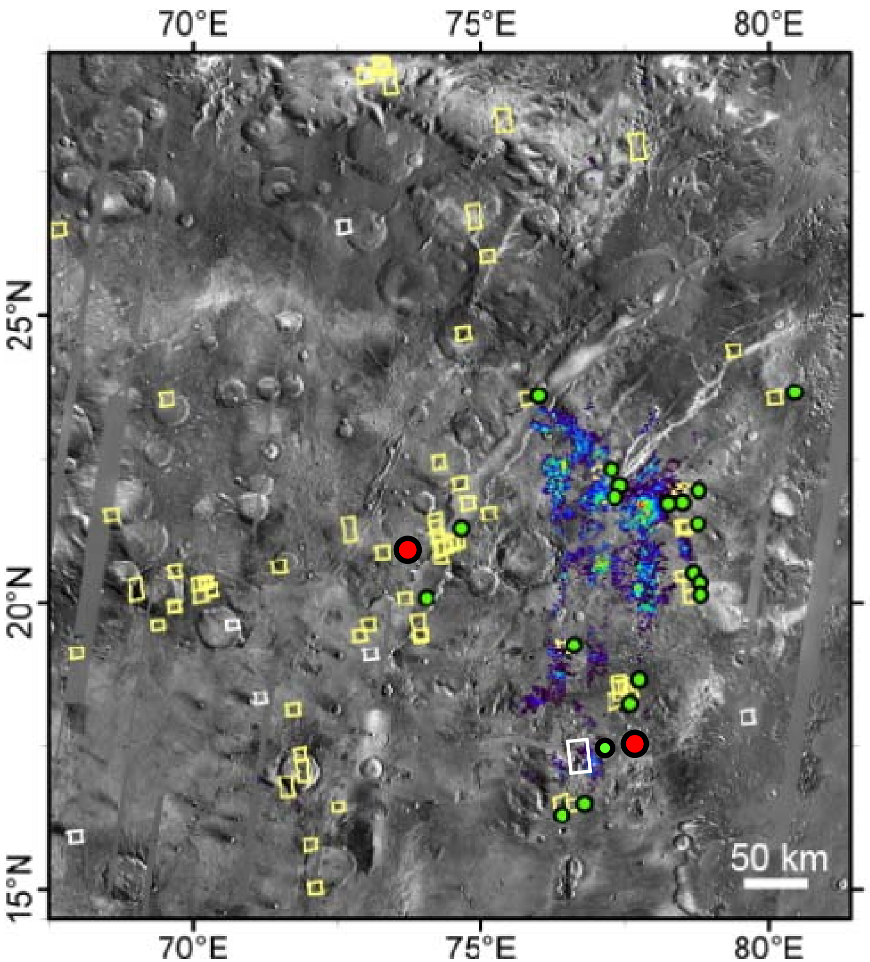
Serpentine in olivine-rich bedrock



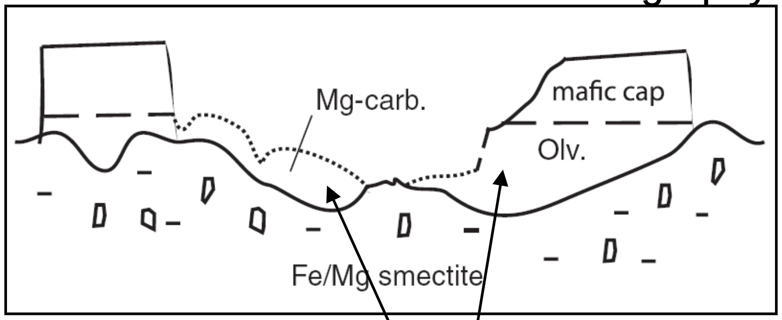
Nili Fossae: distribution of olivine, carbonate, and serpentine

- Where found in stratigraphic section, serpentine is associated with Mg-carbonate and olivine

Ehlmann et al., 2008, *Science*



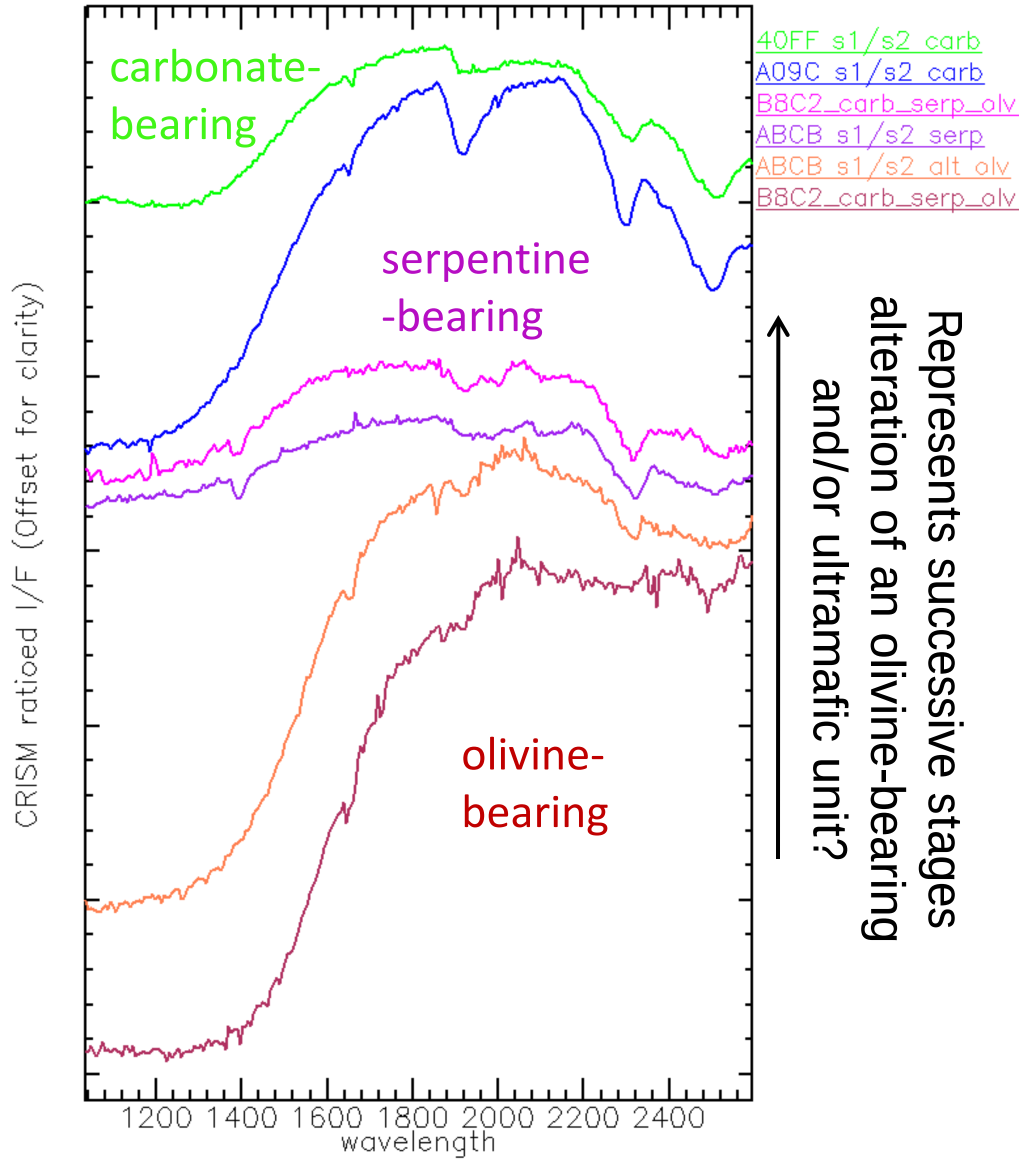
Schematic stratigraphy



And also serpentine. A partially serpentinized olivine body?

VNIR Spectral Variation: Records the Chemical Process?

- Spectra exist of Mars terrains that are consistent with the endmember minerals, but there are also spectra with "in-between" characteristics.

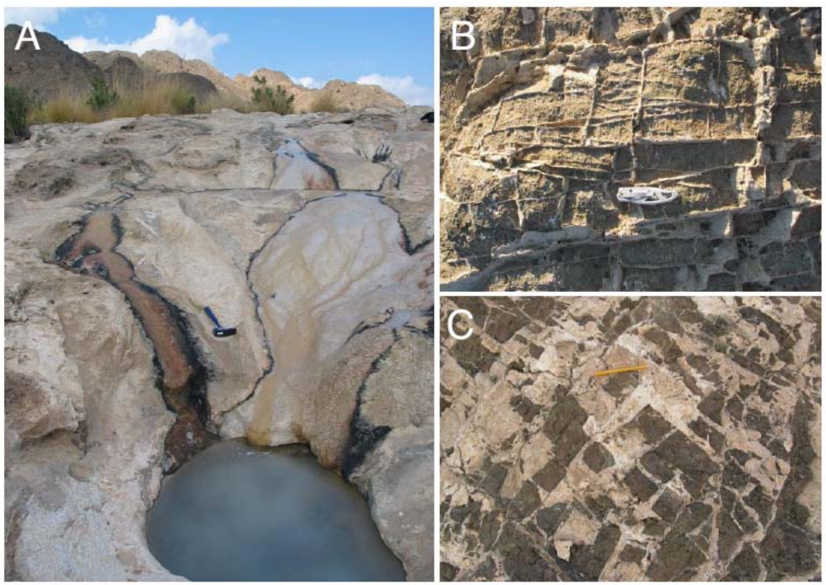


NE Syrtis/Nili Fossae : Potential Terrestrial Analogues

- Weathered peridotites (olivine-rich, serpentinized seafloor rocks)
- Greenstone belts/kimberlites (ancient ultramafic lavas, erupted subaqueously) [Sader et al., 2007]

olivine $(Fe,Mg)_2SiO_4$ [$\xrightarrow[\text{alteration } H_2 \rightarrow CH_4]{\text{partial HT}}$ serpentine $(Fe,Mg)_3Si_2O_5(OH)_2$] $\xrightarrow[\text{T alteration } CO_2]{\text{partial low-}}$ carbonate $(Mg, Fe)CO_3$

Serpentine and carbonate from Oman ophiolite – (Keleman and Mater, 2008)

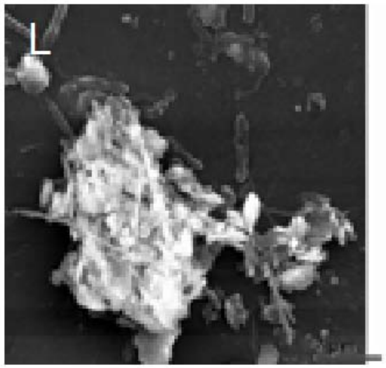


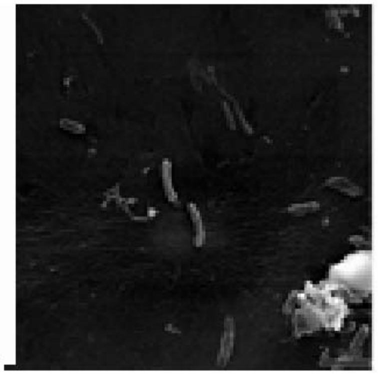
Terrestrial Serpentinizing Systems

- Not only a seafloor process
- Alteration of ultramafic rocks on continents occurs and may be a better Mars analog
- Subject of ongoing study of biology, aqueous geochemistry, mineralogy of such systems

TERRESTRIAL SERPENTINIZING SYSTEMS AS MINERALOGICAL, GEOCHEMICAL (AND BIOLOGICAL?) ANALOGUES FOR MARS. B.L. Ehlmann[1], D. Cardace[2], T. Hoehler[3], D. Blake[3], P. Kelemen[4] [1]Inst. d'Astrophysique Spatiale, U. Paris-Sud XI. [2]Dept. of Geosciences, U. Rhode Island, [3]NASA Ames Research Center, [4]Lamont Doherty Earth Observatory, Columbia U. (corresponding author: bethany.ehlmann@ias.u-psud.fr)


Analogues Workshop, 2011





Cardace, AGU, 2009-2011

Tracking Key Parameters for Biology

$$\underbrace{(Mg,Fe)_2SiO_4}_{\text{Olivine}} + H_2O_{(l)} \rightarrow \underbrace{(Mg,Fe)_3Si_2O_5(OH)_4}_{\text{Serpentine}} + \underbrace{(Mg,Fe)(OH)_2}_{\text{Brucite}} + \underbrace{Fe_3O_4}_{\text{Magnetite}} + H_{2(g)}$$

<u>Key parameters:</u>

(1)hydrogen ⬄ biologically avail. energy

Depends on Fe2+ → Fe3+ conversion

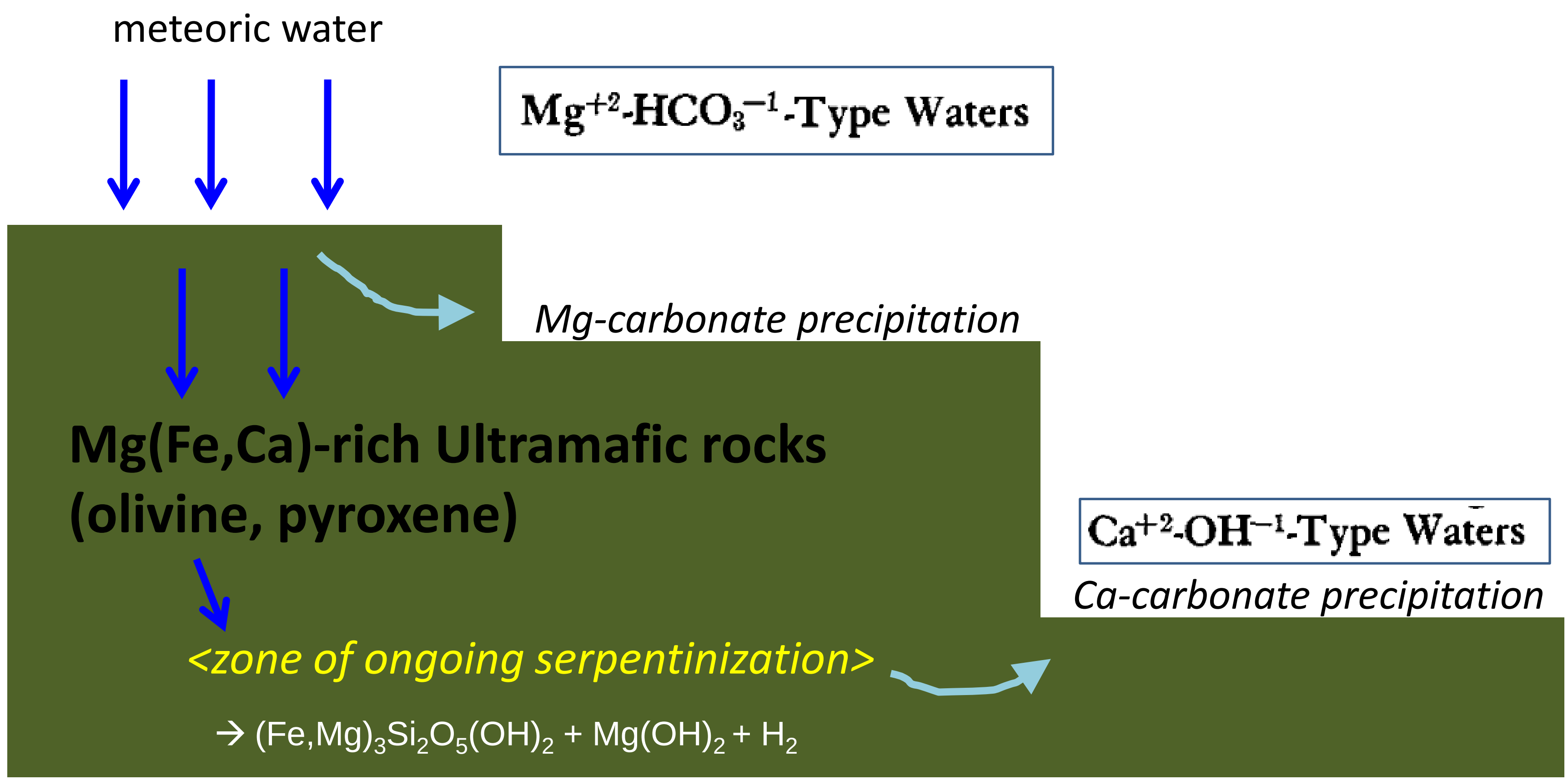
(2)alkalinity ⬄ habitability

Brucite is an indicator. Too much means cell energy expediture on maintence of neutrality, partitioning of carbon into inaccessible phases

(3)mineralogy ⬄ P,T, aqueous chemistry

Mineral assemblage (talc, carbonate, magnetite, serpentine polymorph) depend on physiochemical conditions

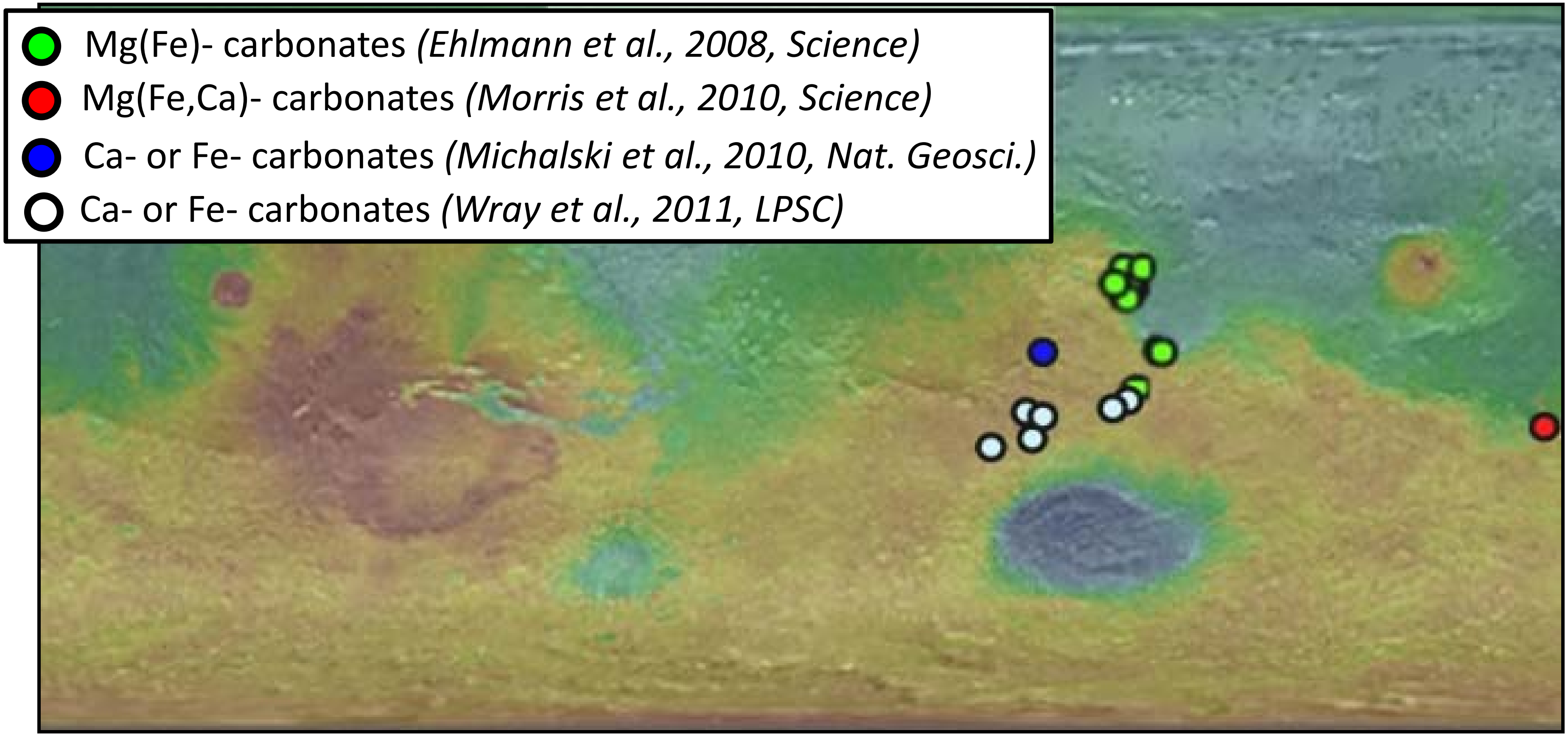
Tracing the Serpenitinization Process through Carbonate Chemistry



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

Locations of Carbonate Rocks on Mars

- Detected Mg carbonate is associated with olivine-rich rocks
- Ca or Fe carbonates reported in mixtures with other phyllosilicate minerals



Relating Spectra from Orbit to Mineralogy on the Ground

- What are the thresholds of detectability of key minerals that are indicators of chemical environment?
  - Carbonate, brucite, etc.?
  - What is the effect of scale? Overprinting of weathering processes?
- Can zones of serpenitinization and a hydrologic system be mapped remotely?

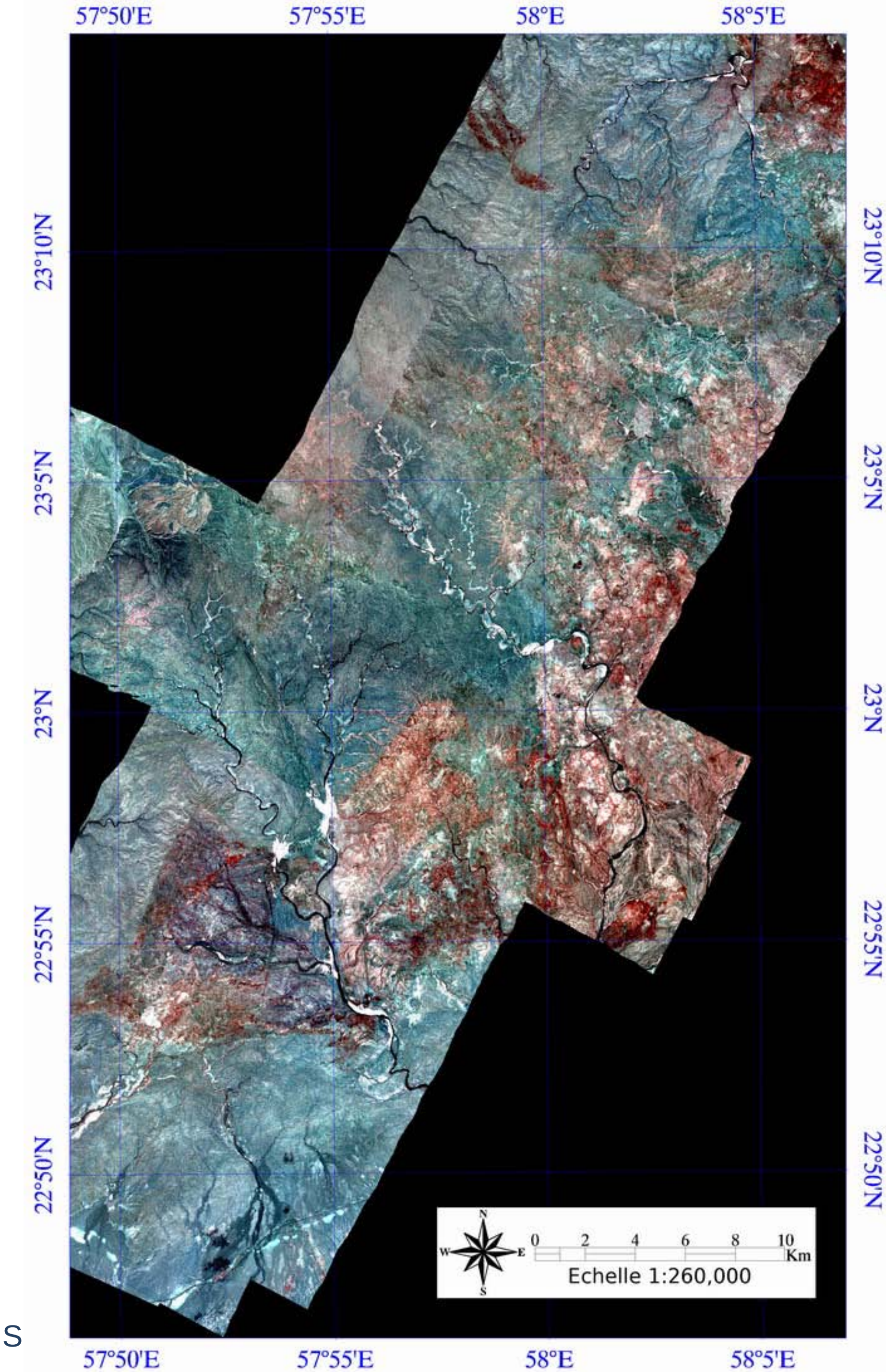
Serpentine and carbonate from Oman ophiolite – (Keleman and Mater, 2008)

Testing at the Oman Ophiolite

HyMap
Airborne
Imaging
Spectrometer

0.4-2.5µm
128 channels

6m/pixel



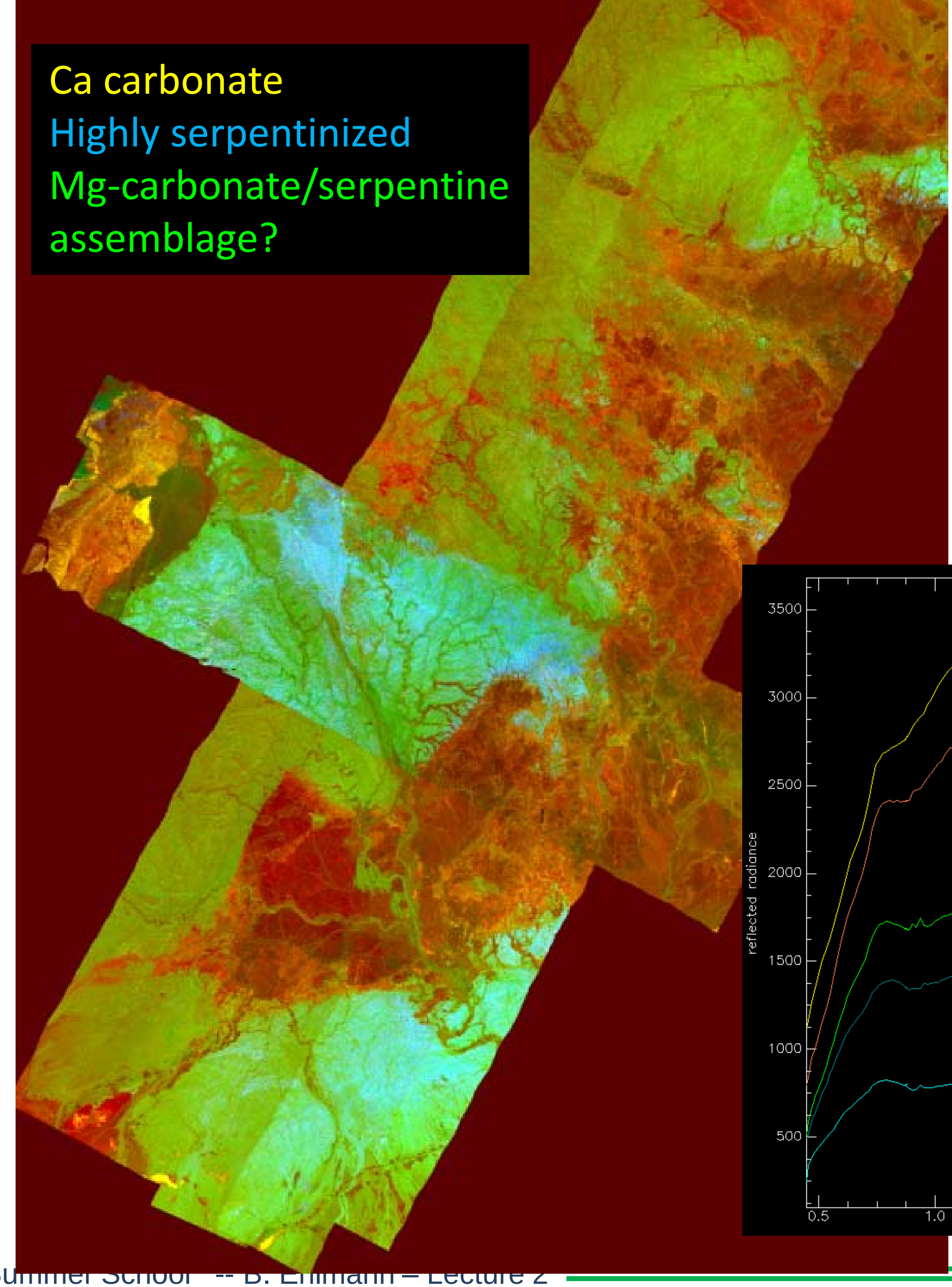
HyMap Airborne Imaging Spectrometer

First Band Mapping for Serpentine and Carbonate Detection

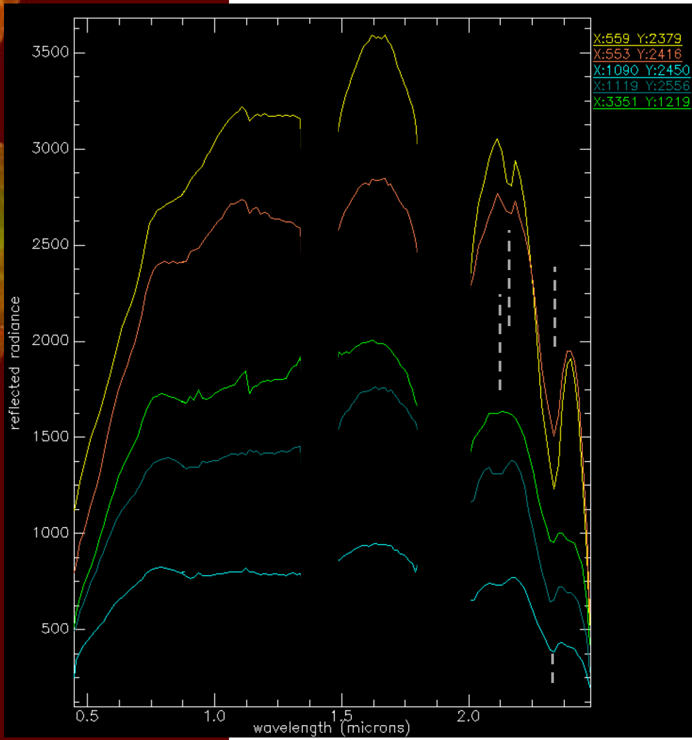
R: 2.3um position

G: depth at 2.3um

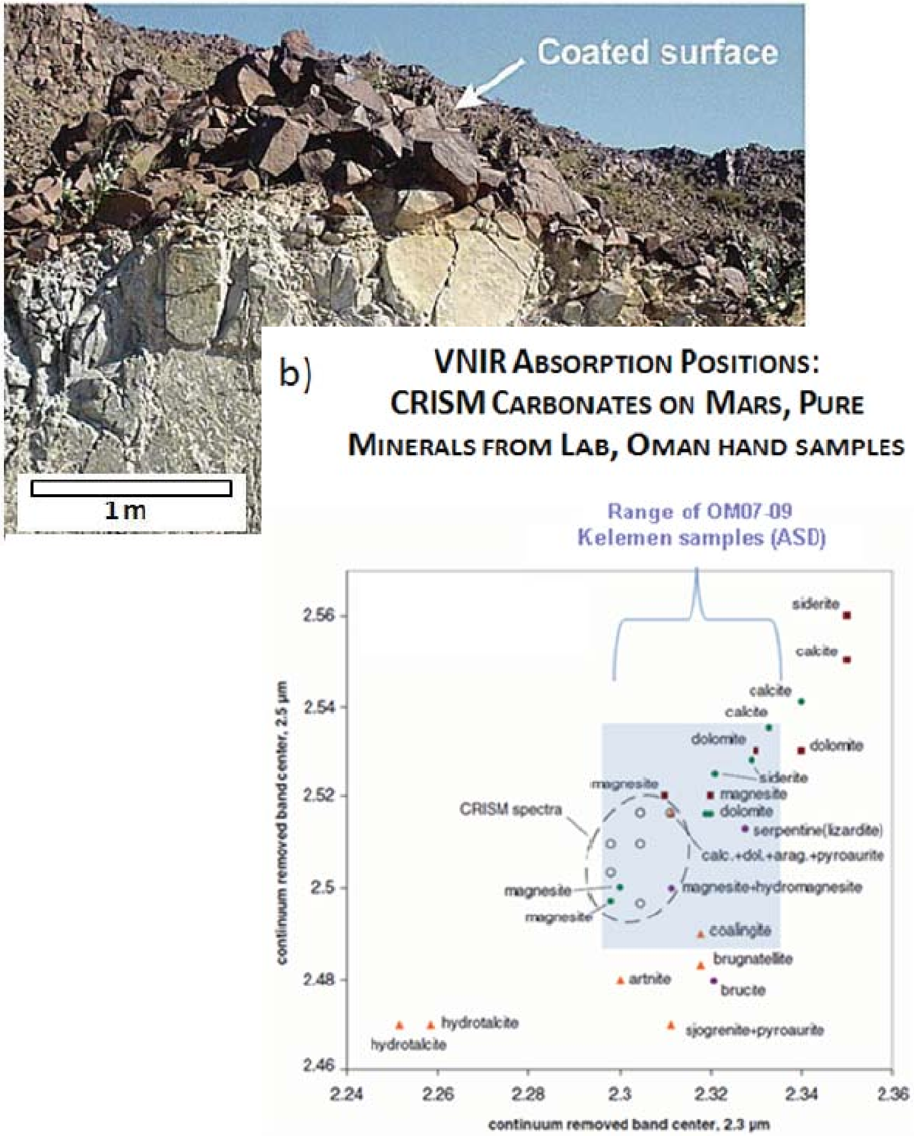
B: depth at 2.1um



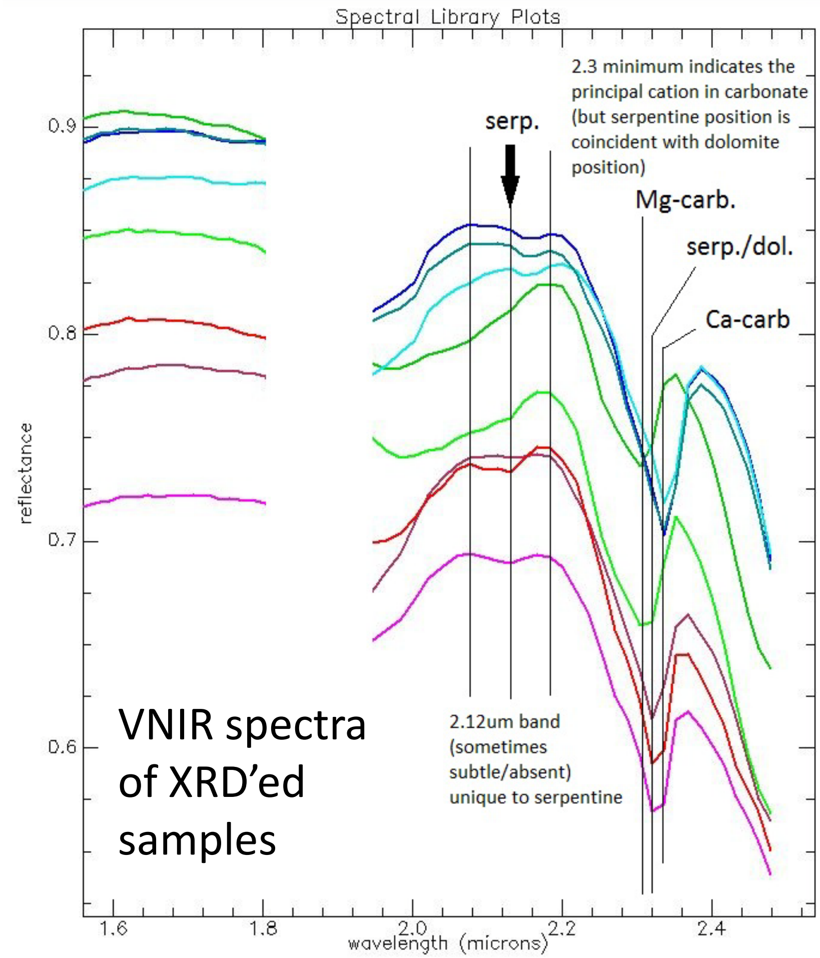
WORK IN PROGRESS!



Groundtruthing at the Oman Ophiolite

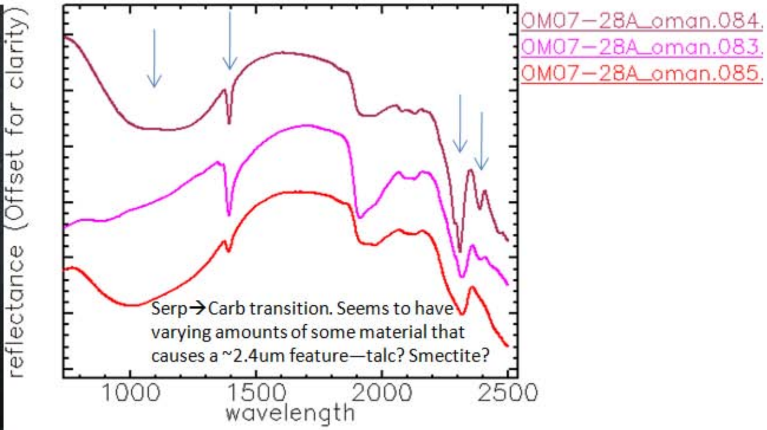


Calcite-dominated
Dolomite-dominated (minor serpentine)
Magnesite-dominated
(no serpentine-dominated in this set)



Groundtruthing at the Oman Ophiolite

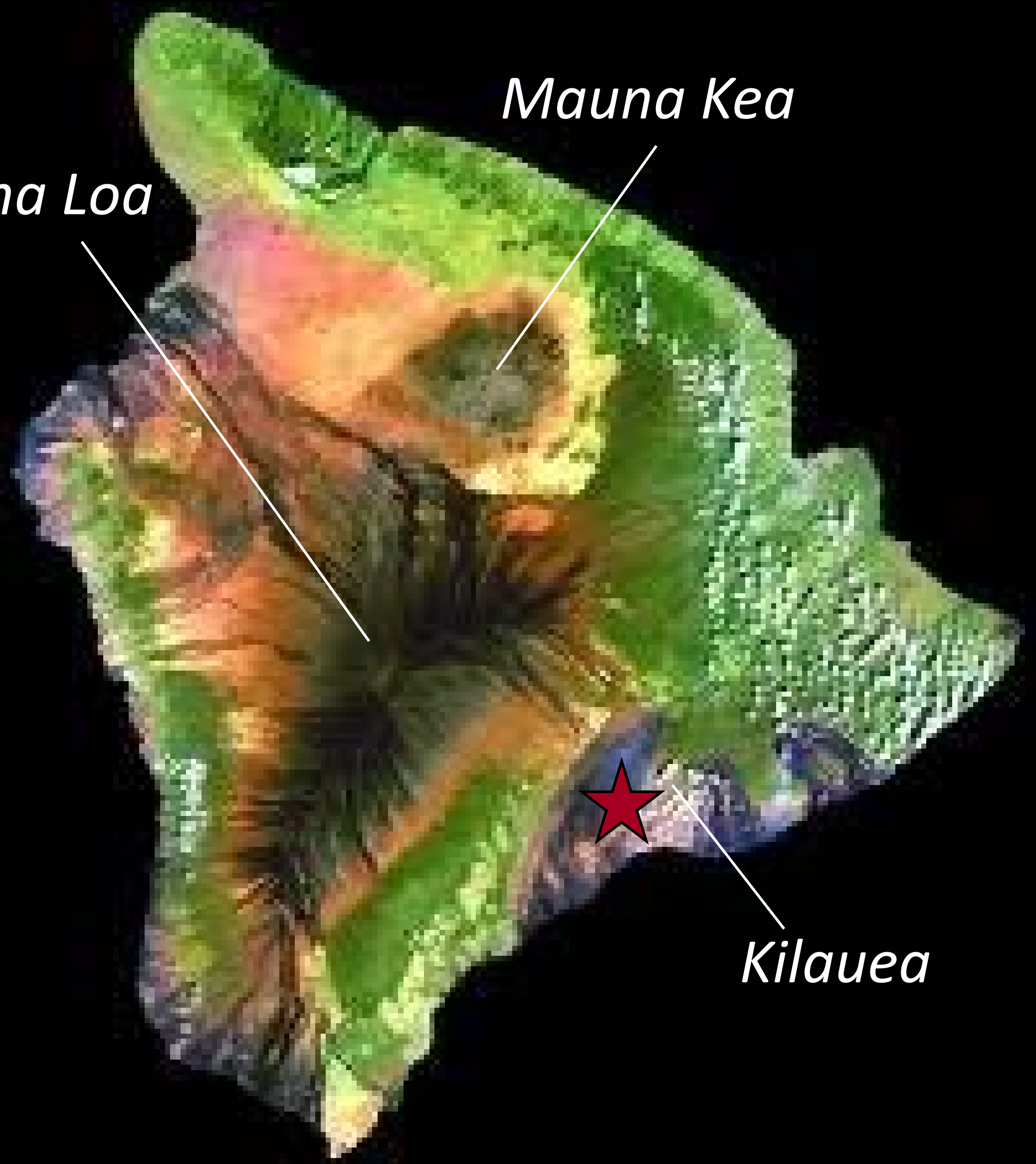
- Analysis of collected rocks in the laboratory
  - XRD
  - Elemental analysis
  - Visible/near-infrared and thermal infrared at small-scale
- Geochemical analyses of spring waters (Kelemen, Streit)



- Next step: sampling spring waters for biology

III. Acid-Sulfate Weathering and Life in Volcanic Vents, Kilauea, Hawaii

Hawaiian Volcanoes as Mars Analogs



- Basaltic island constructed by shield volcano eruptions
- Aqueous alteration by precipitation and groundwaters
- Volcanic vapors and gases affect atmosphere and fluids
- Recent lava flows have little vegetation that would inhibit studies

An Integrated Approach

K. Seelos et al., JGR, 2010

Remote Mapping

Geologic Context: airborne panchromatic images

Spectral Endmember Identification

Airborne Visible/near-InfraRed Imaging Spectrometer (AVIRIS) (0.4-2.5 μm, 224 channels, ~17 m/pixel

Field Observations

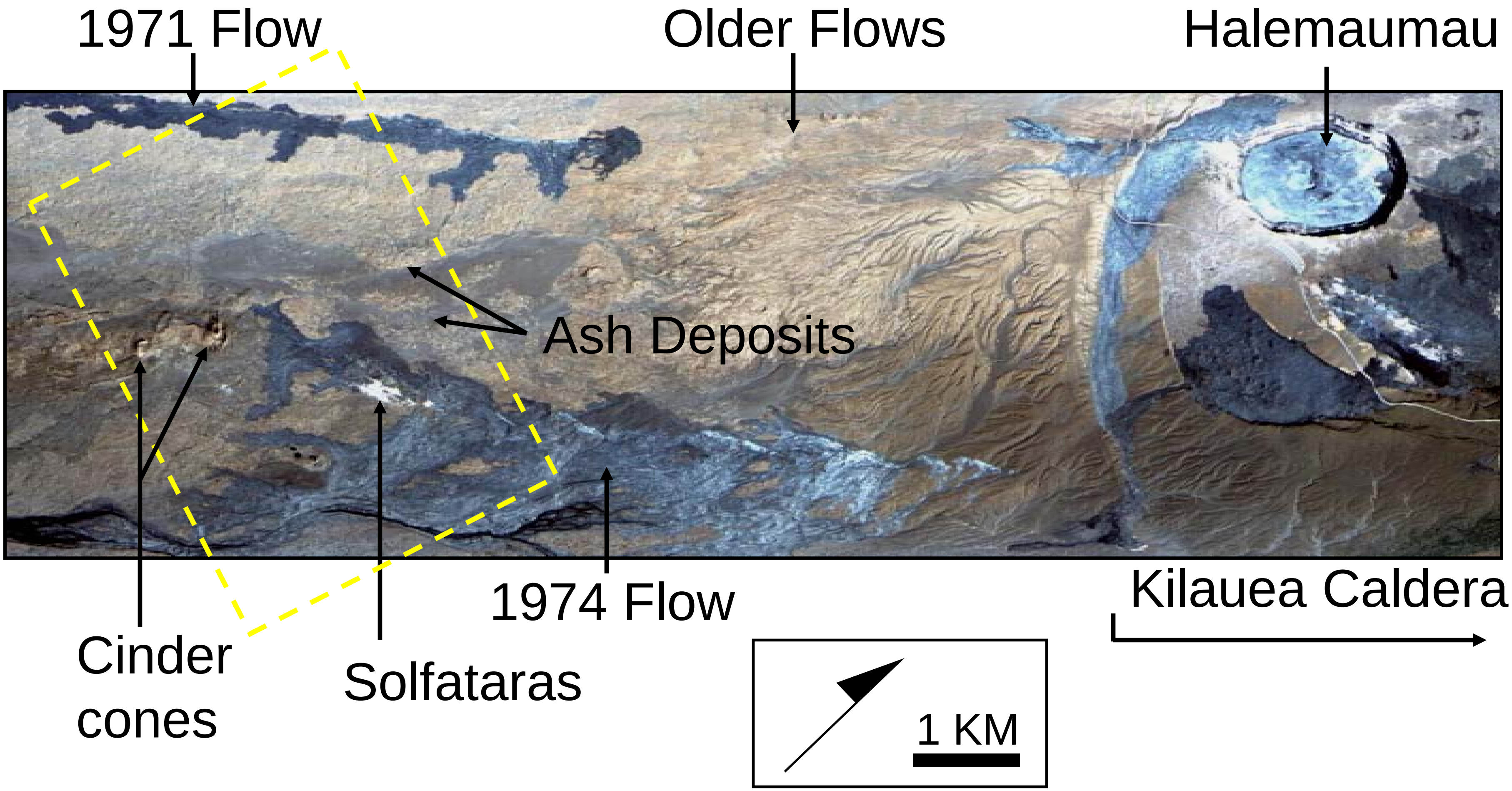
Stratigraphic relationships; active surface processes

Sampling of endmember materials

Laboratory Analyses

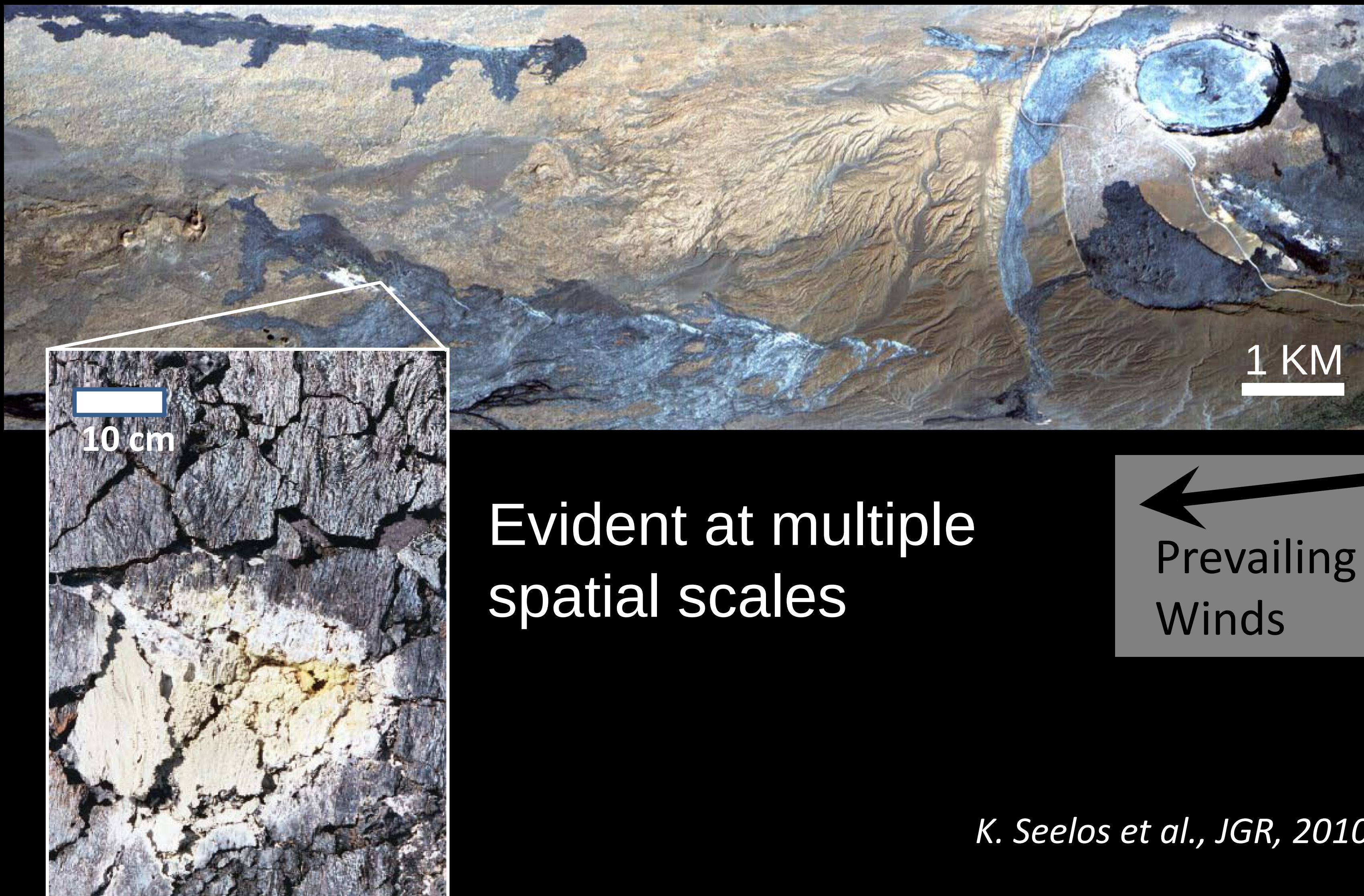
- Reflectance Spectroscopy
- X-Ray Diffraction (XRD)
- Laser-Raman Spectroscopy
- Electron Microprobe

Ka’u Desert from the Air



K. Seelos et al., JGR, 2010

Silica Mobility

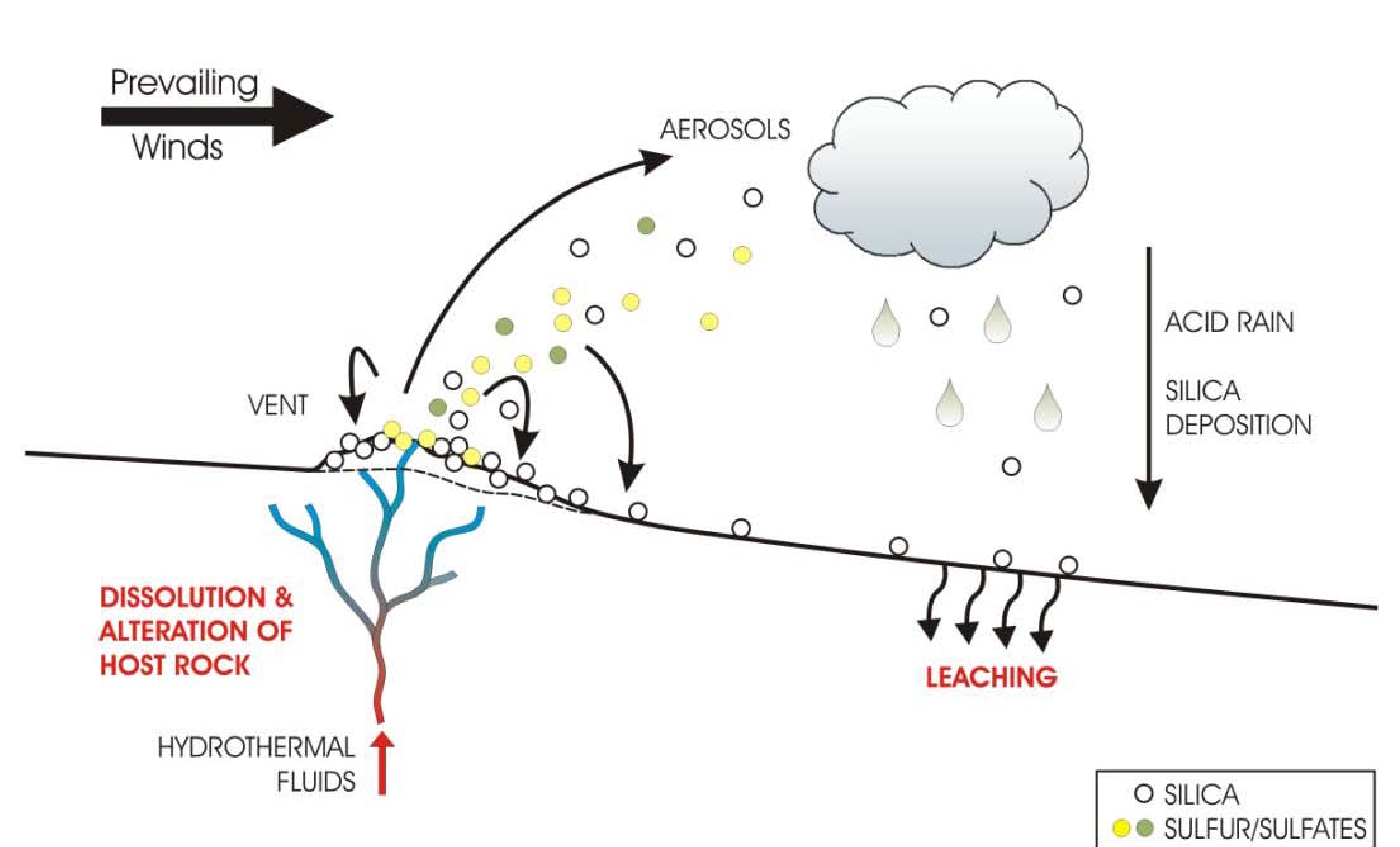


Evident at multiple spatial scales

Prevailing Winds

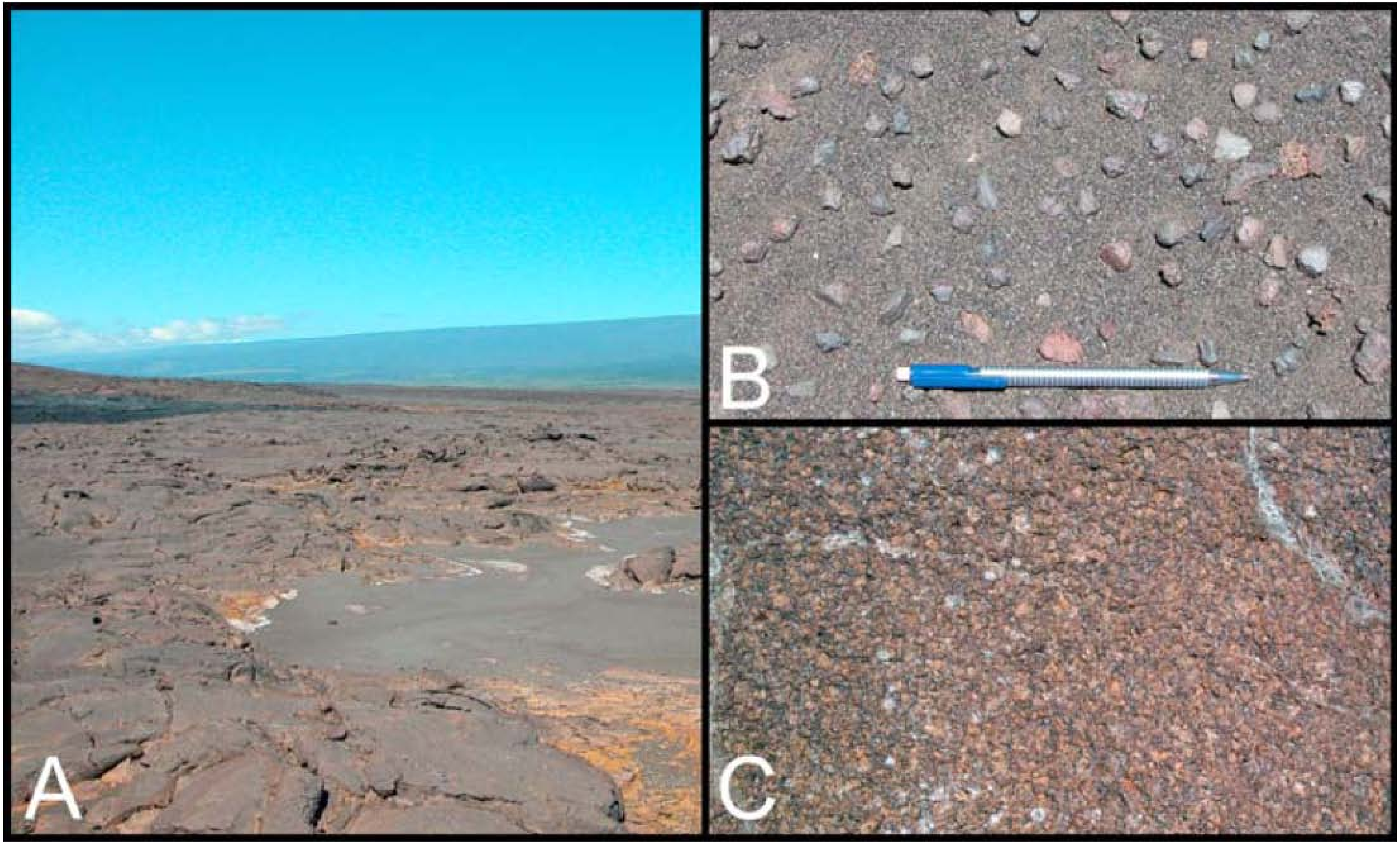
K. Seelos et al., JGR, 2010

Acidic Alteration Environment



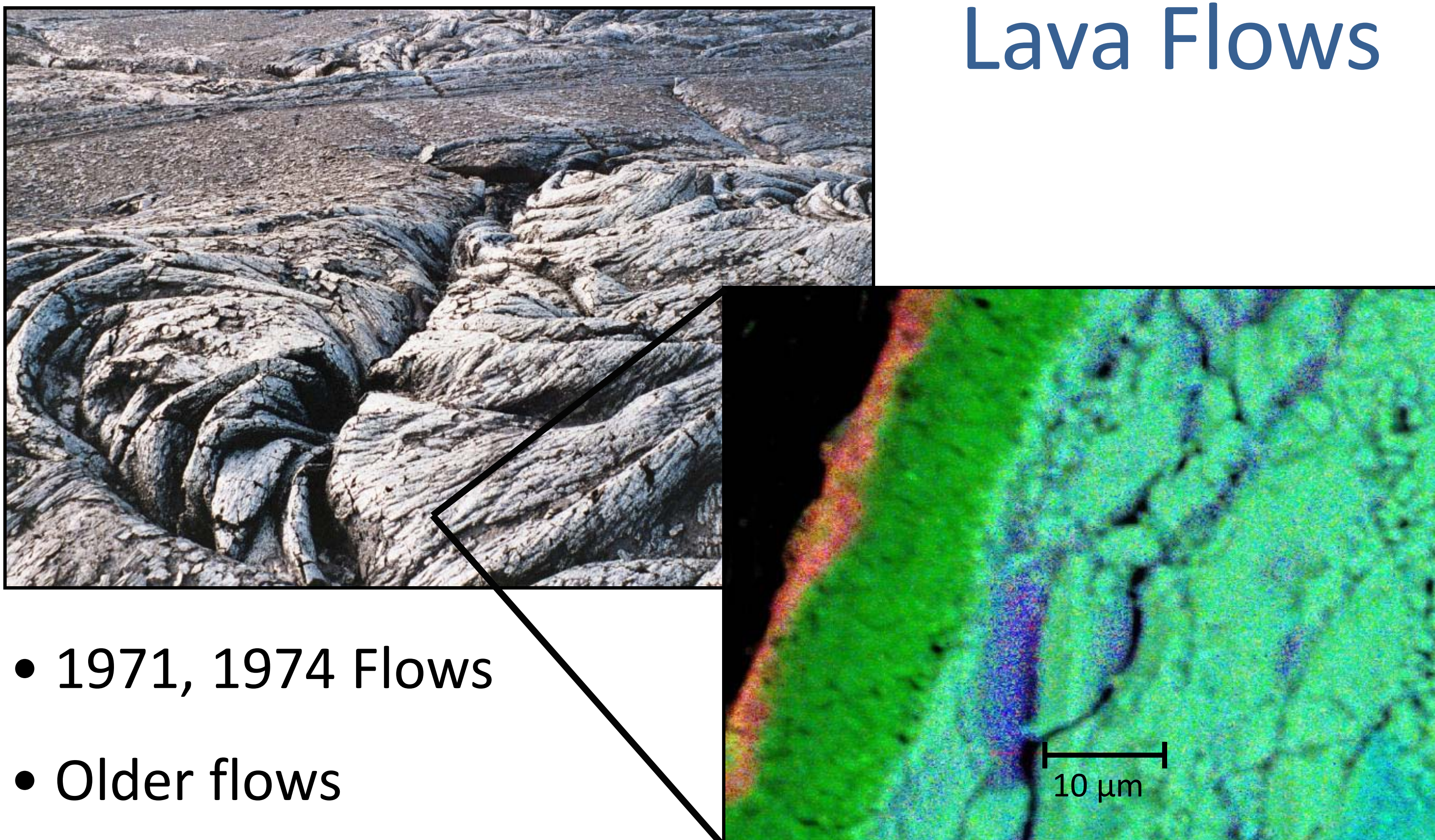
K. Seelos et al., JGR, 2010

Ka'u Desert from the Ground



K. Seelos et al., JGR, 2010

Lava Flows

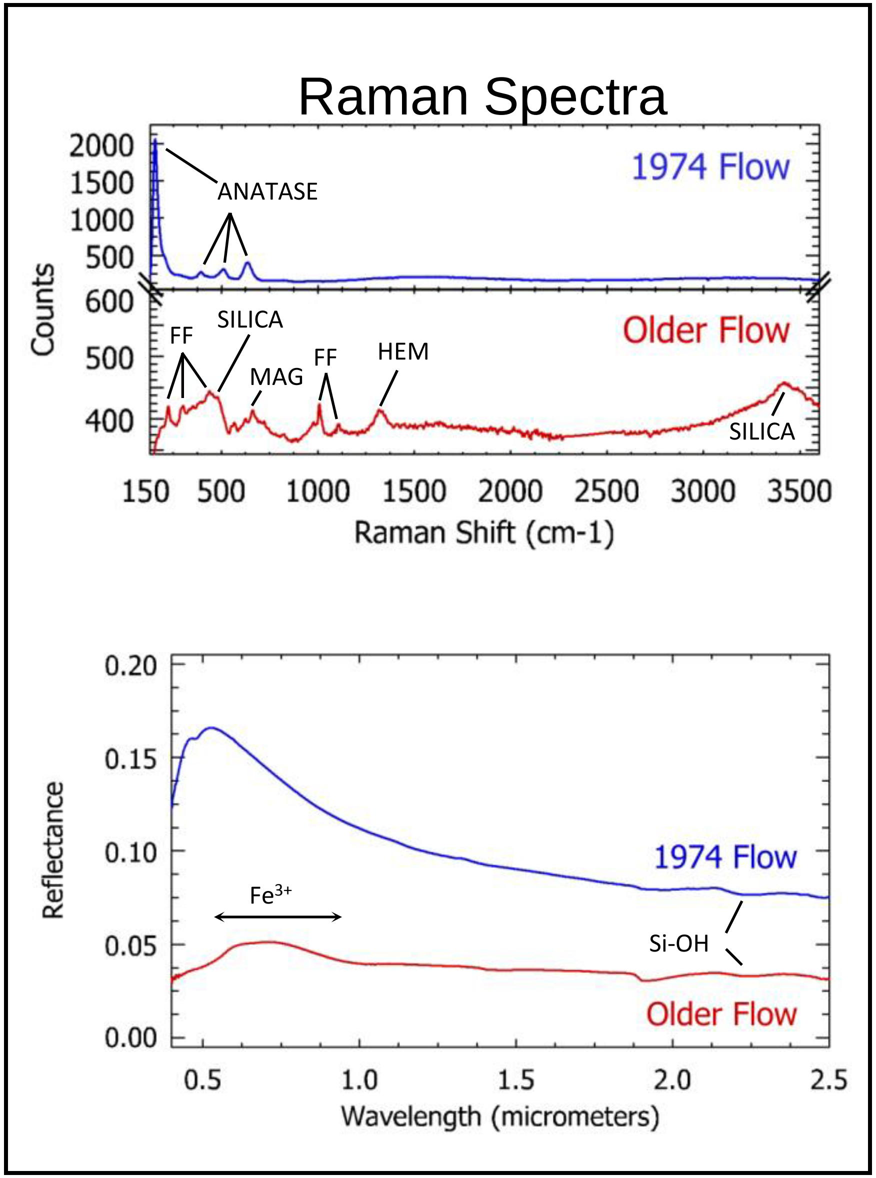


- 1971, 1974 Flows
- Older flows

X-ray image, 1974 flow cross-section
Red=Ti Green=Si Blue=Fe

K. Seelos et al., JGR, 2010

Lava Flows



- 1974 Flow

glassy with coatings of silica and TiO_2

- Older Flows

silica, hematite, fibroferrite

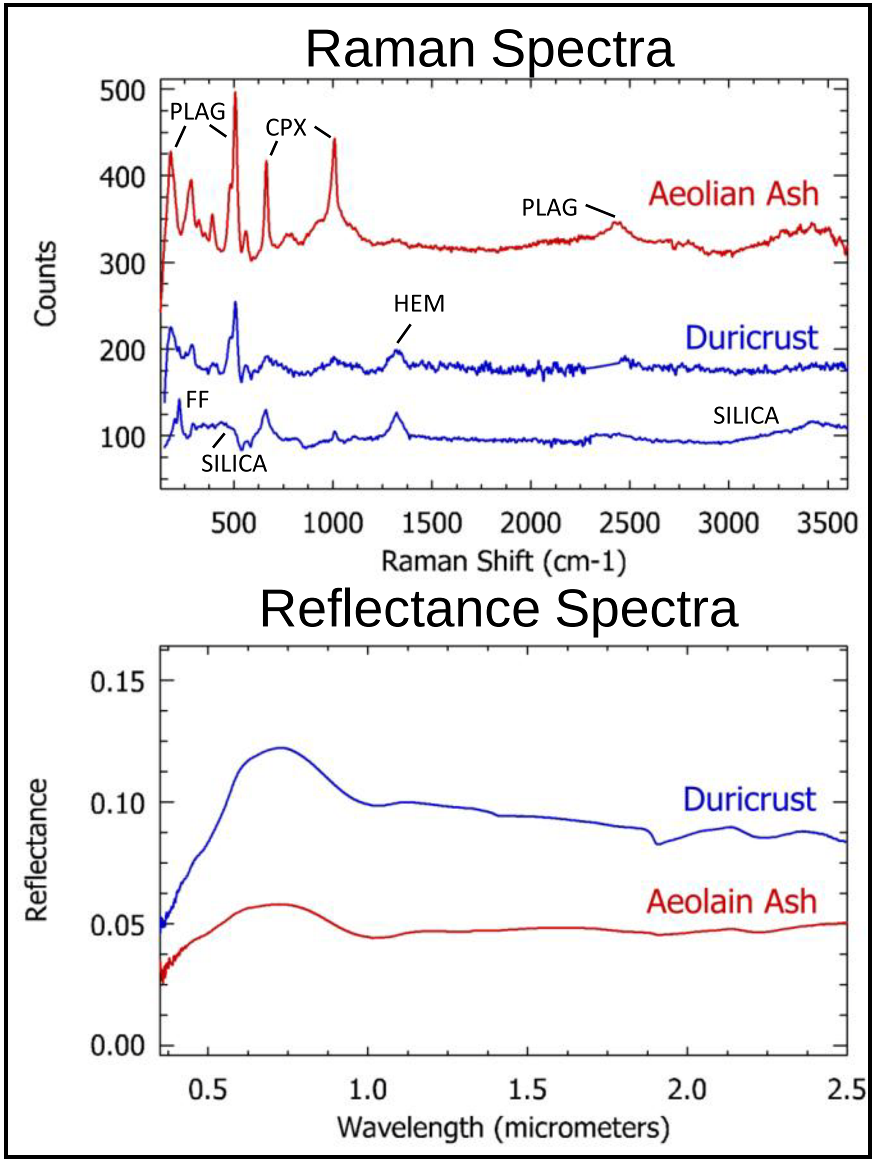
[$Fe^{3+}(SO_4)(OH)\cdot 5(H_2O)$]

also magnetite, olivine

K. Seelos et al., JGR, 2010

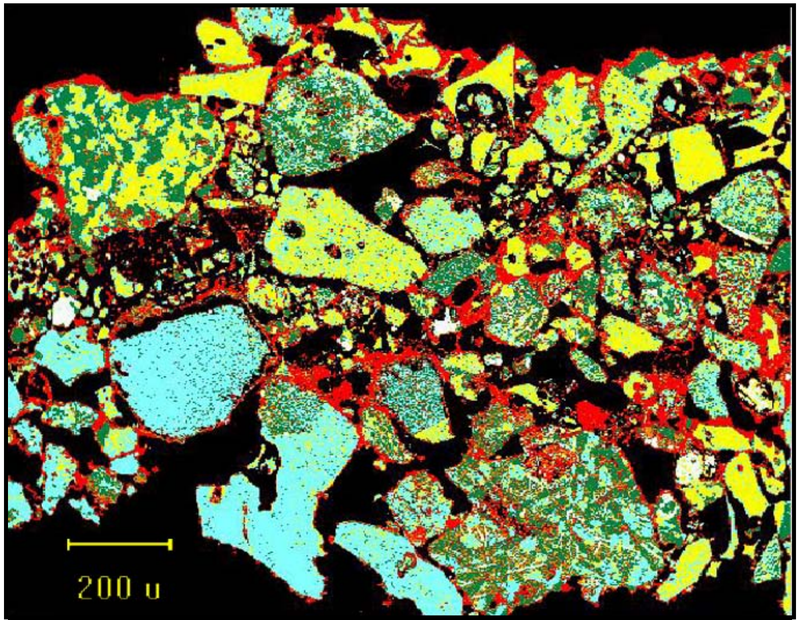
K. Seelos et al., JGR, 2010

Ash Deposits



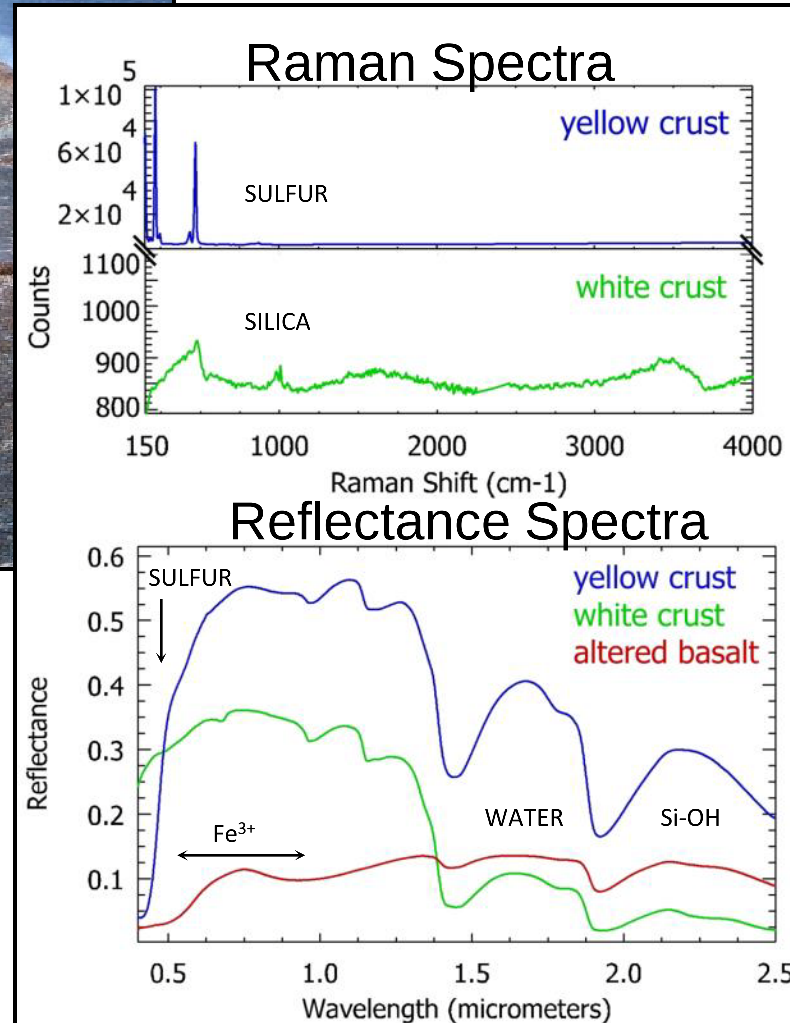
K. Seelos et al., JGR, 2010

- Loose grains: *pyroxene, plagioclase, hematite, amorphous silica*
- Crusts: *same as above + more hematite, silica, fibroferrite, and jarosite*



Backscattered electron image of ash red = silica cement

Solfataras

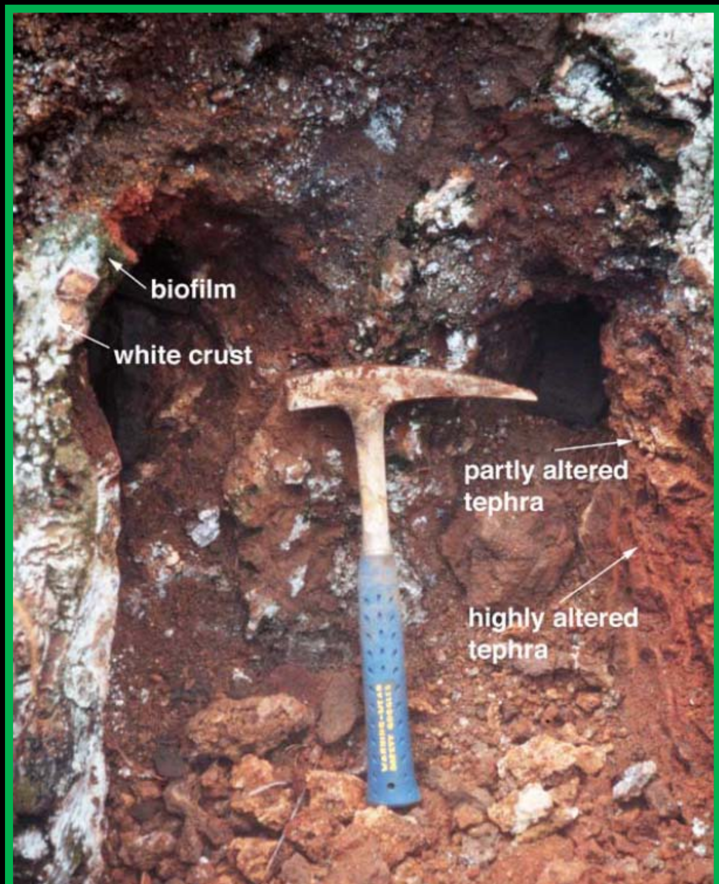


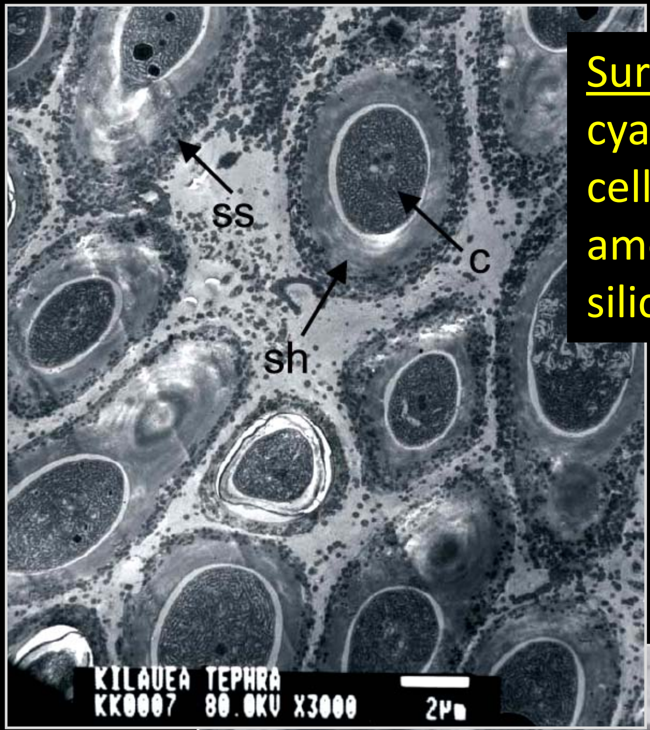
- Surface Incrustations *amorphous silica, native sulfur*
- Altered Host Rock *goethite, silica, gypsum*

K. Seelos et al., JGR, 2010

Kilauea Vents as Abodes of Life

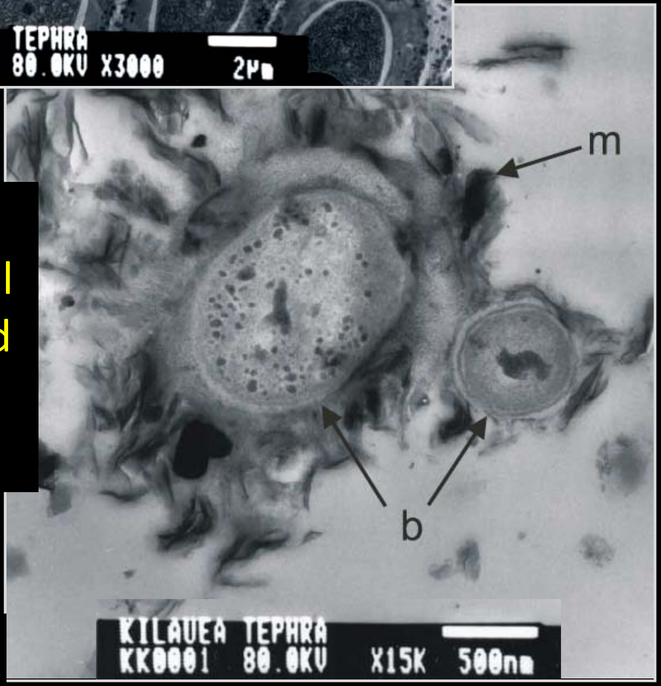
- indigenous microorganisms are ubiquitously encrusted in fine-grained inorganic phases





<u>Surface</u>: cyanobacterial cells with amorphous silica sphreules

<u>Subsurface:</u> Intact bacterial cells encrusted in amorphous Al,Fe silicate



Konhauser et al., 2002, G-cubed

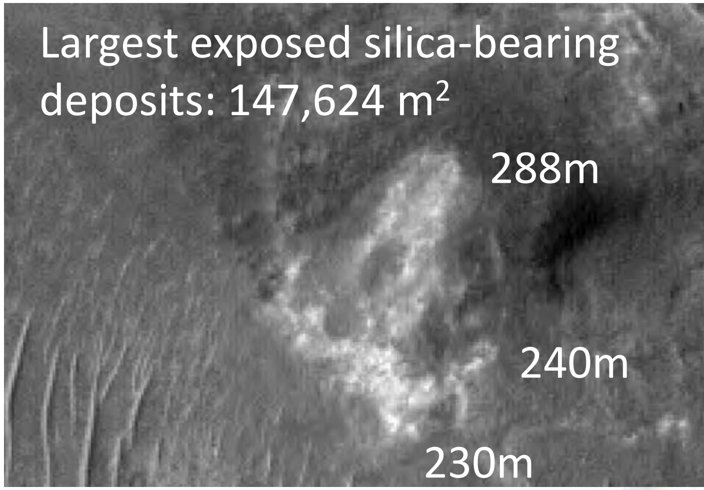
Implications for Mars?

- Spectral detection of regional silica enhancement may imply a presence of hydrothermal vents at a smaller scale → these hydrothermal vents indicate increased habitability potential.

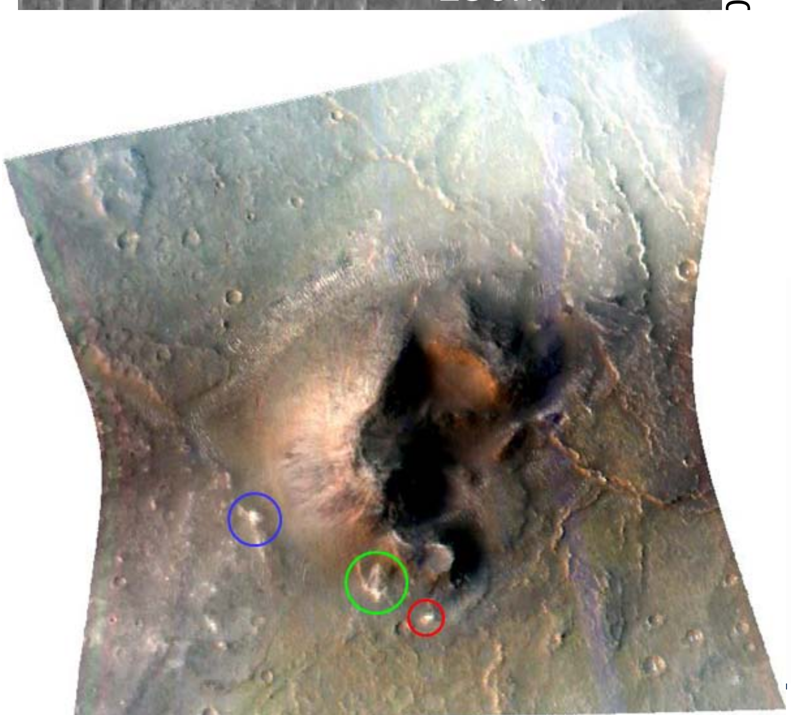
- CRISM onboard the 2005 MRO is analogous in spatial and spectral resolution to AVIRIS → detection of Ka’u Desert-like terrains will be possible.

Volcanic Hydrothermal Silica Deposits

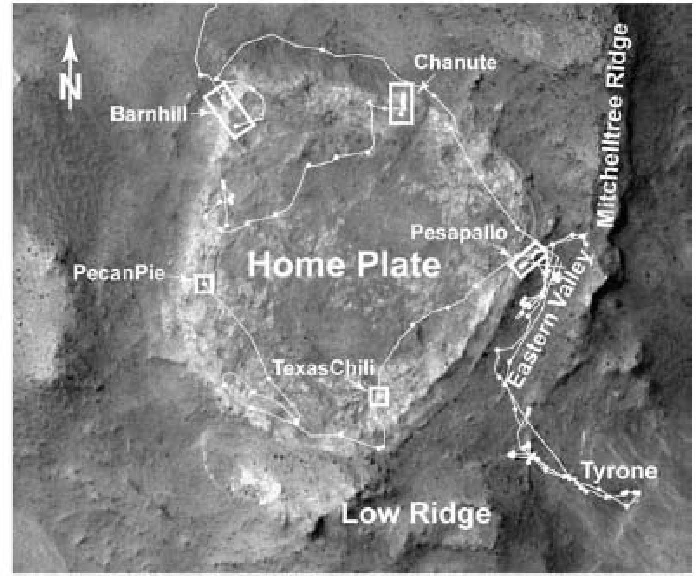
Skok et al., *Nature Geosci*, 2010

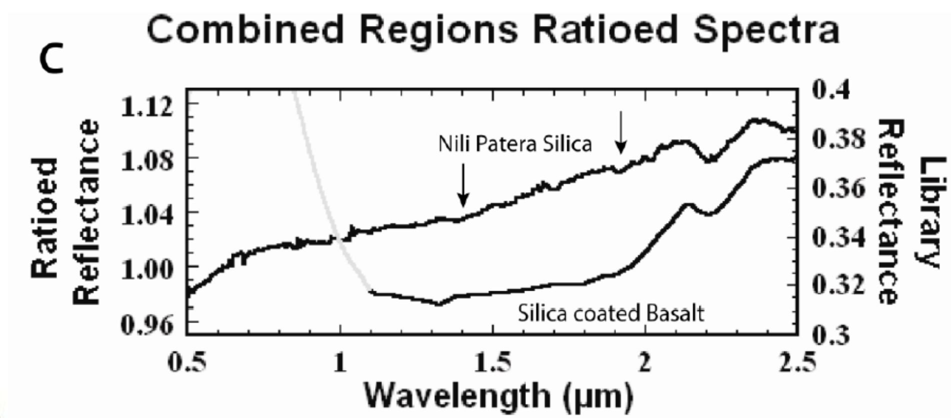


(Skok et al., *Nature Geosci*, 2010



Acid-sulfate volcanic feature, Gusev Crater *(Schmidt et al., 2009, JGR)*





Conclusions & Outstanding Questions

- Interpreting Mars orbital data benefits from "groundtruthing" studies at similar locations on Earth
- The environments of modern and ancient Mars may be similar to terrestrial environments
- Important to understand what is knowable and unknowable from planetary data
  - What are the limits of data collection abilities in the field?
- Water-rock alteration on Earth supports microbial communities. Ongoing work to characterize diversity….
  – Next frontier of research: biosignatures of microbe-rock interactions?

Metabolic opportunities and the deep biosphere

At this site of ongoing subsurface metamorphism, we find a rich geochemically constrained metabolic landscape, shown here as calculated values of Gibbs Energy for a number of metabolic niches.

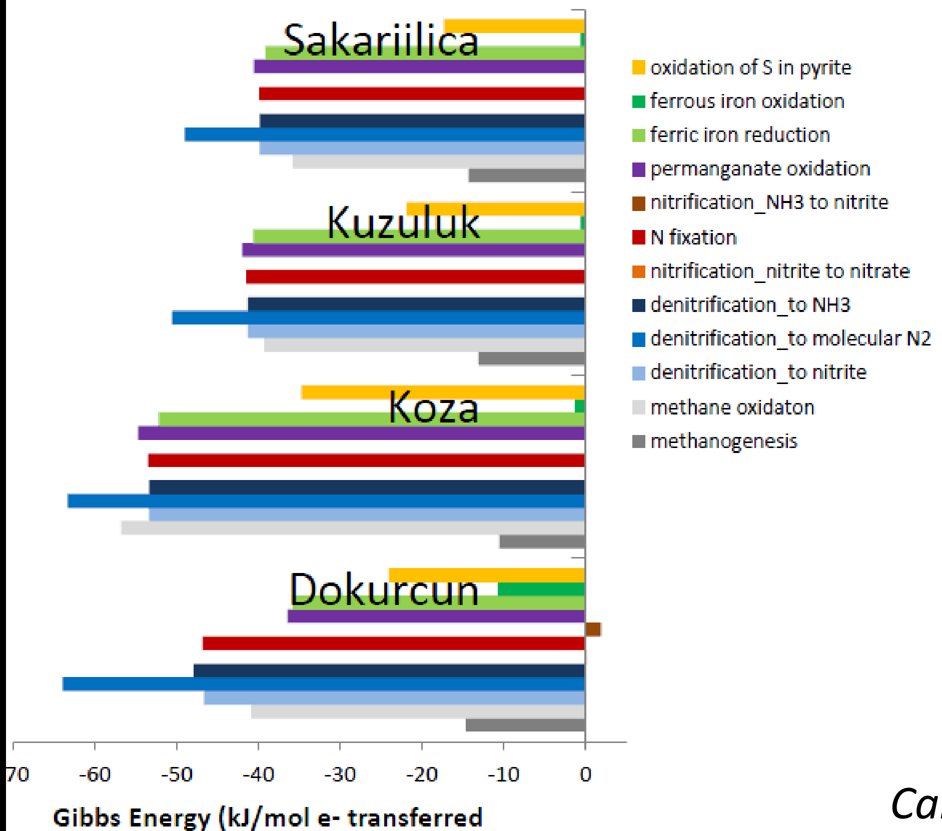


Figure 4. Values for Gibbs Energy of reaction, kJ per mole of electrons transferred in a given metabolism, are shown as colored bars coded by metabolic reaction, clustered by field site. Recall that Gibbs Energy <0 is a necessary condition of thermodynamic feasibility. As developed in Amend and Shock (2001), in vertical order from top to bottom in legend, reactions considered are:

$Pyrite + 3.5O_{2(aq)} + H_2O_{(l)} \leftrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$
$2Fe^{2+} + 0.5O_{2(aq)} + 2H^+ \leftrightarrow 2Fe^{3+} + H_2O_{(l)}$
$H_{2(aq)} + 2Fe^{3+} \leftrightarrow 2Fe^{2+} + 2H^+$
$MnO_4^- + 0.5H_{2(aq)} \leftrightarrow MnO_4^{2-} + H^+$
$NO_2^- + 0.5O_{2(aq)} \leftrightarrow NO_3^-$
$0.5N_{2(aq)} + 1.5H_{2(aq)} \leftrightarrow = NH_{3(aq)}$
$NH_{3(aq)} + 1.5O_{2(aq)} \leftrightarrow H^+ + NO_2^- + H_2O_{(l)}$
$NO_3^- + 4H_{2(aq)} + H^+ \leftrightarrow NH_{3(aq)} + 3H_2O_{(l)}$
$NO_3^- + 2.5H_{2(aq)} + H^+ \leftrightarrow 0.5N_{2(aq)} + 3H_2O_{(l)}$
$NO_3^- + H_{2(aq)} \leftrightarrow NO_2^- + H_2O_{(l)}$
$CH_{4(aq)} + 2O_{2(aq)} \leftrightarrow CO_{2(aq)} + 2H_2O_{(l)}$
$CO_{2(aq)} + 4H_{2(aq)} \leftrightarrow CH_{4(aq)} + 2H_2O_{(l)}$

Cardace et al., 2010, AGU