Mineral signatures of glacial environments and implications for past climates on Mars

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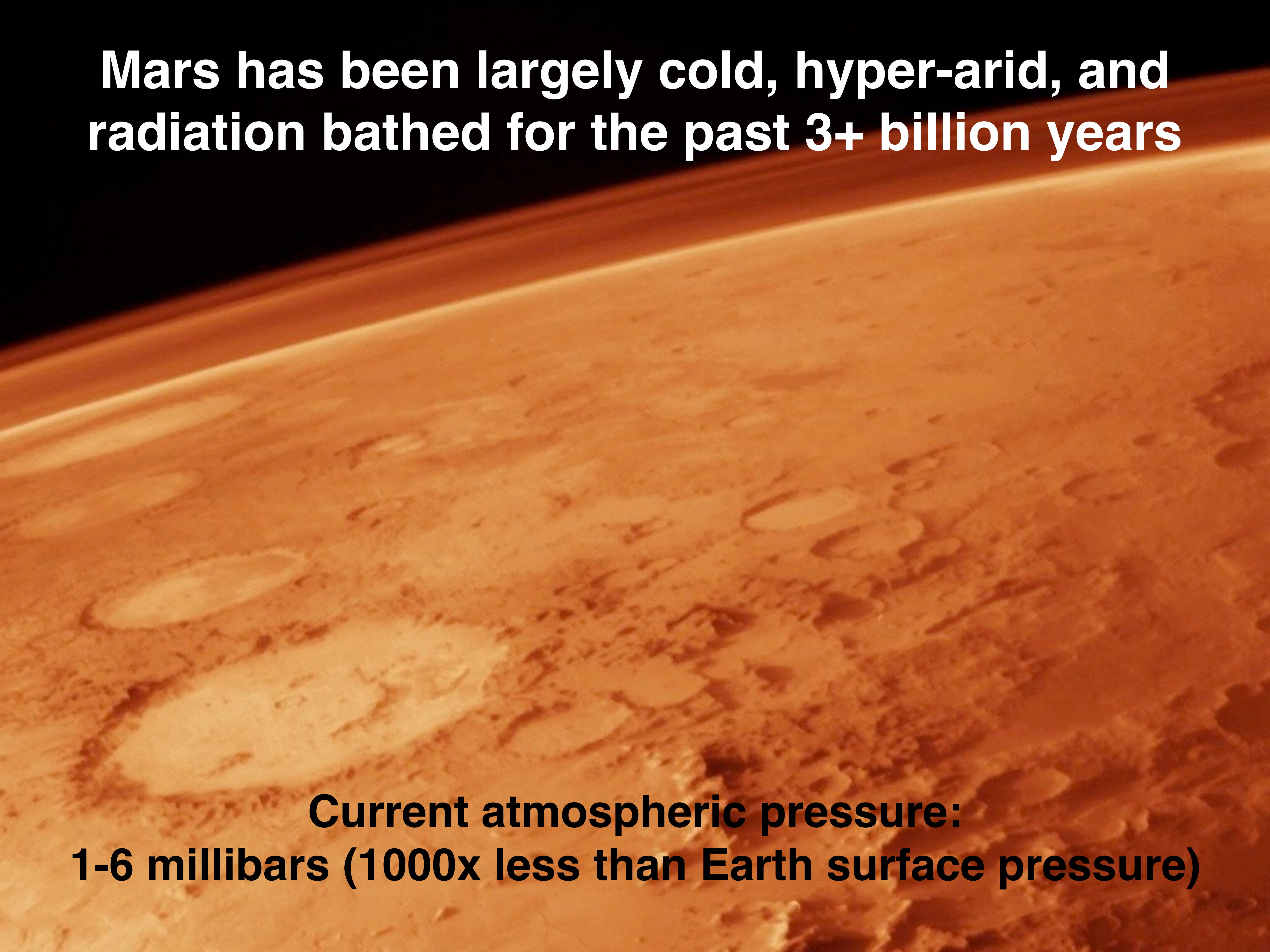
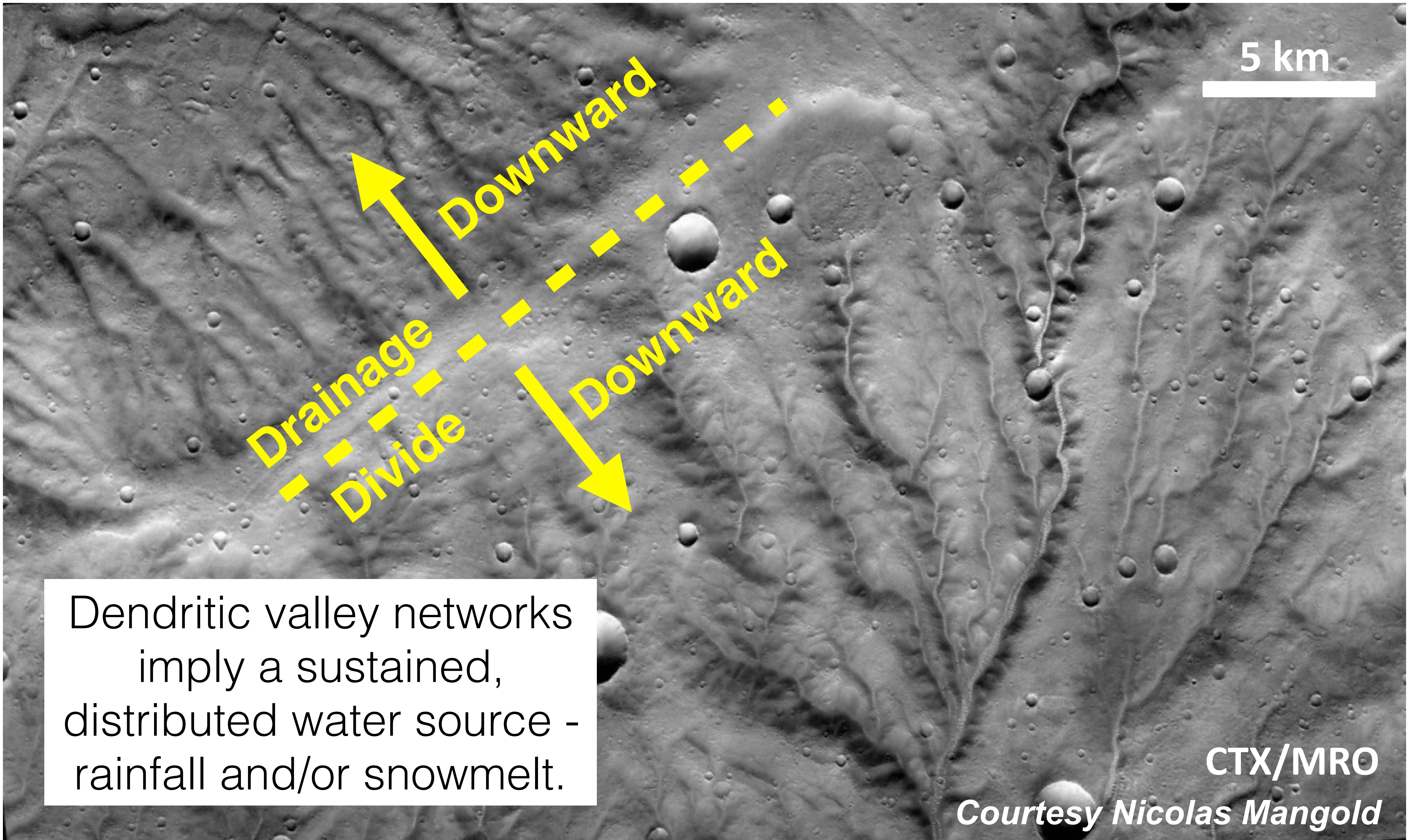
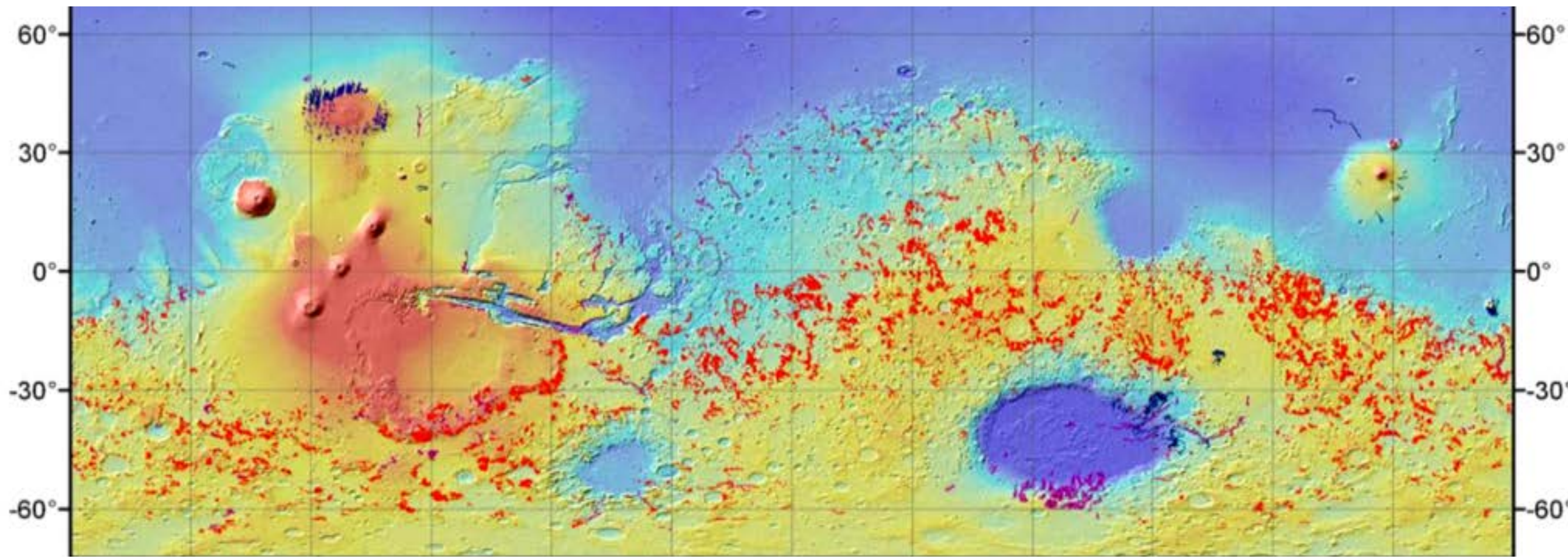

Mars has been largely cold, hyper-arid, and radiation bathed for the past 3+ billion years
Current atmospheric pressure:
1-6 millibars (1000x less than Earth surface pressure)

There is abundant evidence from landforms for a previously more temperate climate on Mars



Crater densities suggest that the valleys date consistently from 3.4-3.8 billion years ago



Red lines = Valley networks

Di Achille and Hynek (2010)

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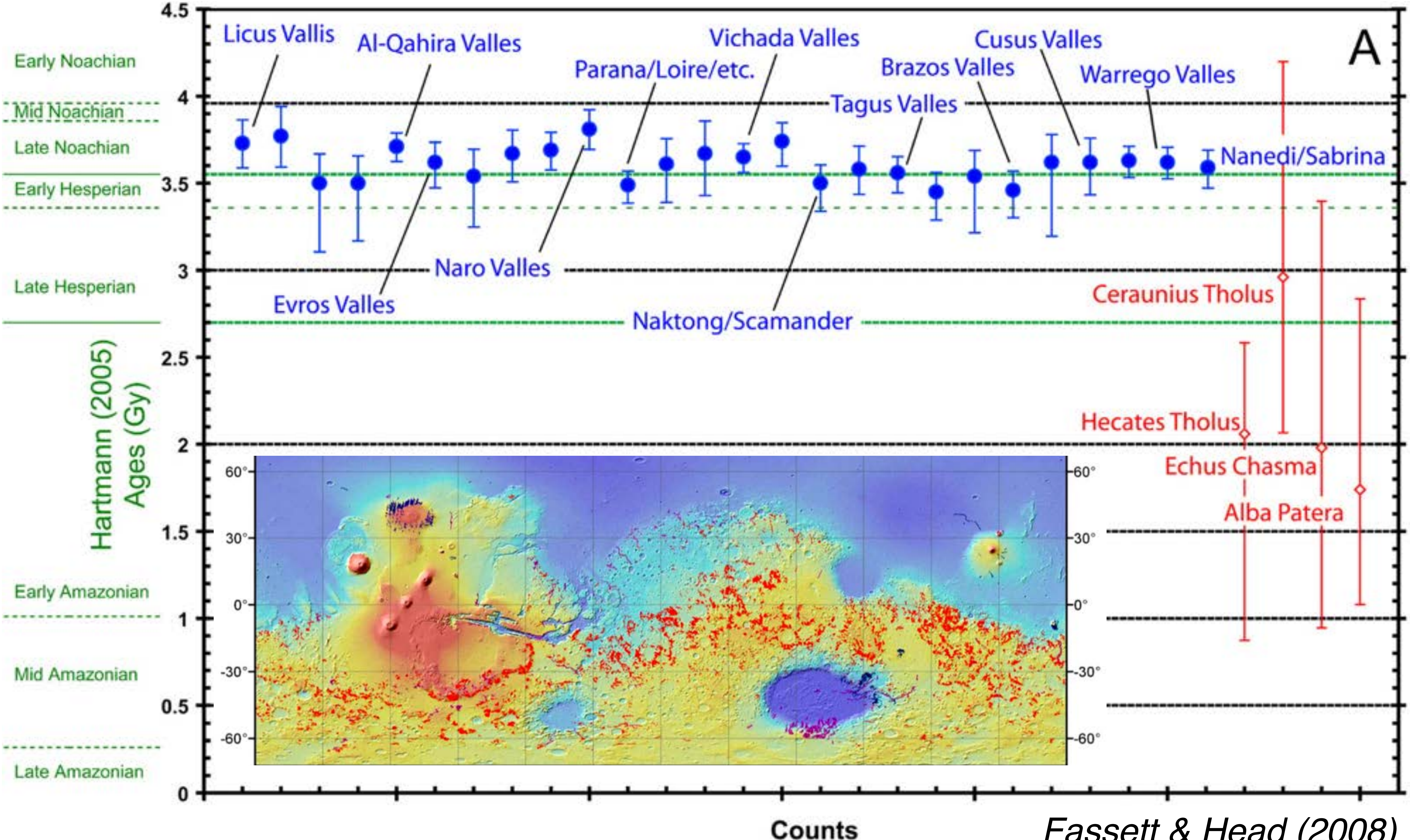
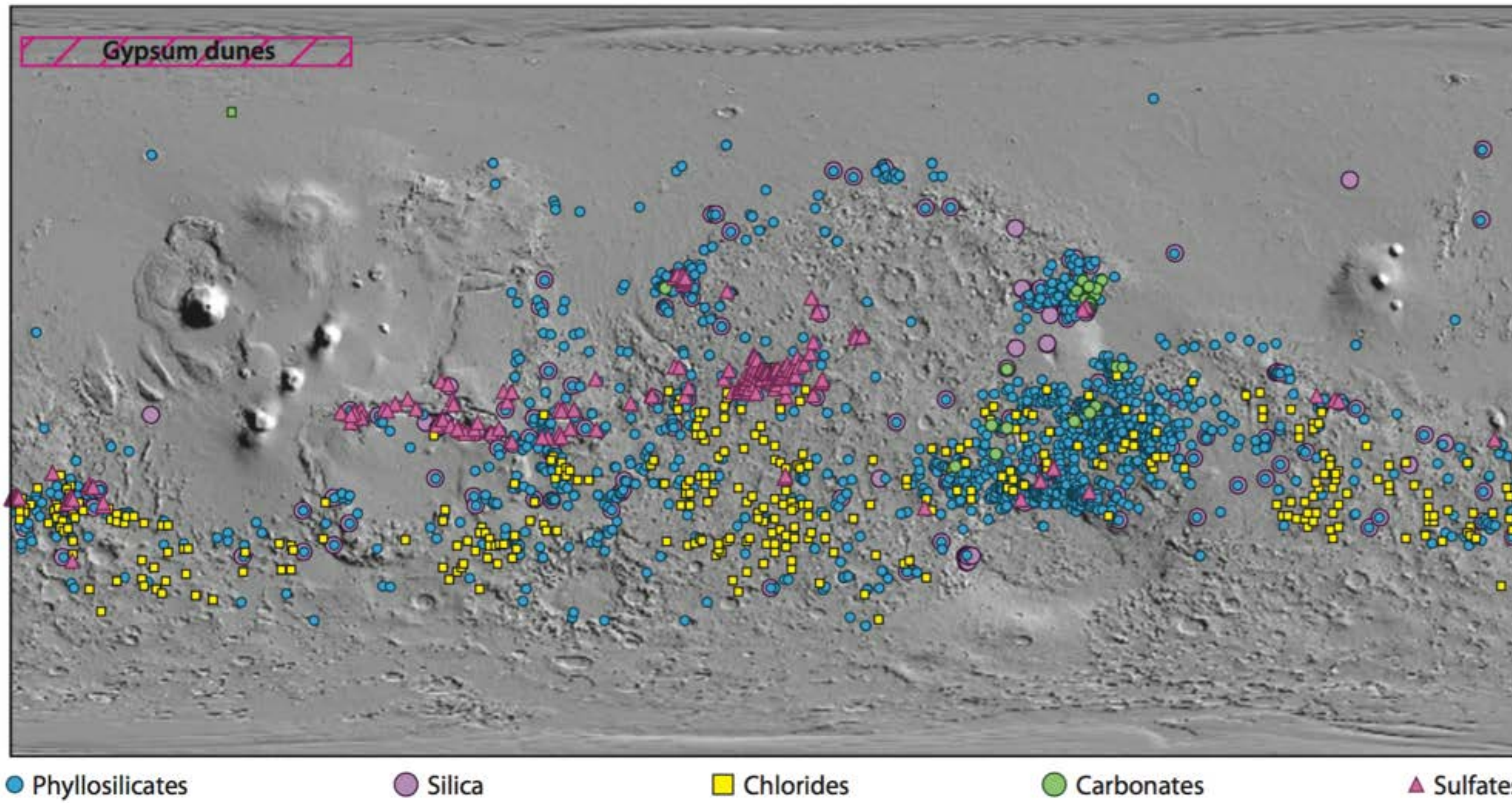


Fassett & Head (2008)

Surfaces from this period also exhibit diverse minerals formed via sustained contact with water

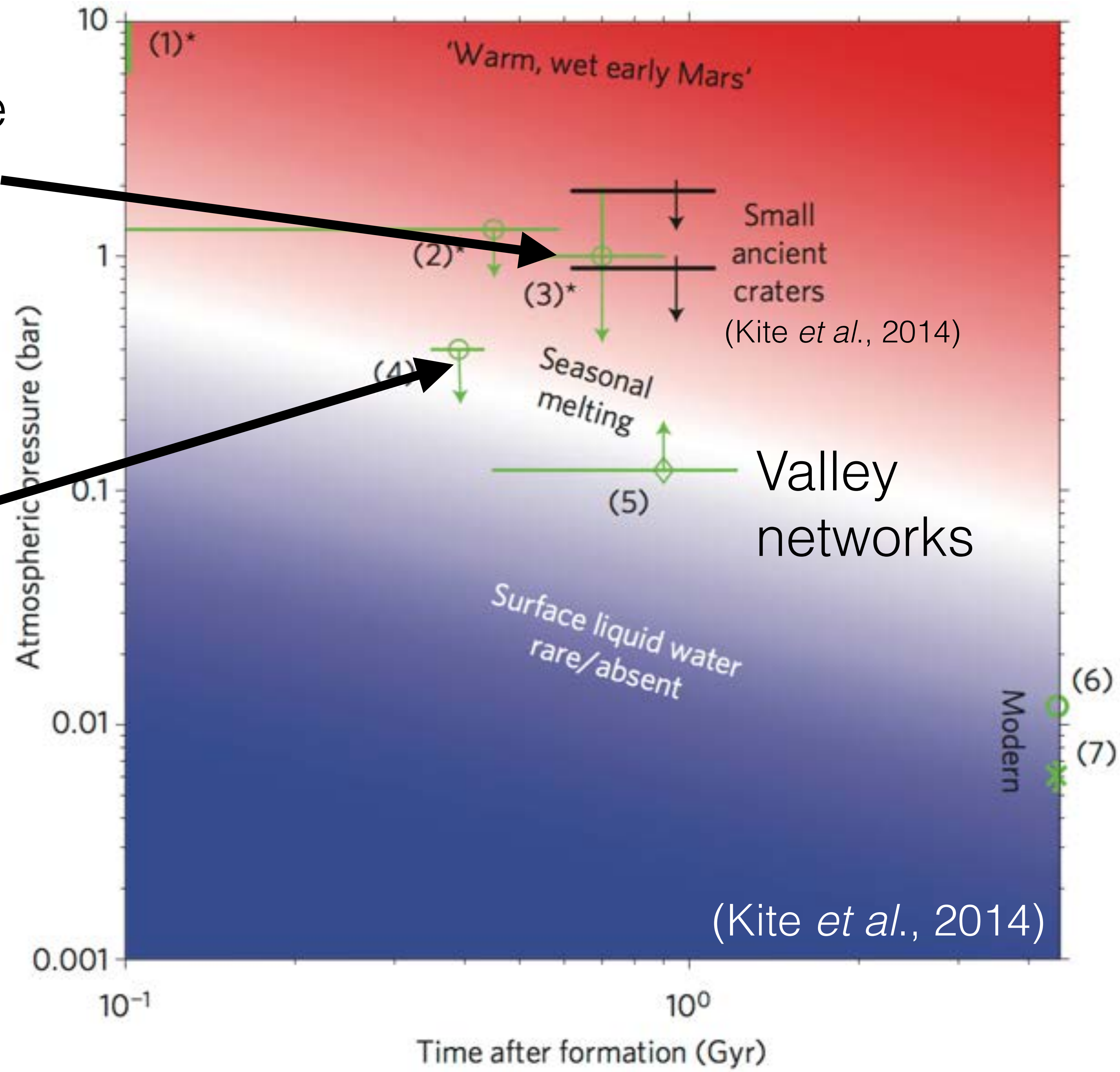


Ehlmann and Edwards (2014)

Measurements and models suggest atmospheric pressures >100's mbar and probably <1 bar

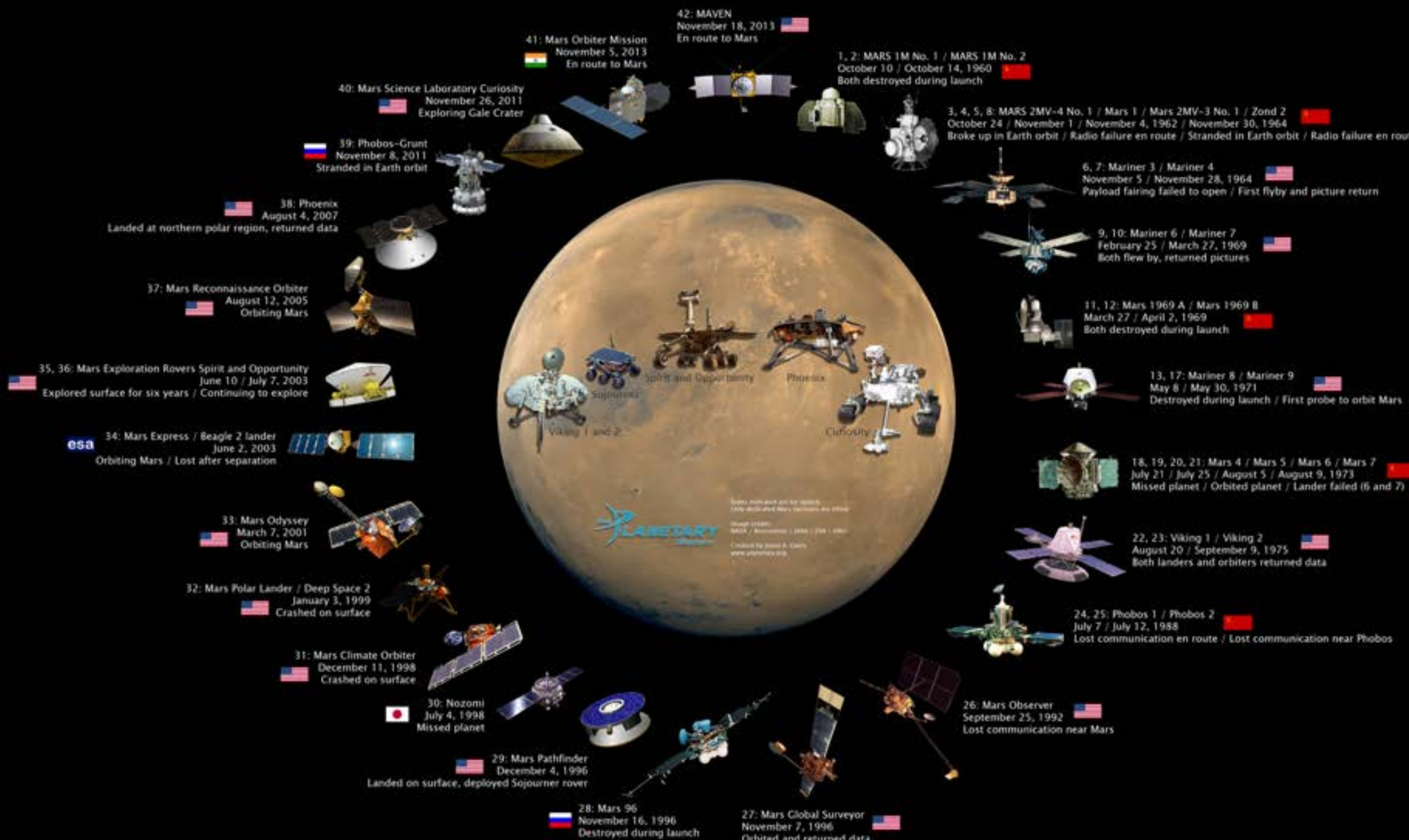
Estimation of CO2 pressure from carbonate deposits
(Hu *et al.*, 2015)

Paleobarometers from isotopes (D/H, Ar36, etc.)
(*e.g.*, Webster *et al.*, 2013)



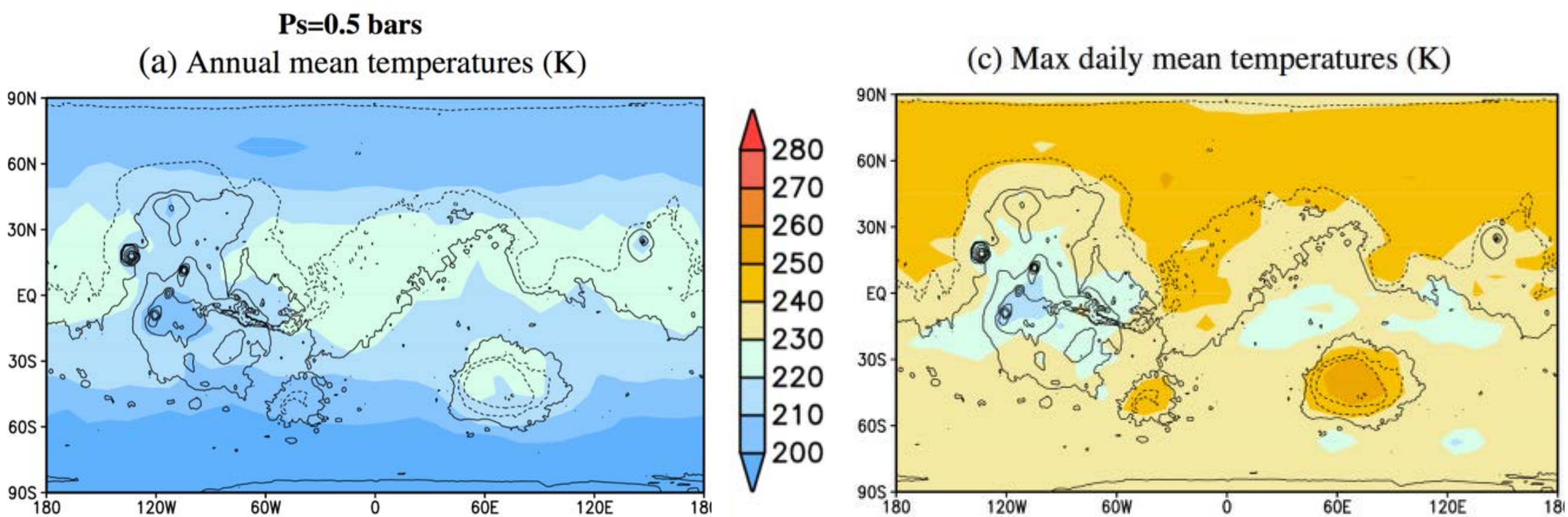

Mars now...
Mars 4 billion years ago -
a habitable world?
Mars was Earth-like at the time when life was
first starting on Earth …but we don’t have a
good record on Earth from this time period!

Mars Exploration Family Portrait



HOWEVER…

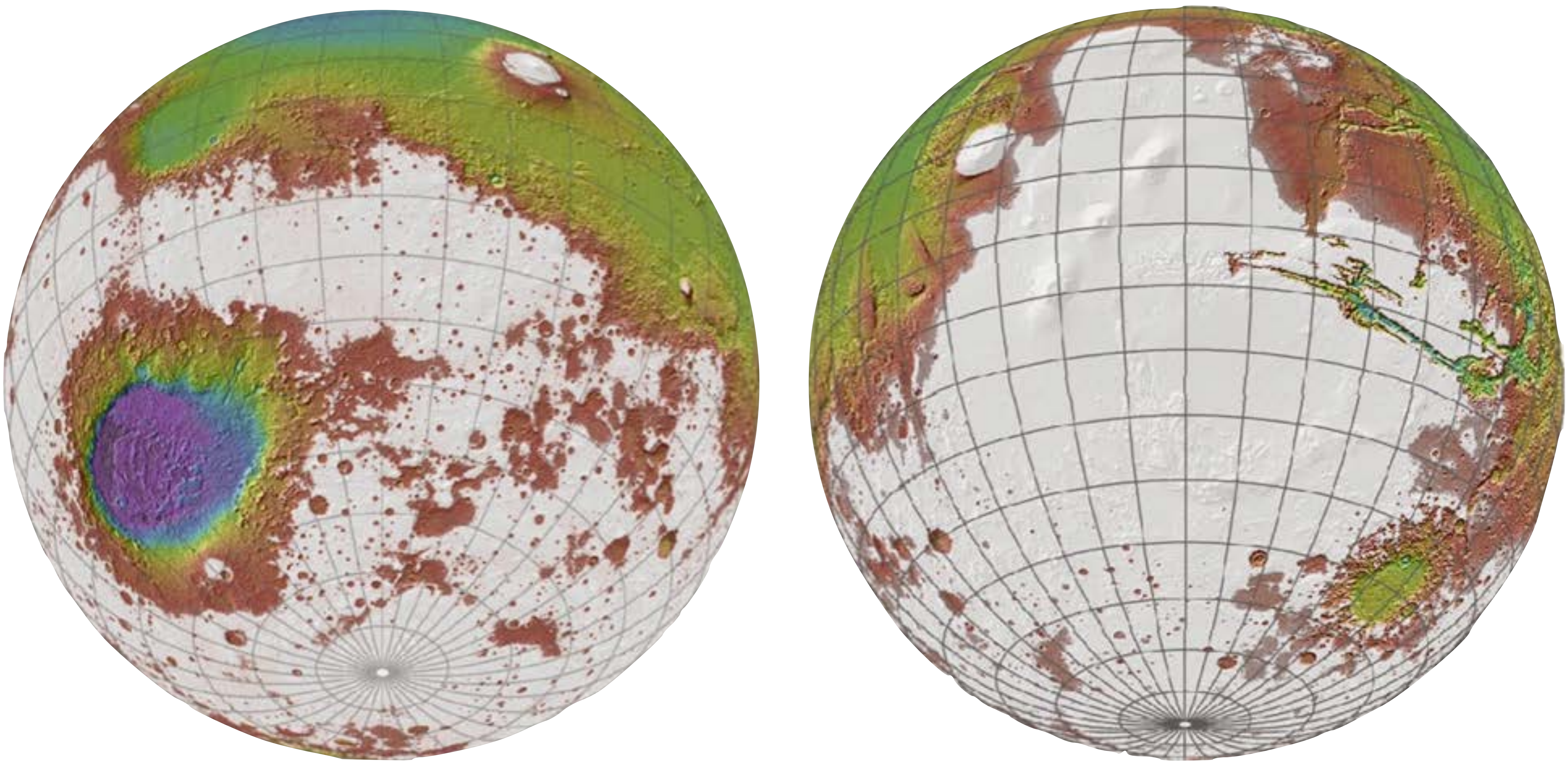
Climate models are unable to produce sustained surface temperatures on ancient Mars above 0^{o}C



Forget et al. (2013)

Was the early climate cold and only transiently wet?

In a cold climate, the topographic dichotomy may trap water in ice sheets in the highlands

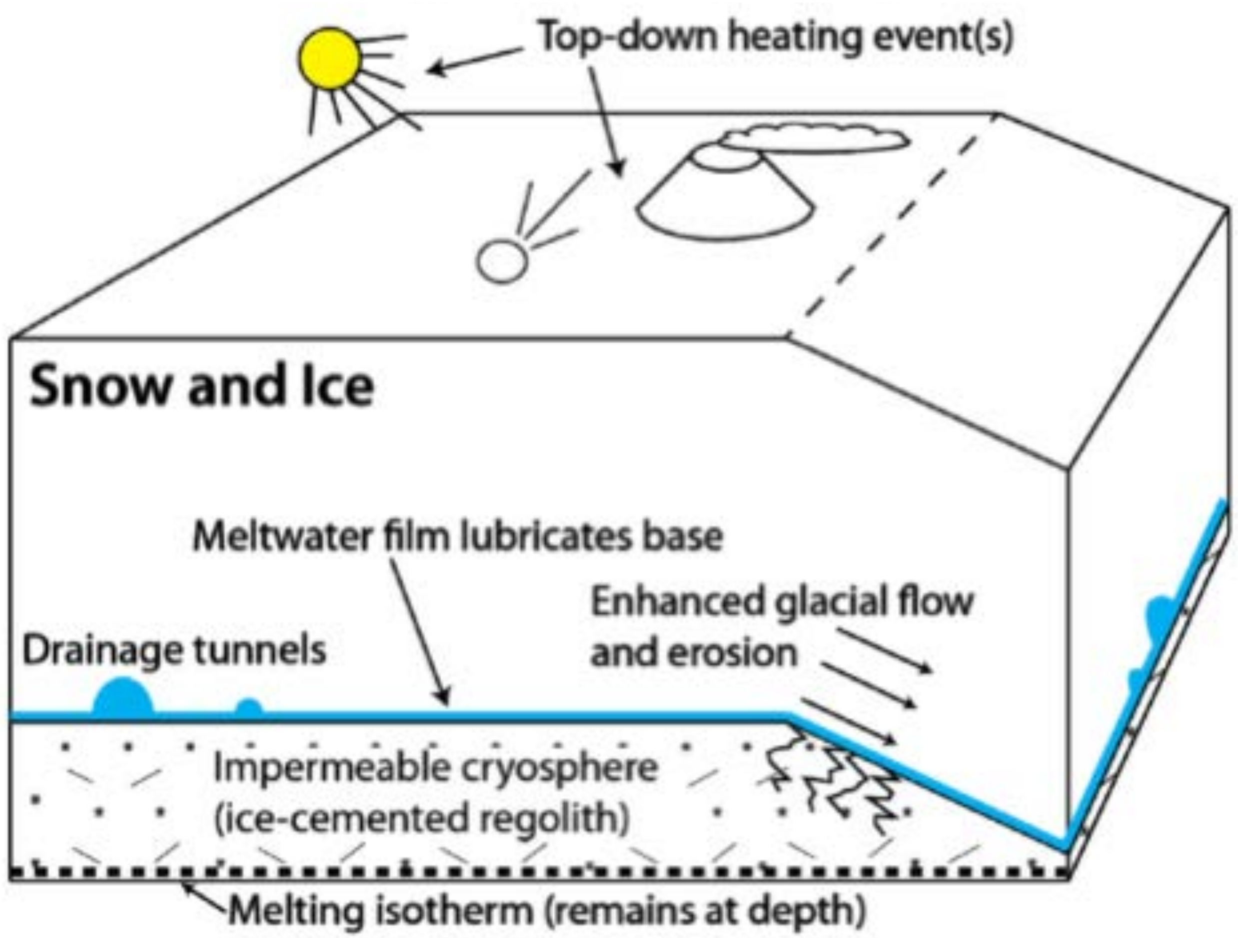


Known as the “Late Noachian icy highlands” model, applies for pressures >100’s mbar

Wordsworth *et al*. (2013)
Fastook & Head (2014)
Kress & Head (2015)

The ice sheet would have been largely frozen to the bed, with only localized melting and erosion

Limited geothermal heat flux on Mars would have inhibited basal melting (Cassanelli *et al*., 2015)



Melt largely as top-down melting, no prolonged liquid water (Wordsworth *et al*., 2013)

The late Noachian icy highlands model is highly controversial with many open questions

- Is the icy highlands end member truly representative of the entire time period?
- If so, what drives transient warming events?
- Are these warming events long enough to create the observed non-glacial hydrologic features?
- Are the observed possible glacial morphologies Noachian in age, or related to later glaciations?

- **<u>This study</u>: Is the *mineralogy* of ancient Mars consistent with weathering in a perennially cold climate?**

We would expect similar cold-climate weathering mechanisms on a cold and icy Noachian Mars as on Earth

Alpine and arctic soils weathered by snow melt are dominated by poorly-crystalline phases

- In mature temperate soils with slow to moderate weathering rates, crystalline clay minerals dominate (Singer, 1980)
- But very rapid leaching, as during seasonal melt, favors the formation of poorly crystalline phases (Ziegler et al., 2003)

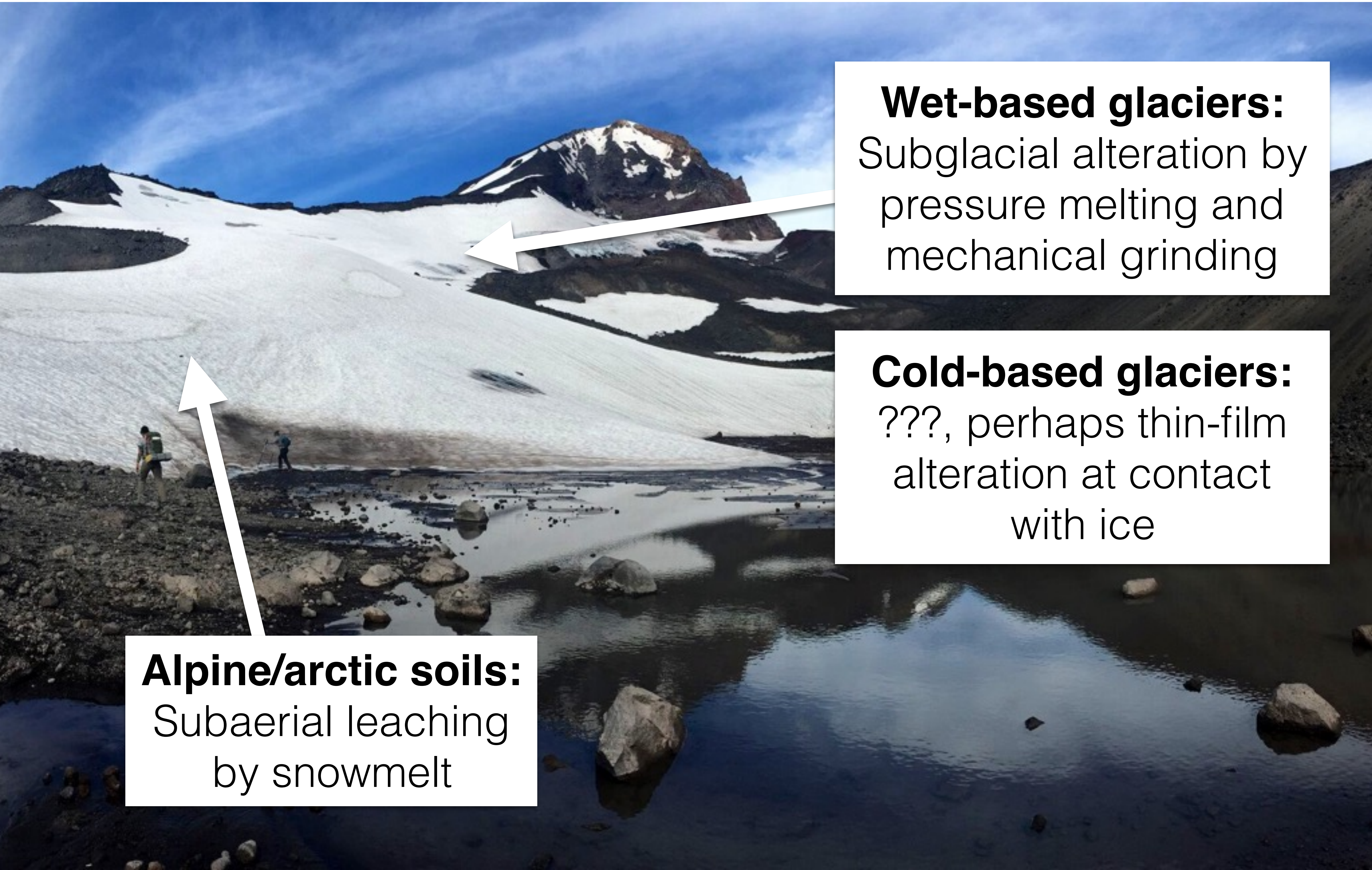
allophane-dominated soils

snow line

smectite-dominated soils

Alexander et al. (1993)
Tsai et al. (2010)

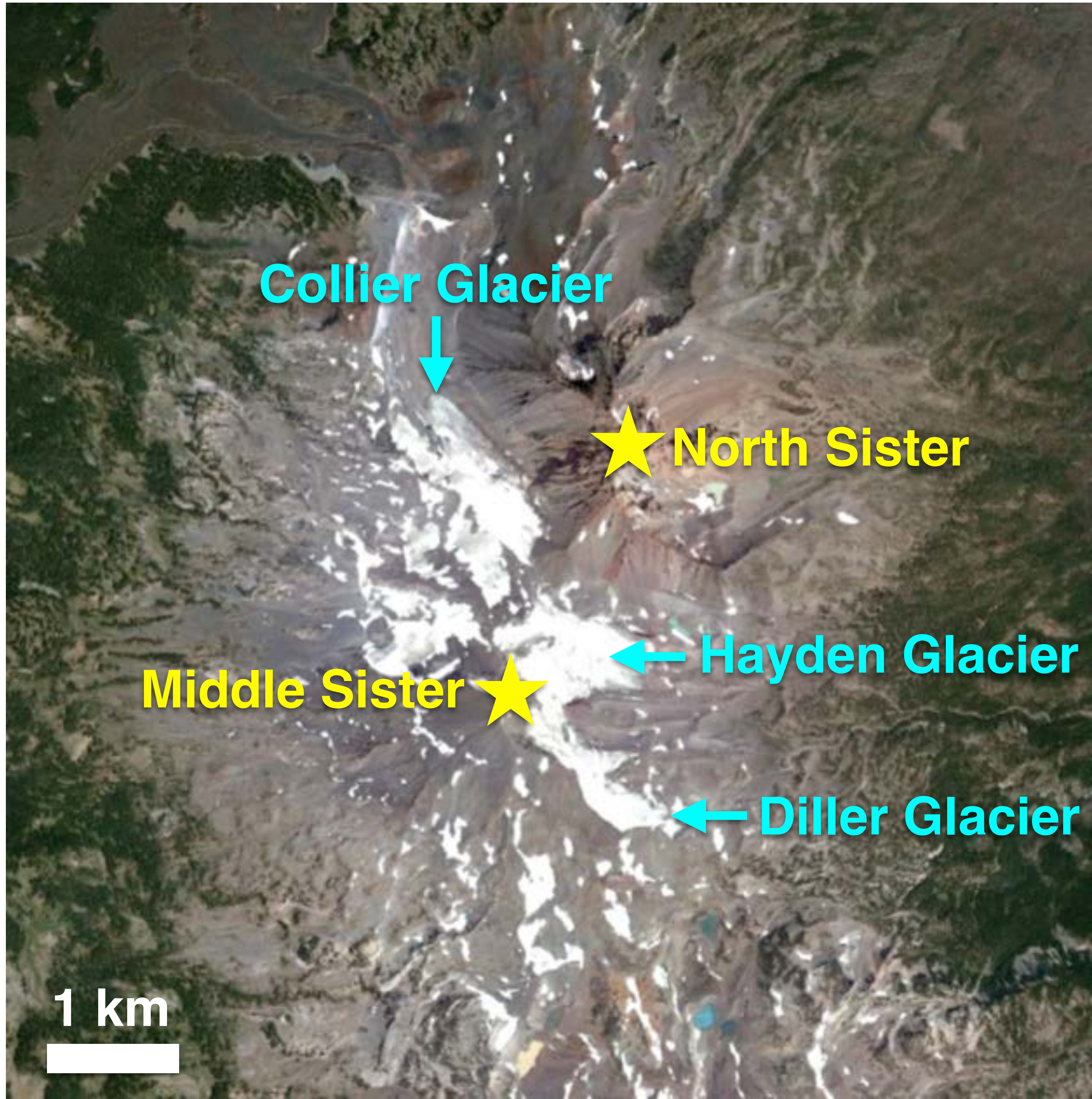
We would expect similar cold-climate weathering mechanisms on a cold and icy Noachian Mars as on Earth



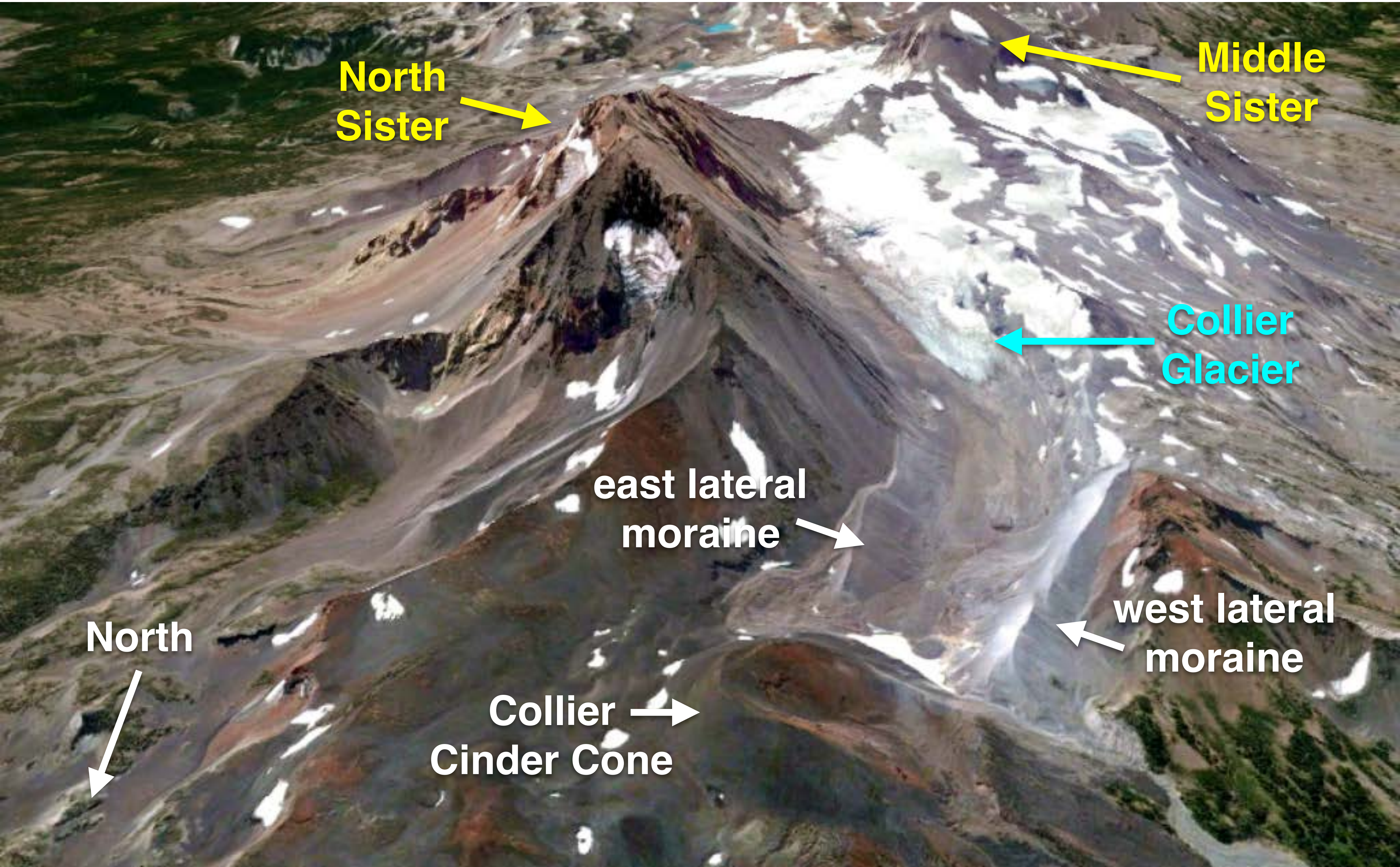
Little is known about the mineralogy of glacial weathering, and even less about glacial weathering on mafic terrains

- Most studies have focused on water chemistry - not solid phases (*Sharp et al. 1995; Tranter et al. 2002; Anderson 2000)*
- Without a systematic study, we do not have enough information to search for glacially weathered terrains on the surface of Mars.
- **<u>This study</u>: What is the mineralogy of glacial weathering?**

Field site: Three Sisters volcanic complex, Cascade Range, Central Oregon



Collier Glacier is a classic U-shaped valley with large lateral moraines



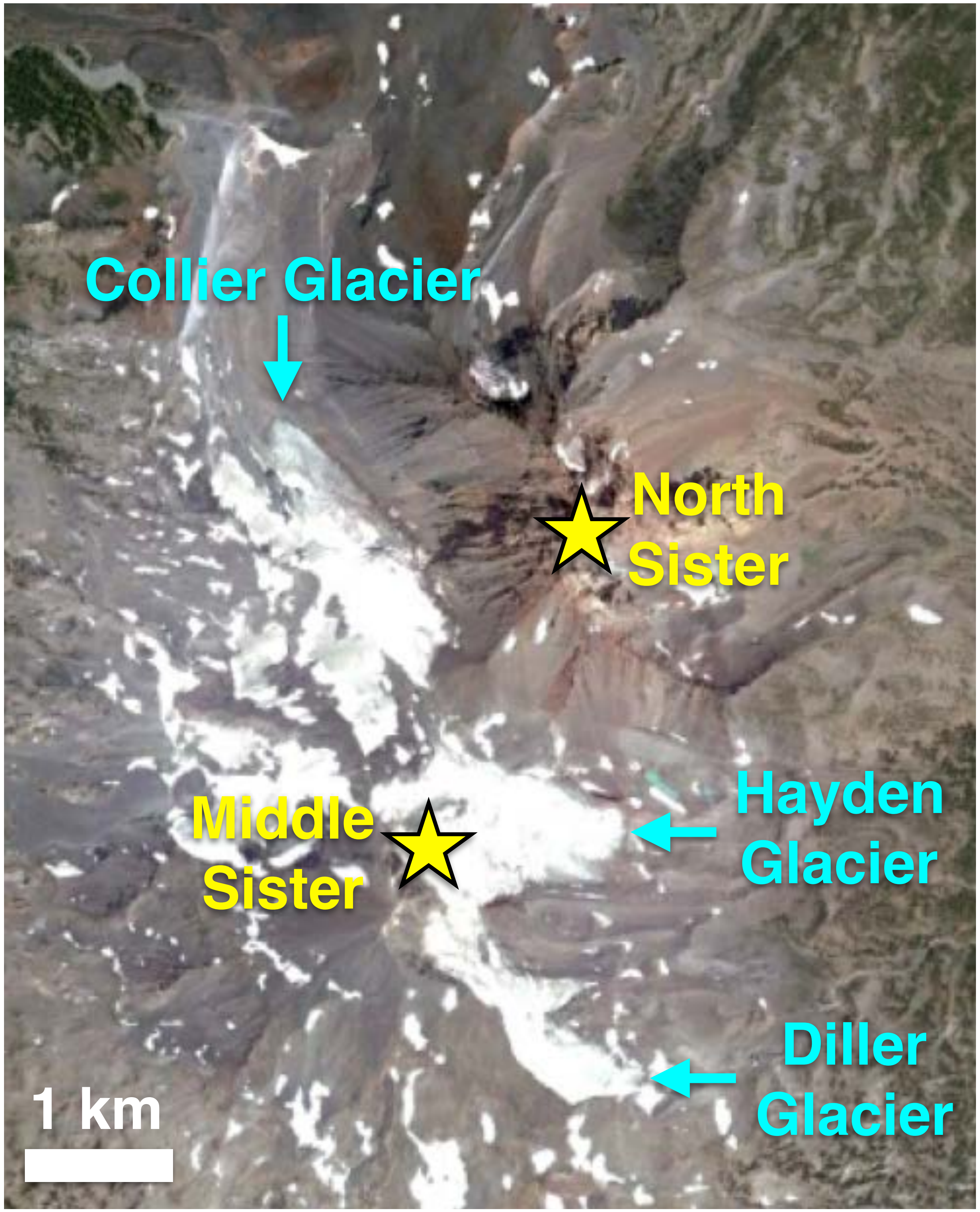
Site rationale: These glaciers have retreated over 1 km in the past 100 years due to climate change

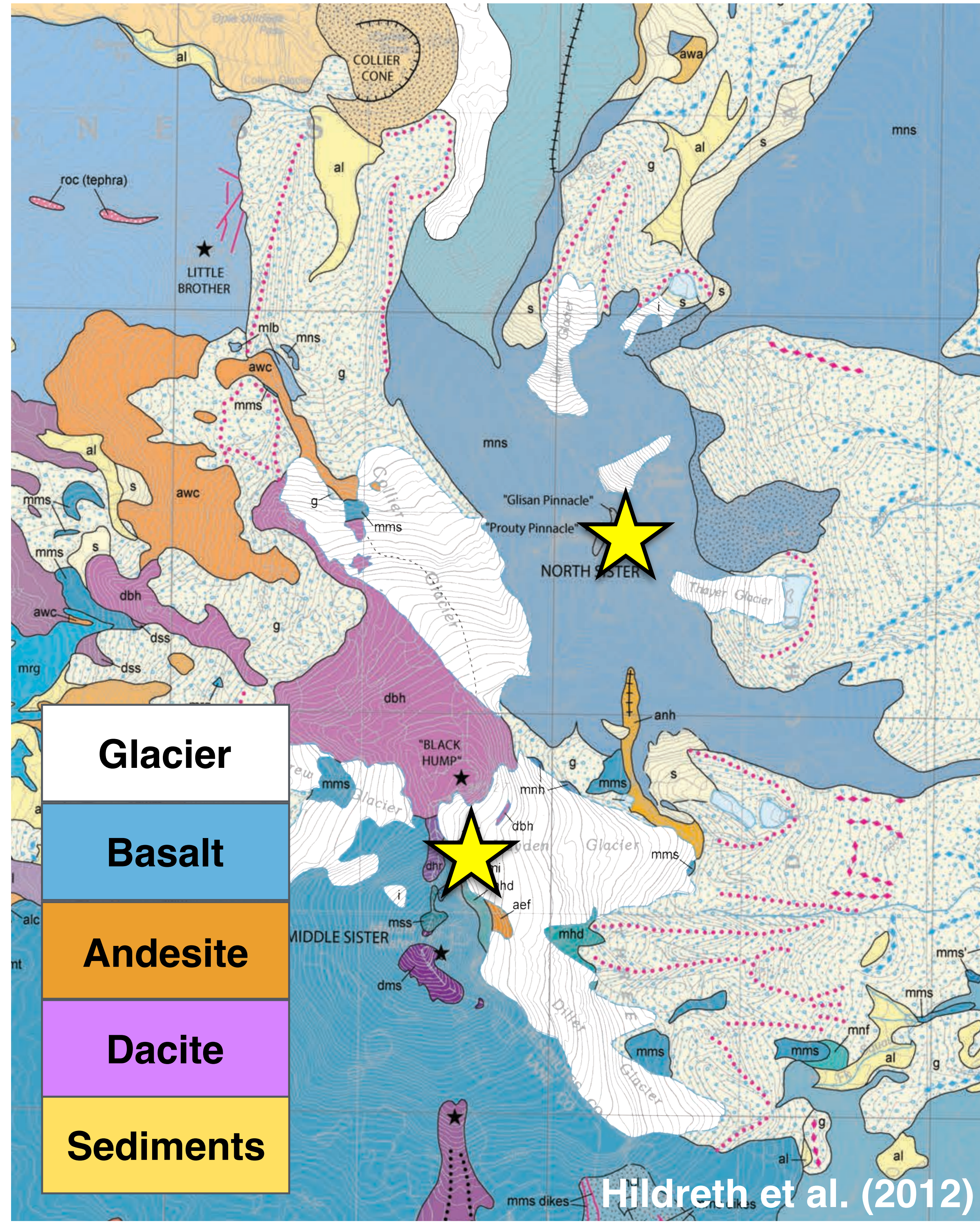
2011 Jim O'Connor

1914 EF Martin


8/7/2016

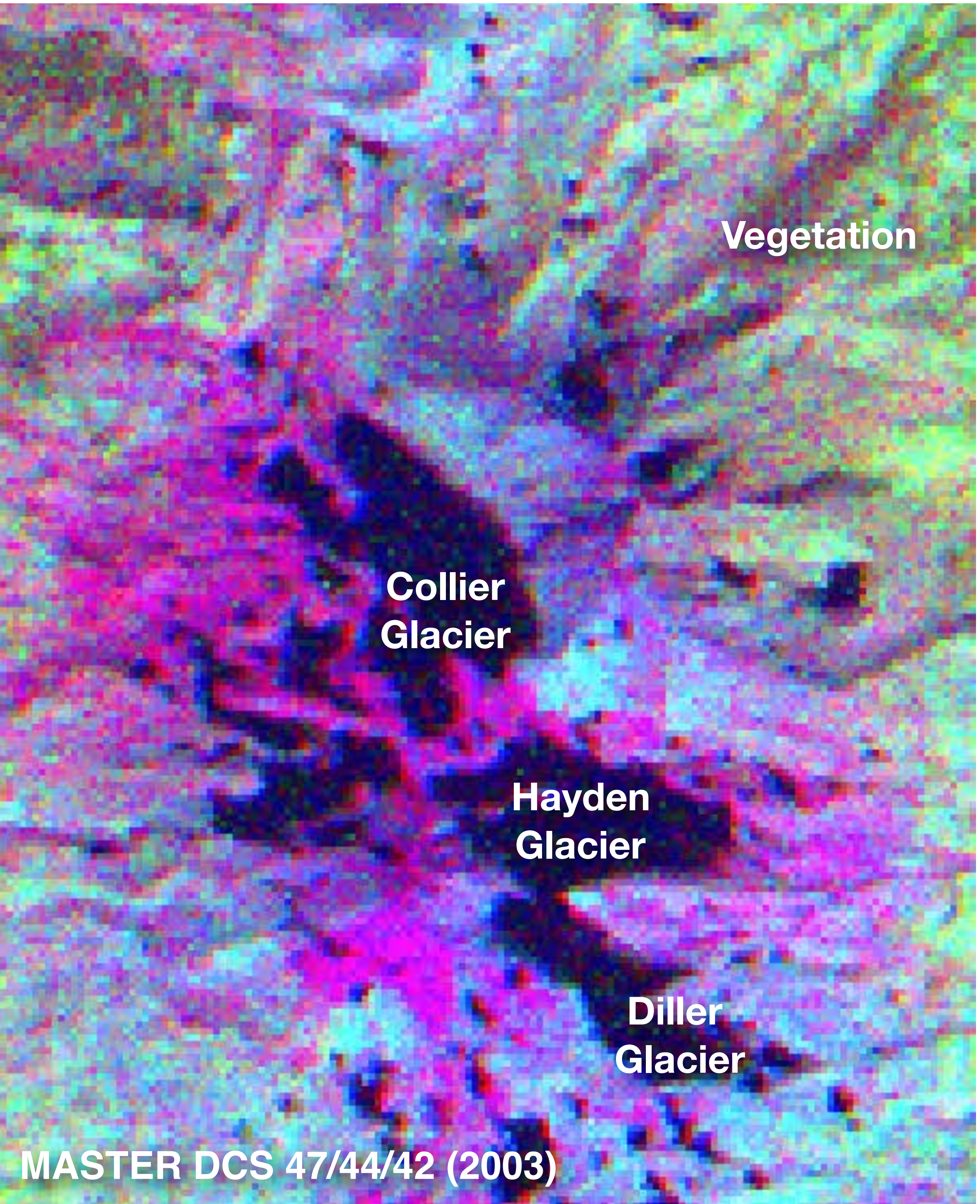
Site Rationale: The Three Sisters are the most mafic glaciated peaks in the US, thus are a good Mars analog

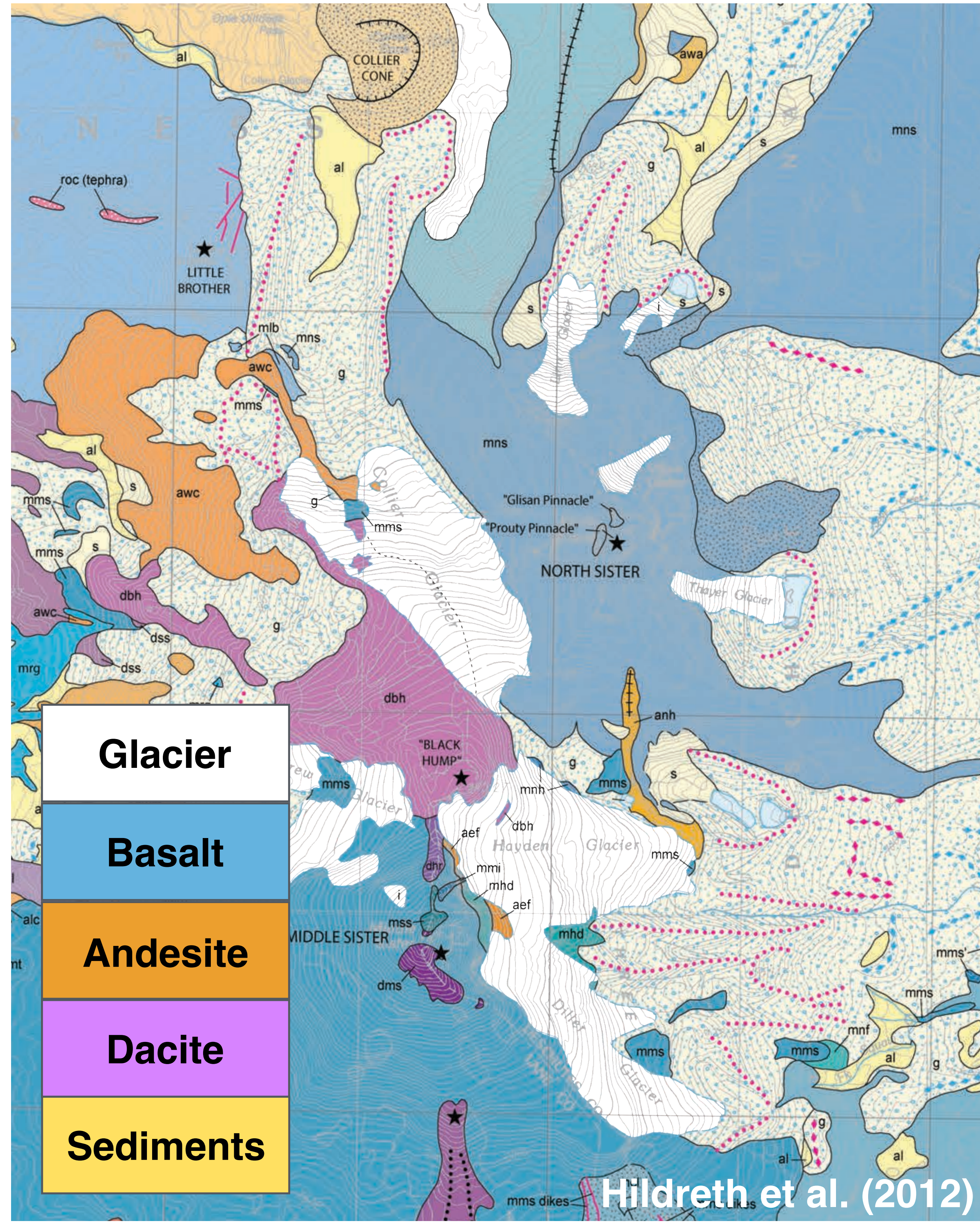




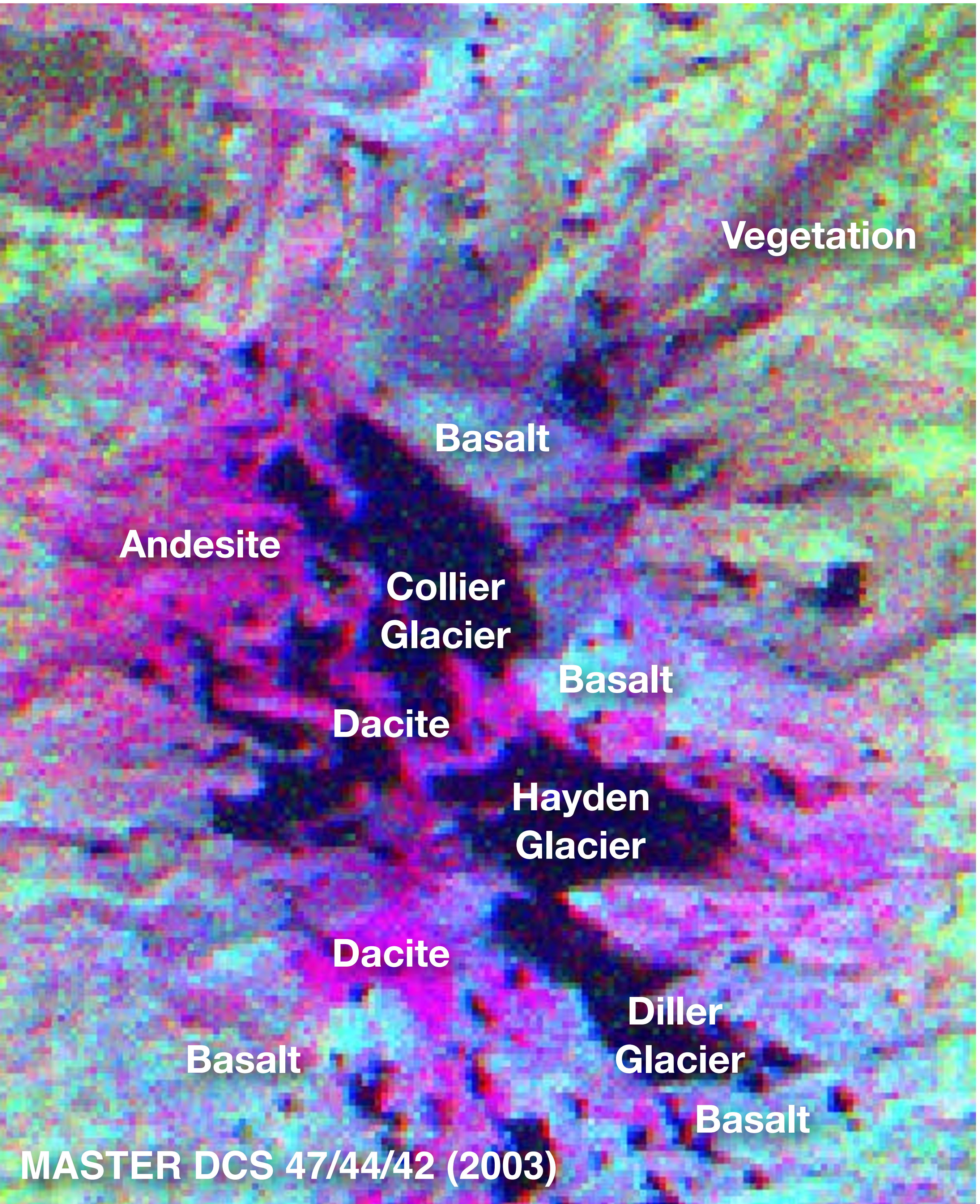
First question: Can we detect signs of glacial alteration in remote sensing data?

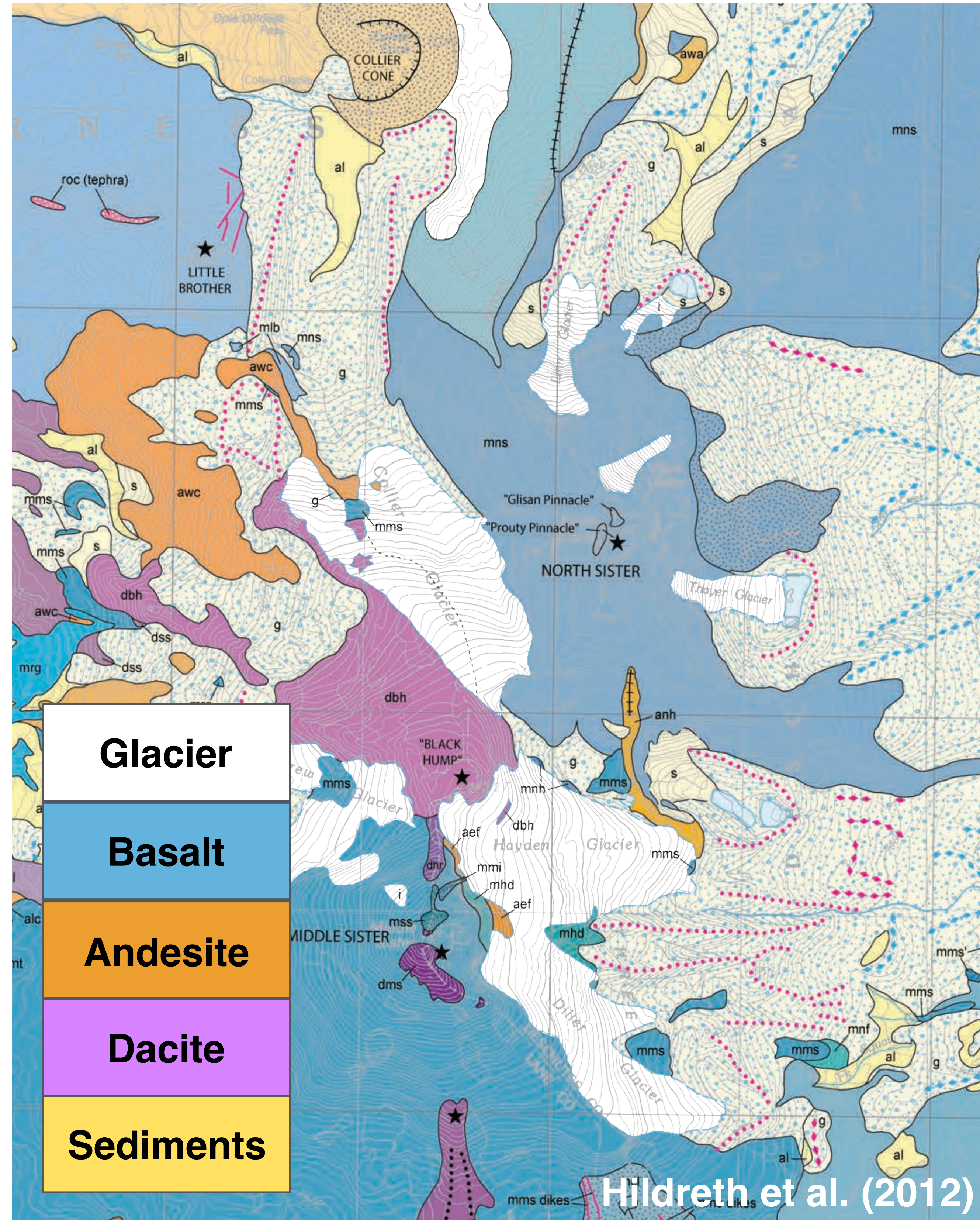
Thermal-infrared imagery shows high-silica (pink) vs. mafic (blue) volcanics.



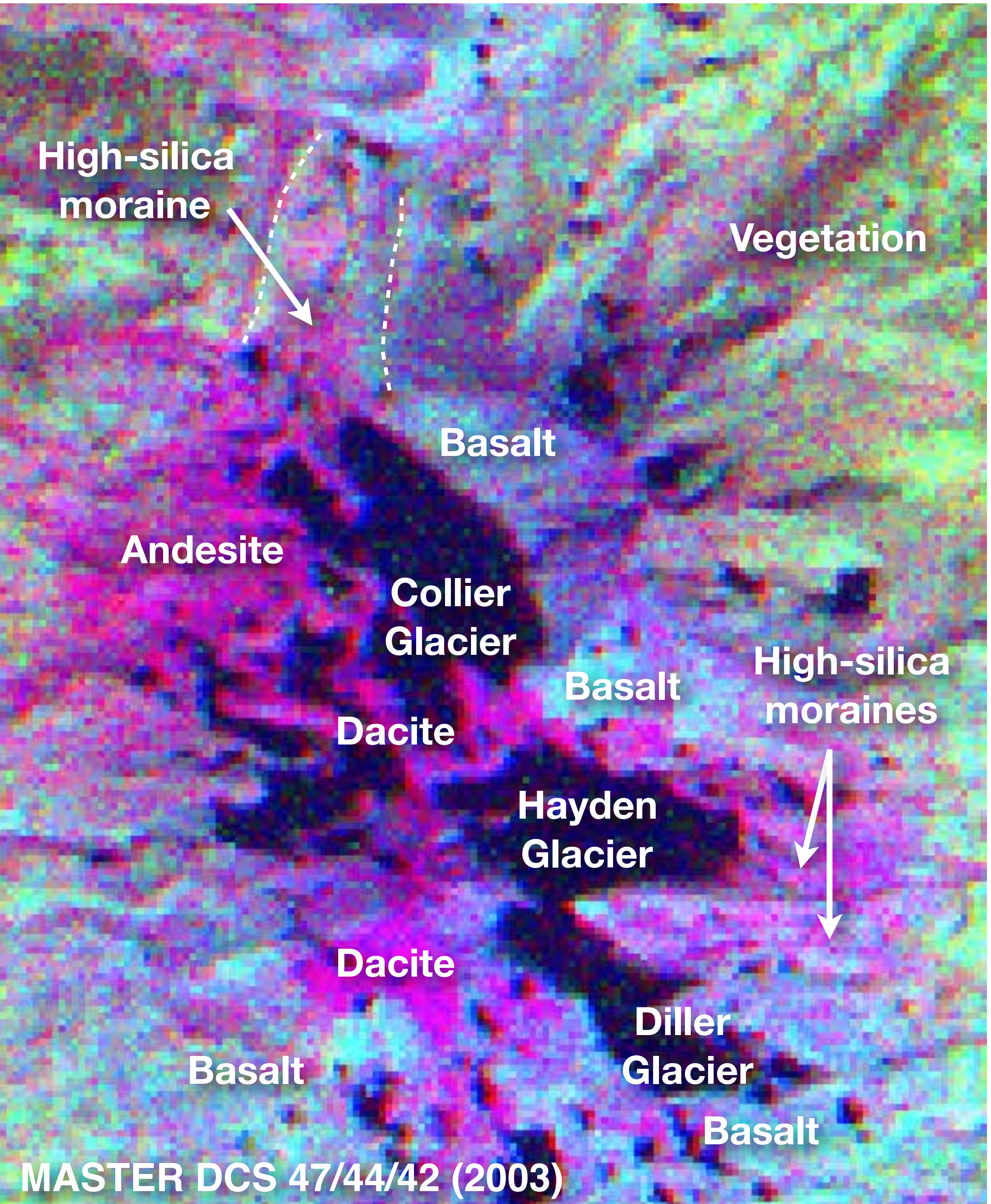


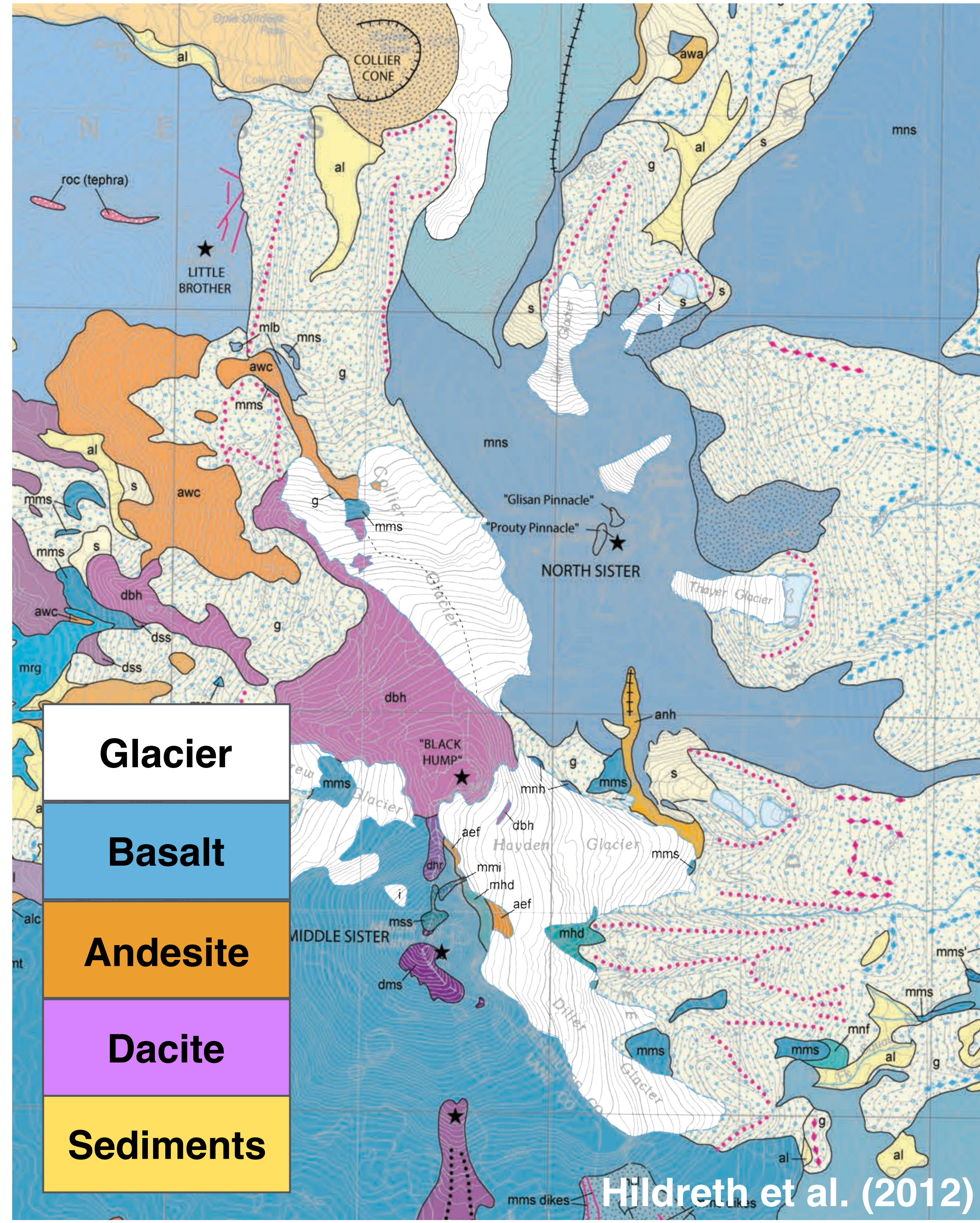
Thermal-infrared imagery shows high-silica (pink) vs. mafic (blue) volcanics.



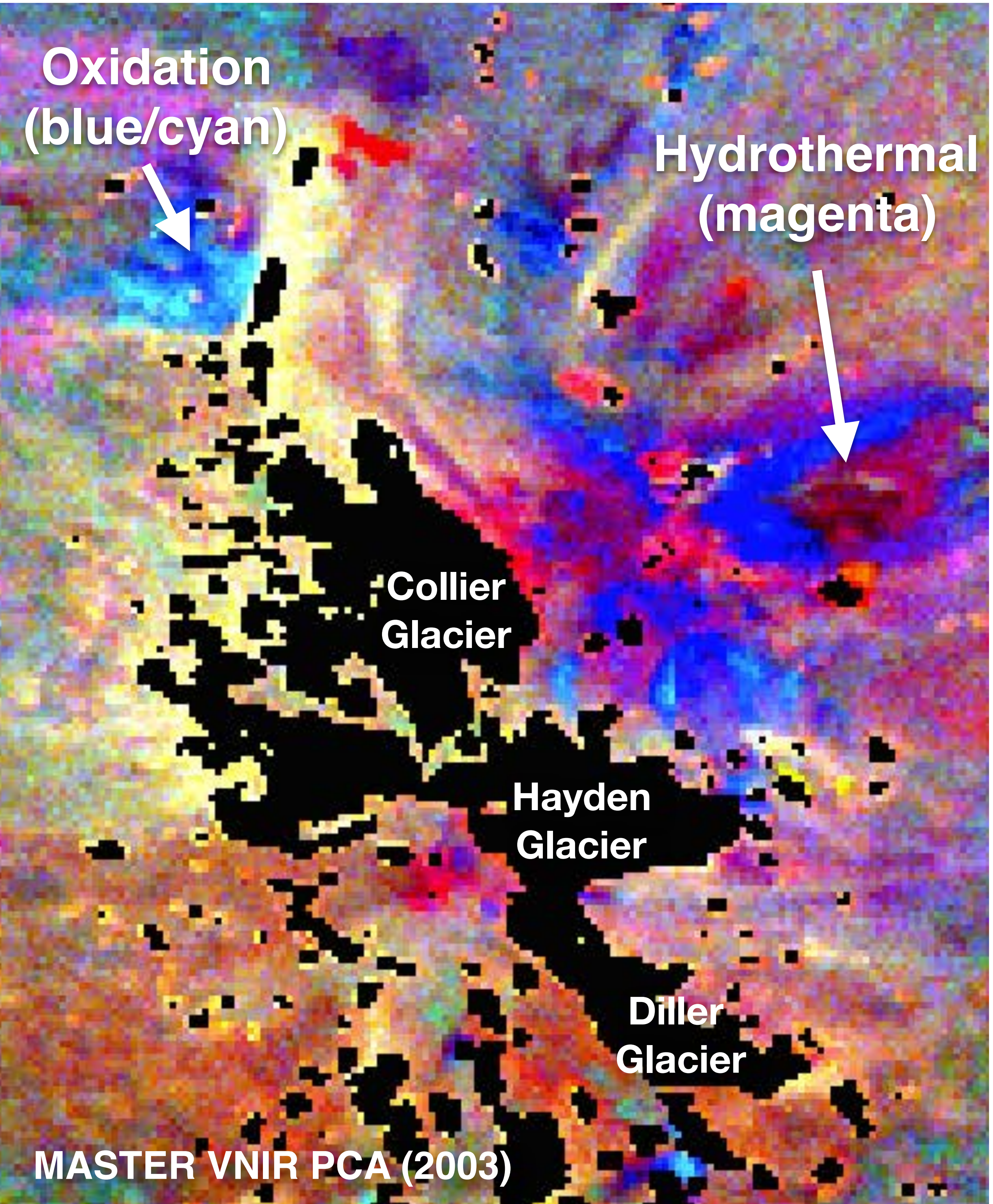


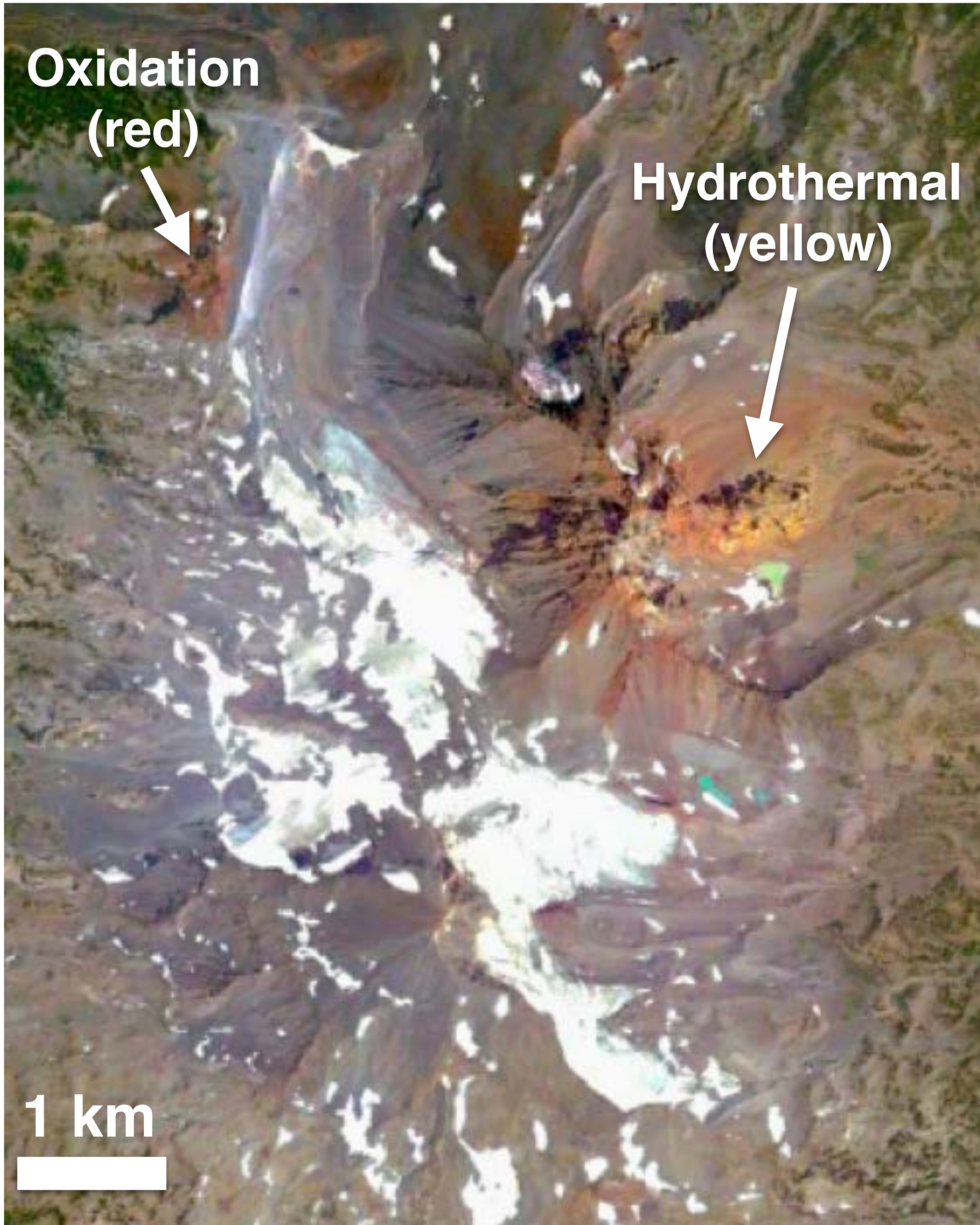
However, glacial till plains look more silicic than expected - is this due to alteration?





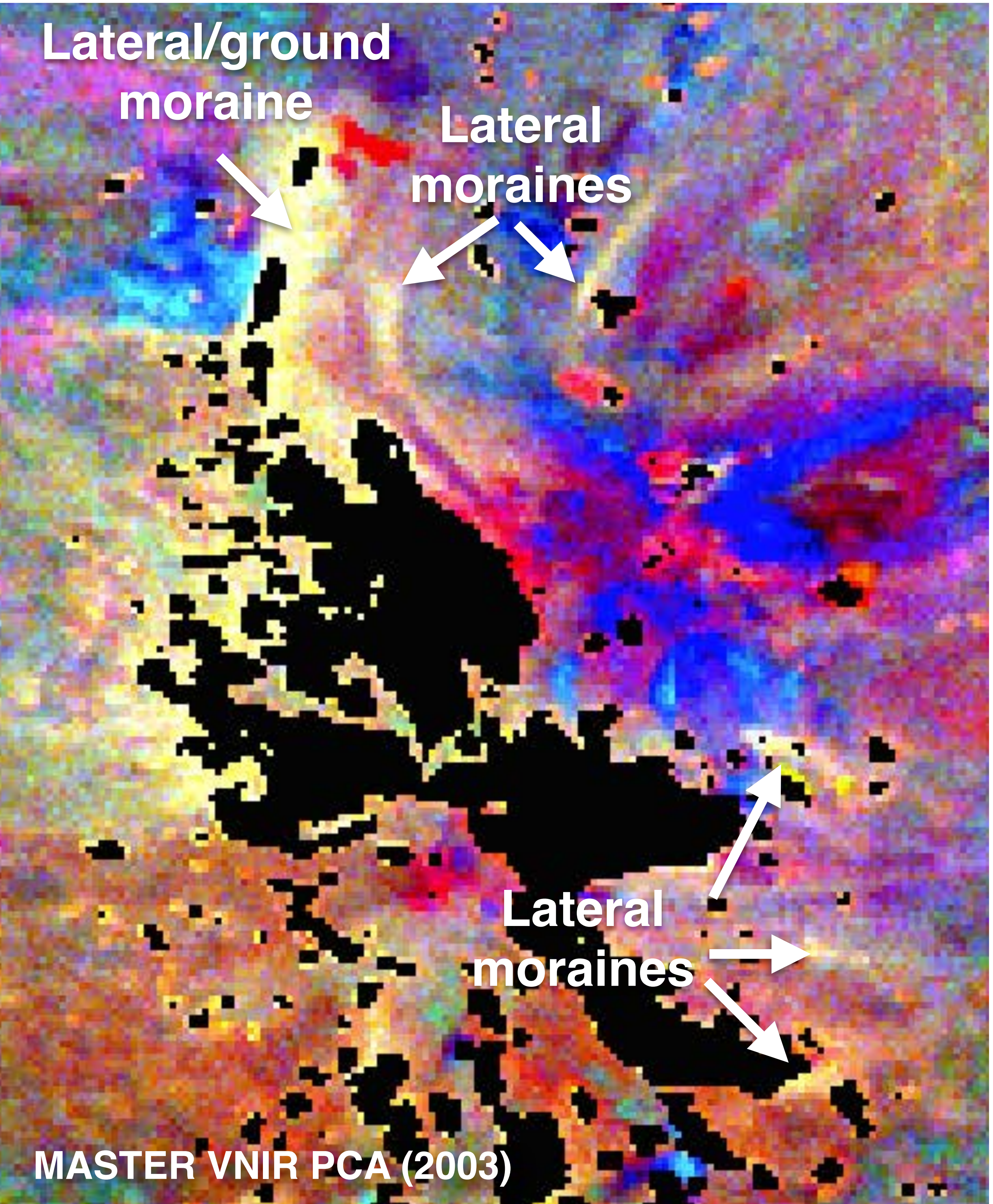
Visible/Near-infrared spectral variability is dominated by syn-eruptive "volcanic" alteration

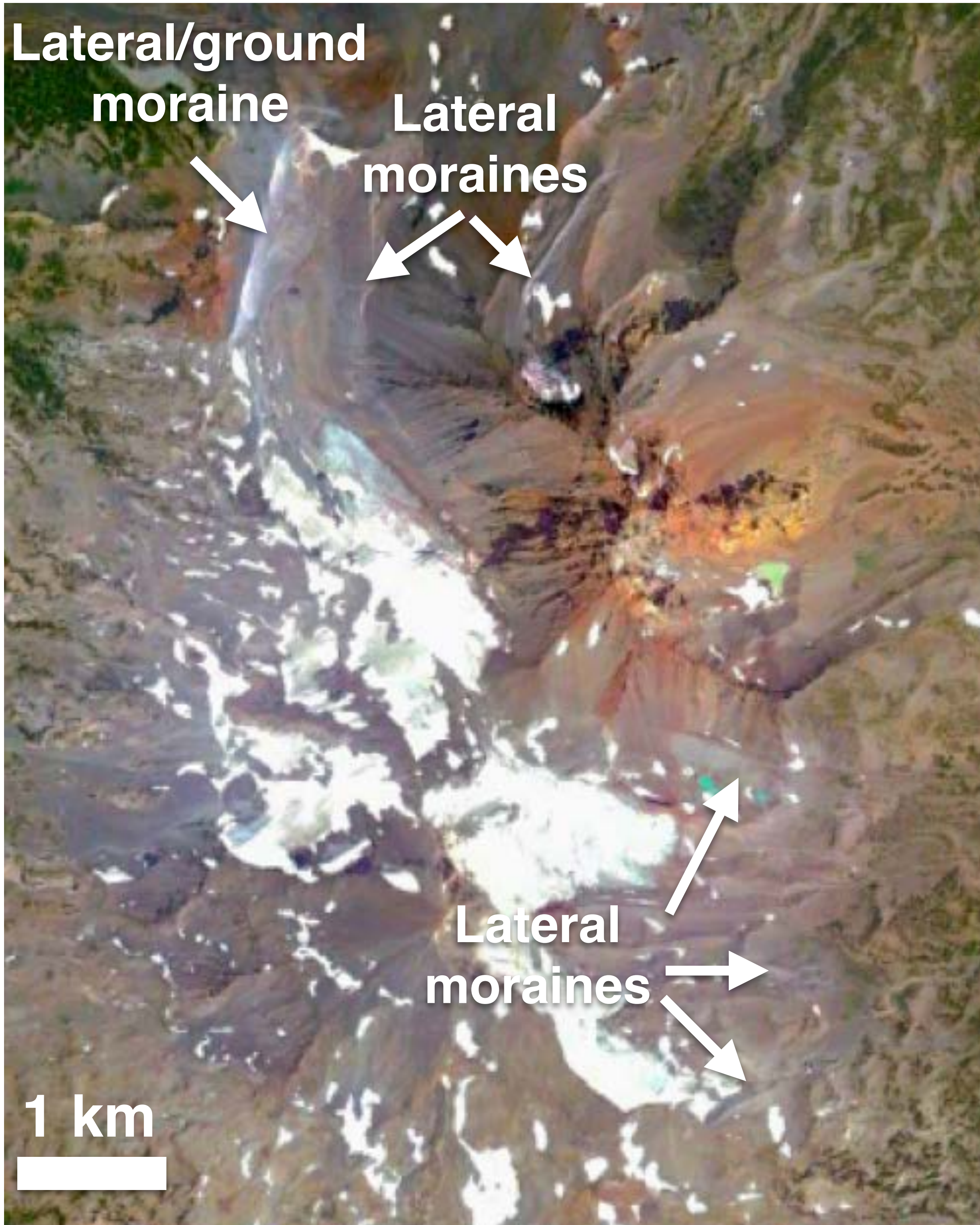





“Rainbow Moraine” is composed
of volcanically altered rocks

Glacial moraines have a distinct VNIR spectral character (yellow) - is this due to alteration?

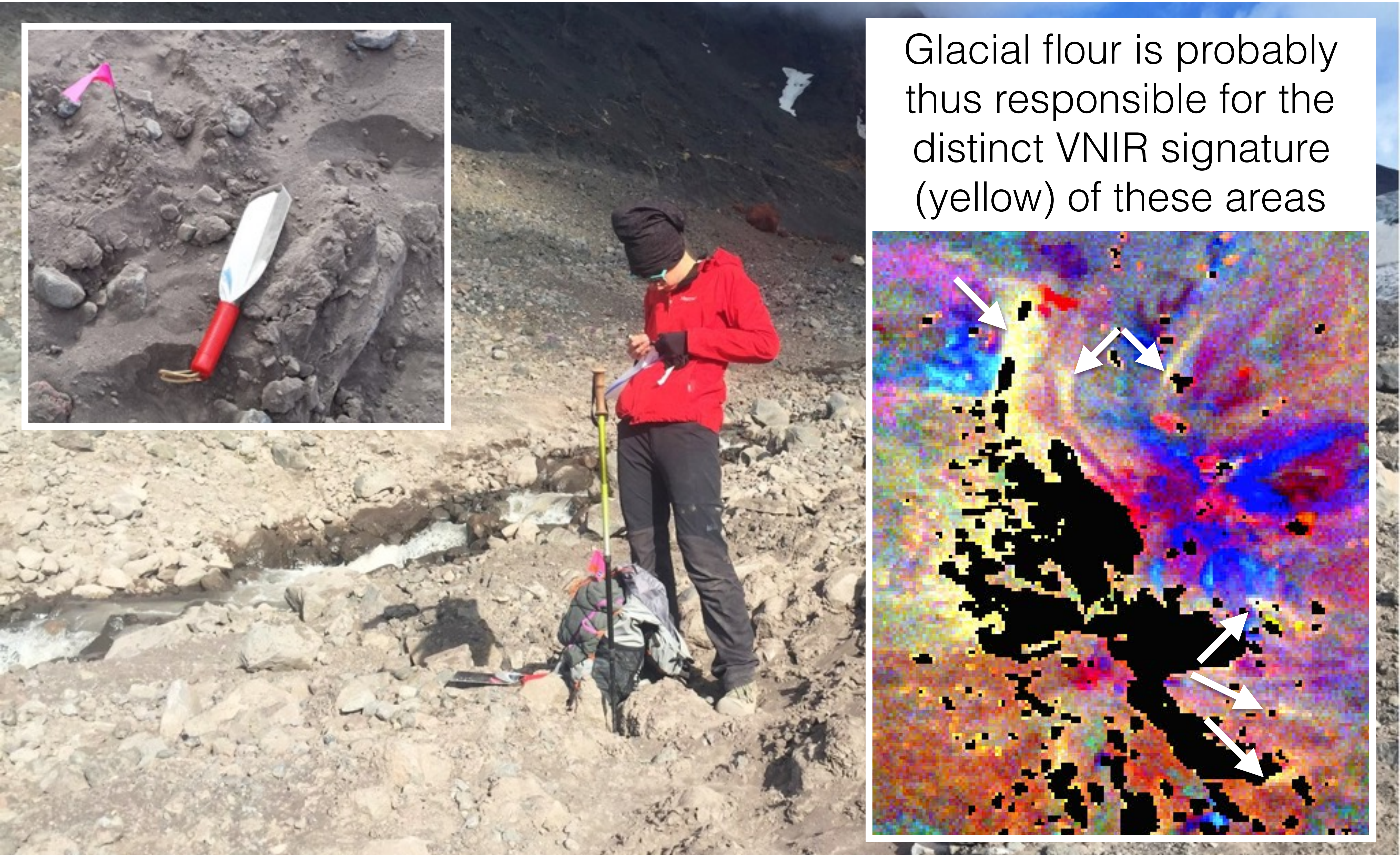




Second question: Can we detect signs of glacial alteration in the field and lab?

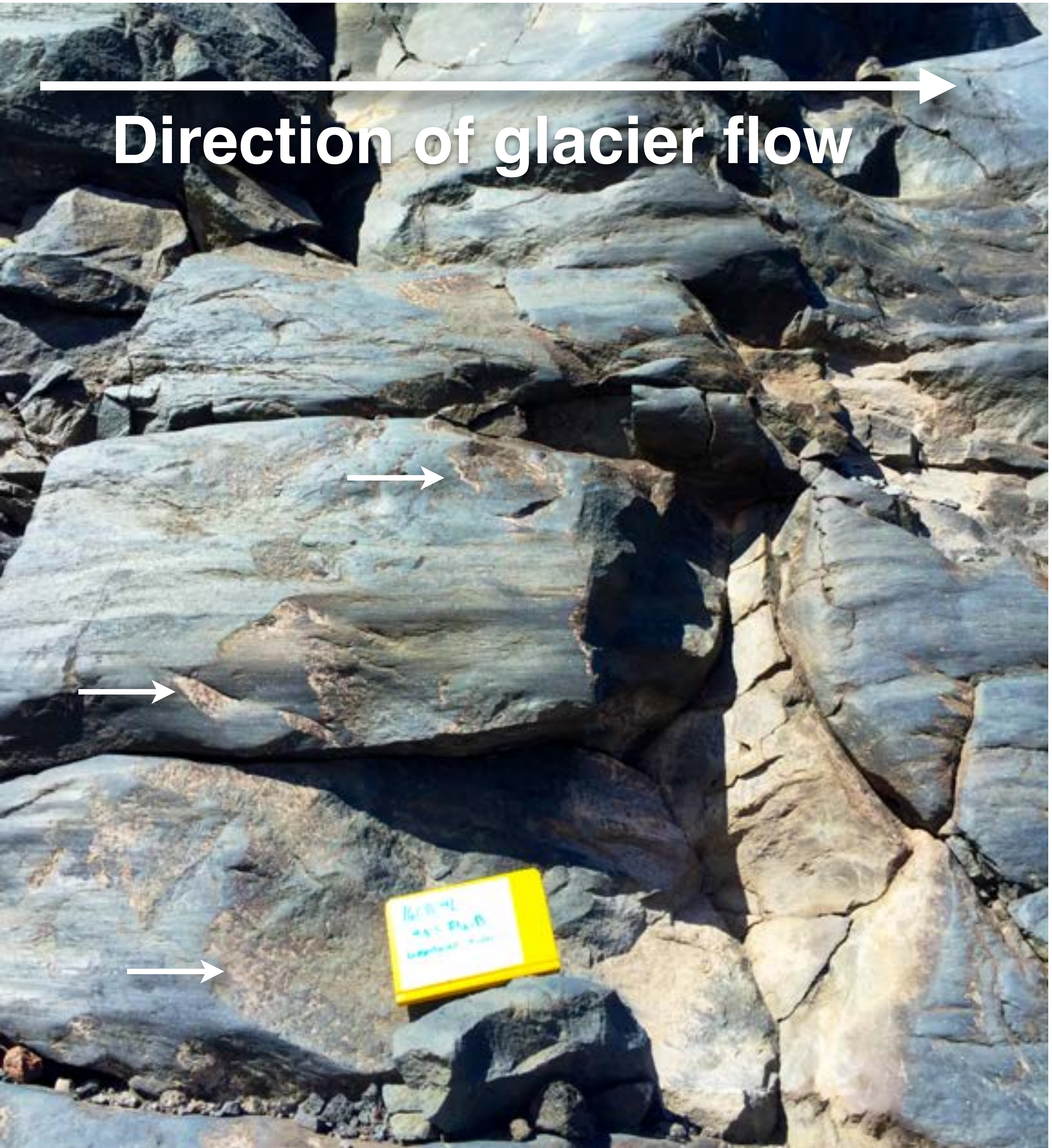
(1) Survey the distribution of possible alteration phases
—> Acquire rocks and sediments, map visible compositional trends

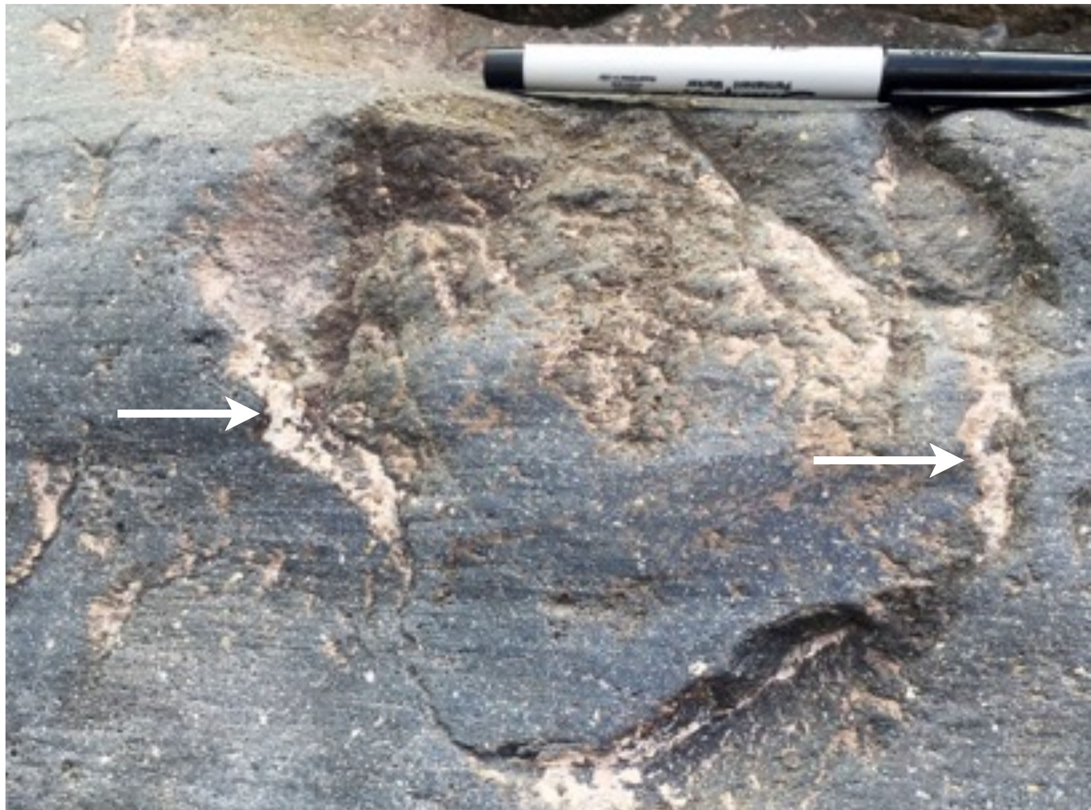
Glacial flour is the dominant phase by surface area in lateral moraines and proximal to the glacier



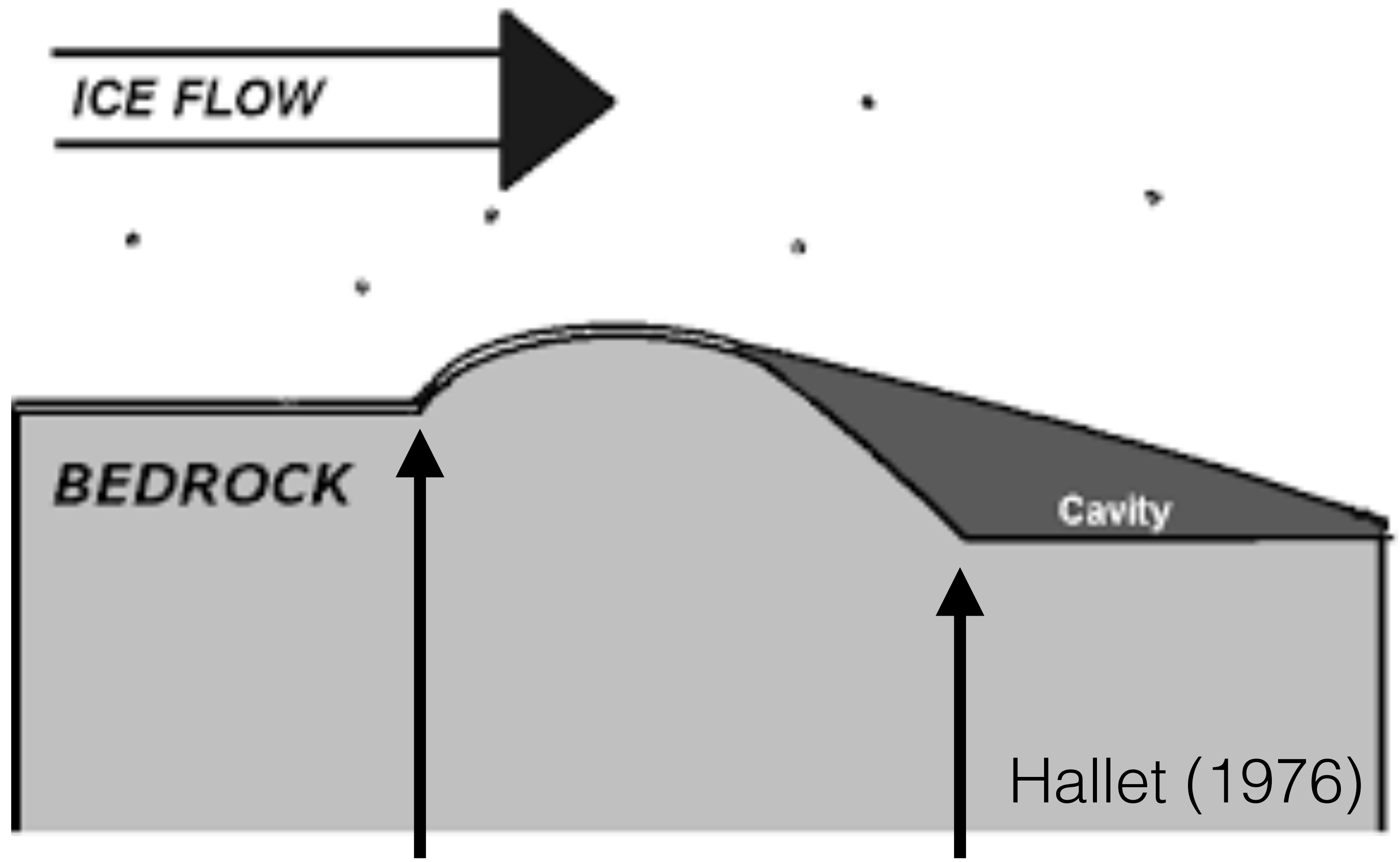
Glacial flour is probably thus responsible for the distinct VNIR signature (yellow) of these areas

Subglacially precipitated glaze is present on recently exposed glacially scoured lava flows.





“Regelation films” precipitate subglacially due to pressure melting and refreezing.



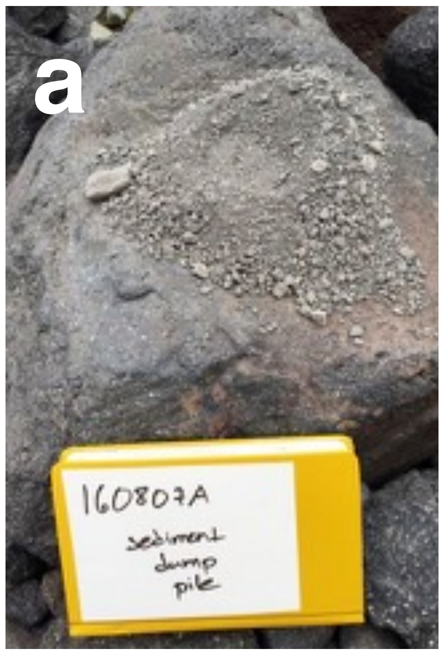
Stoss: Pressure melting, dissolution of bedrock/till. Solution becomes supersaturated.

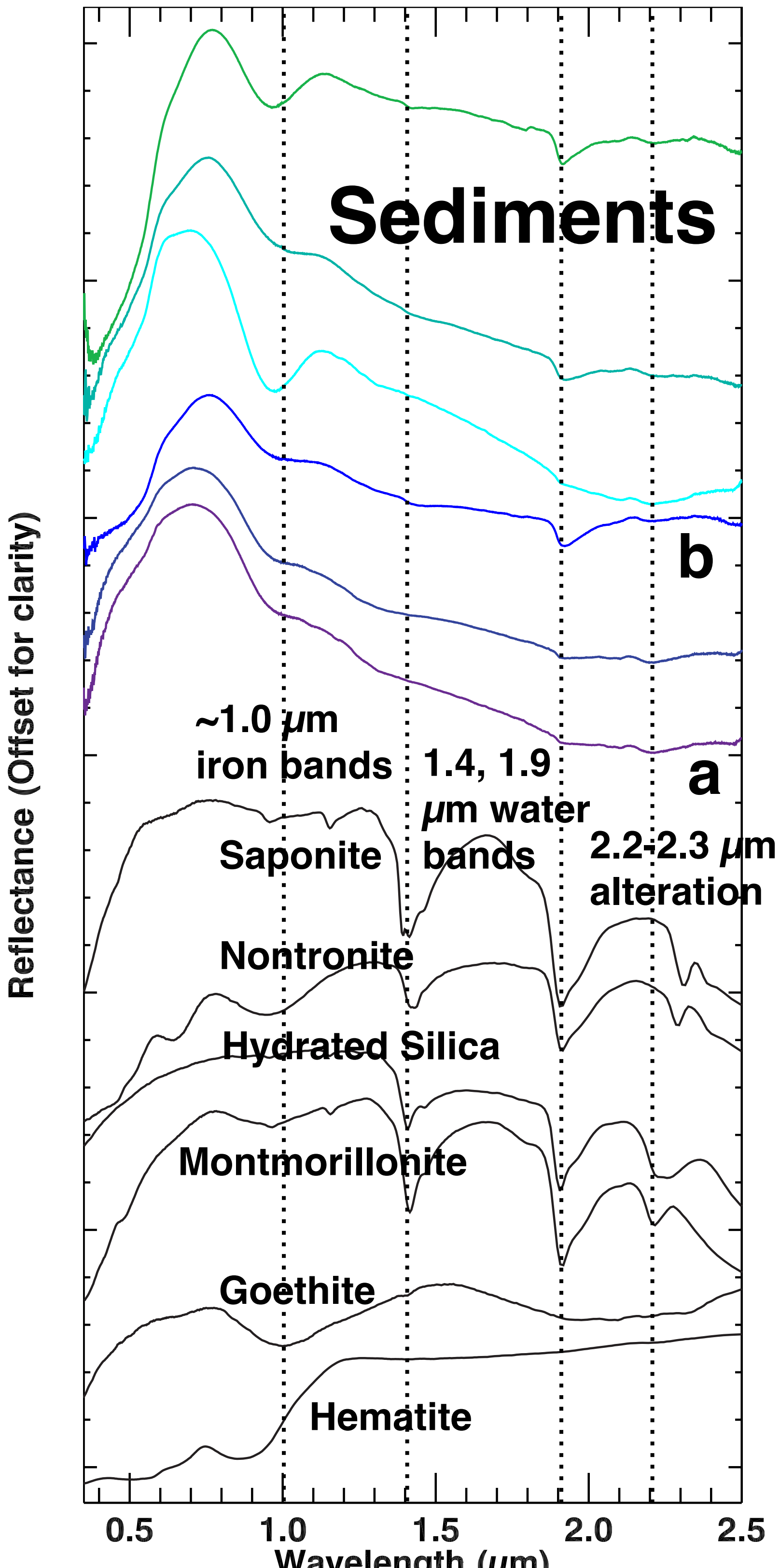
Lee: Release of pressure, refreezing. Freeze forces ions out of solution: precipitation!

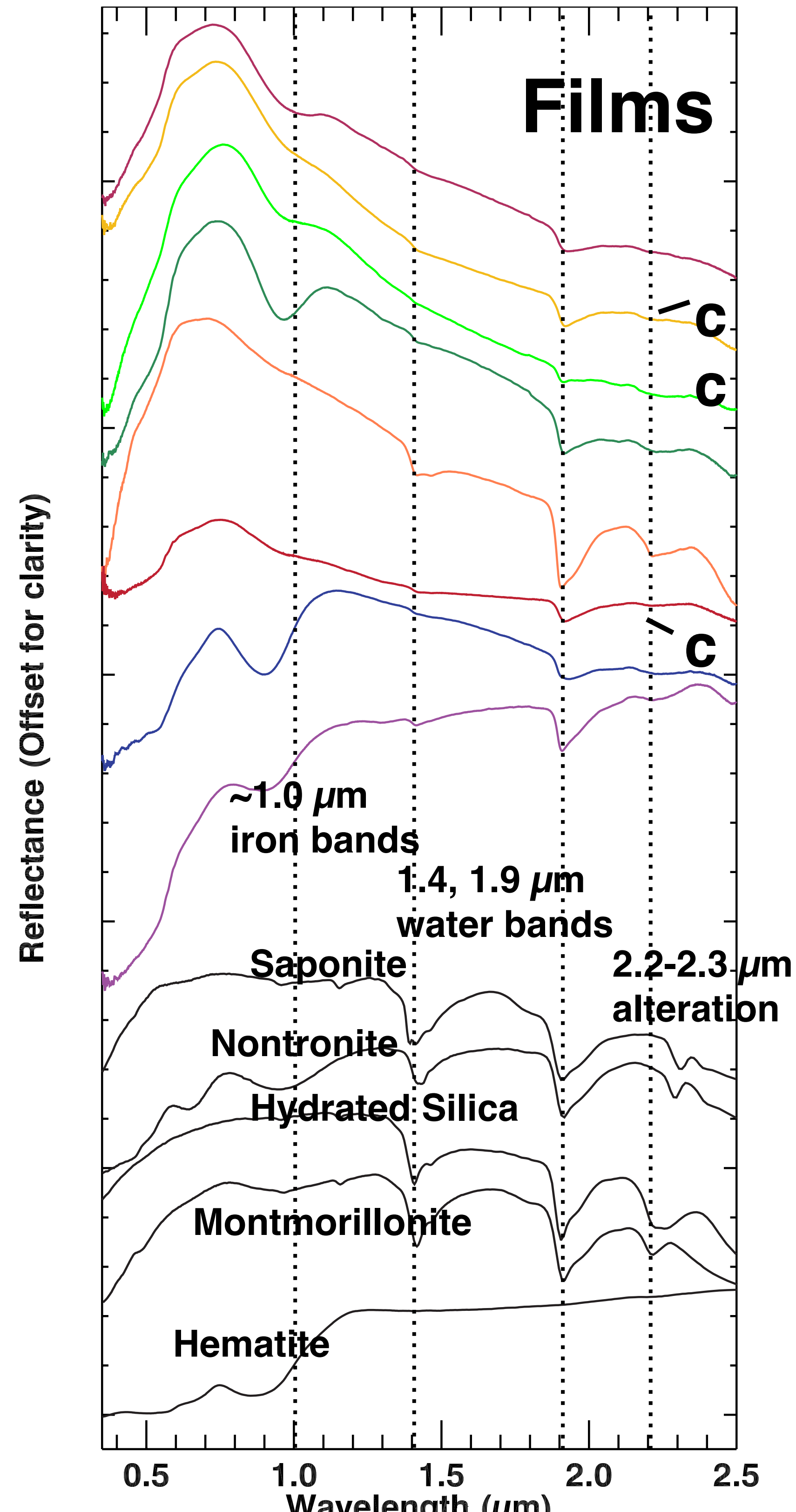
Second question: Can we detect signs of glacial alteration in the field and lab?

(2) Determine spectral signatures and mineralogy of alteration phases
—> Field VNIR spectra of outcrops
—> Lab VNIR/TIR spectra
—> XRD, SEM, TEM, XRF

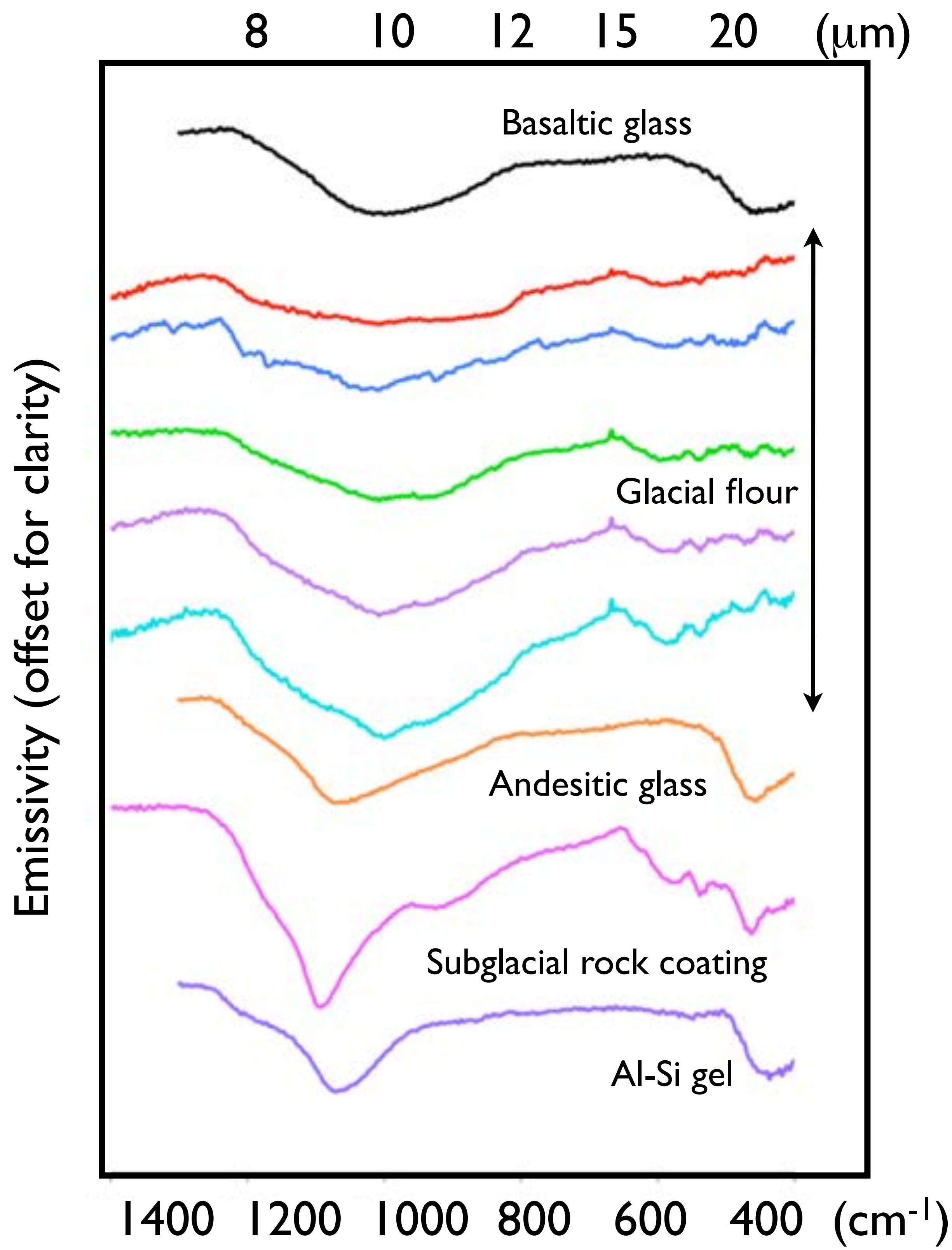
VNIR spectra of glacial sediments and regelation films show clear alteration, mainly hydrated silica.







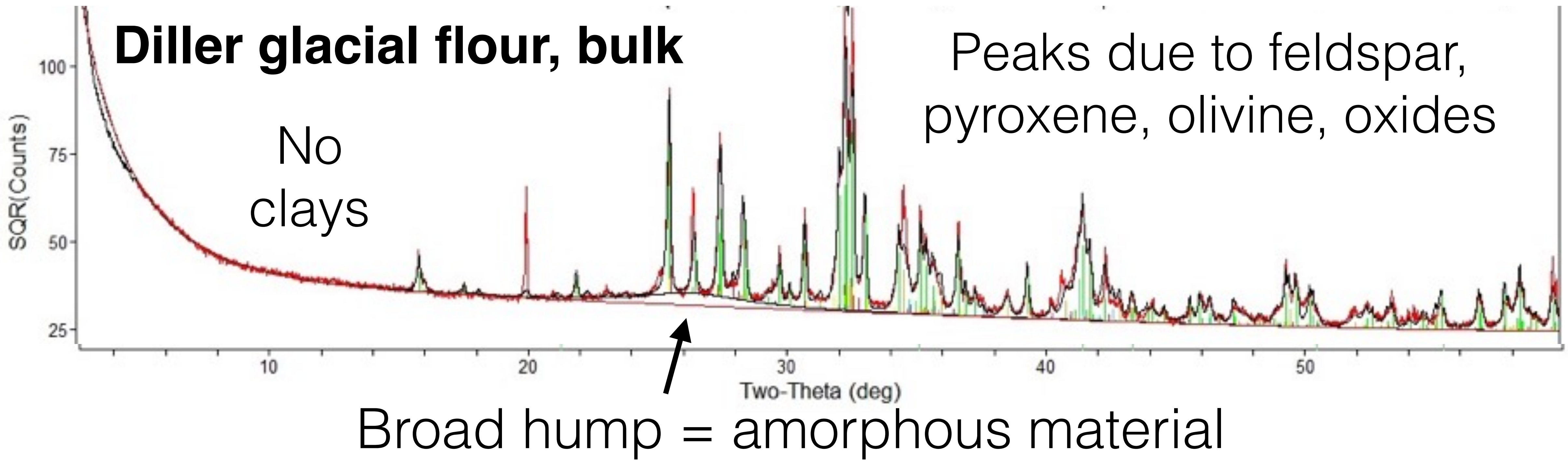
Thermal-infrared spectra are dominated by poorly crystalline components.

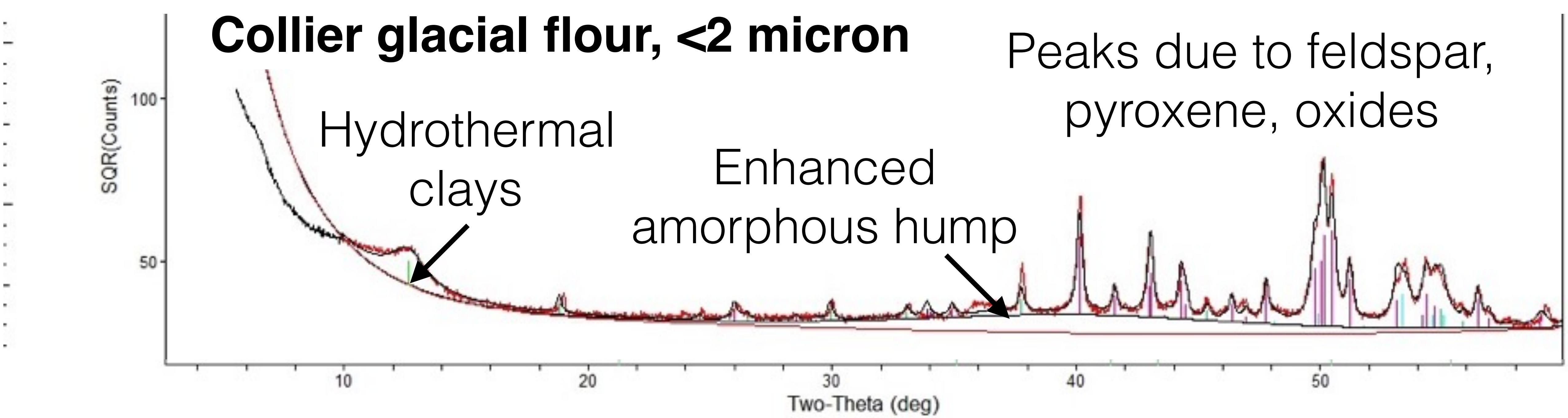


Broad U- to V-shaped absorptions of glacial flour are best modeled by mafic glass — a substitute for an unknown Fe-rich amorphous silicate phase

In contrast, rock coatings are best modeled by typical Al-Si gel, supporting a silica glaze interpretation.

XRD indicates that glacial flour is composed of primary minerals and an amorphous component

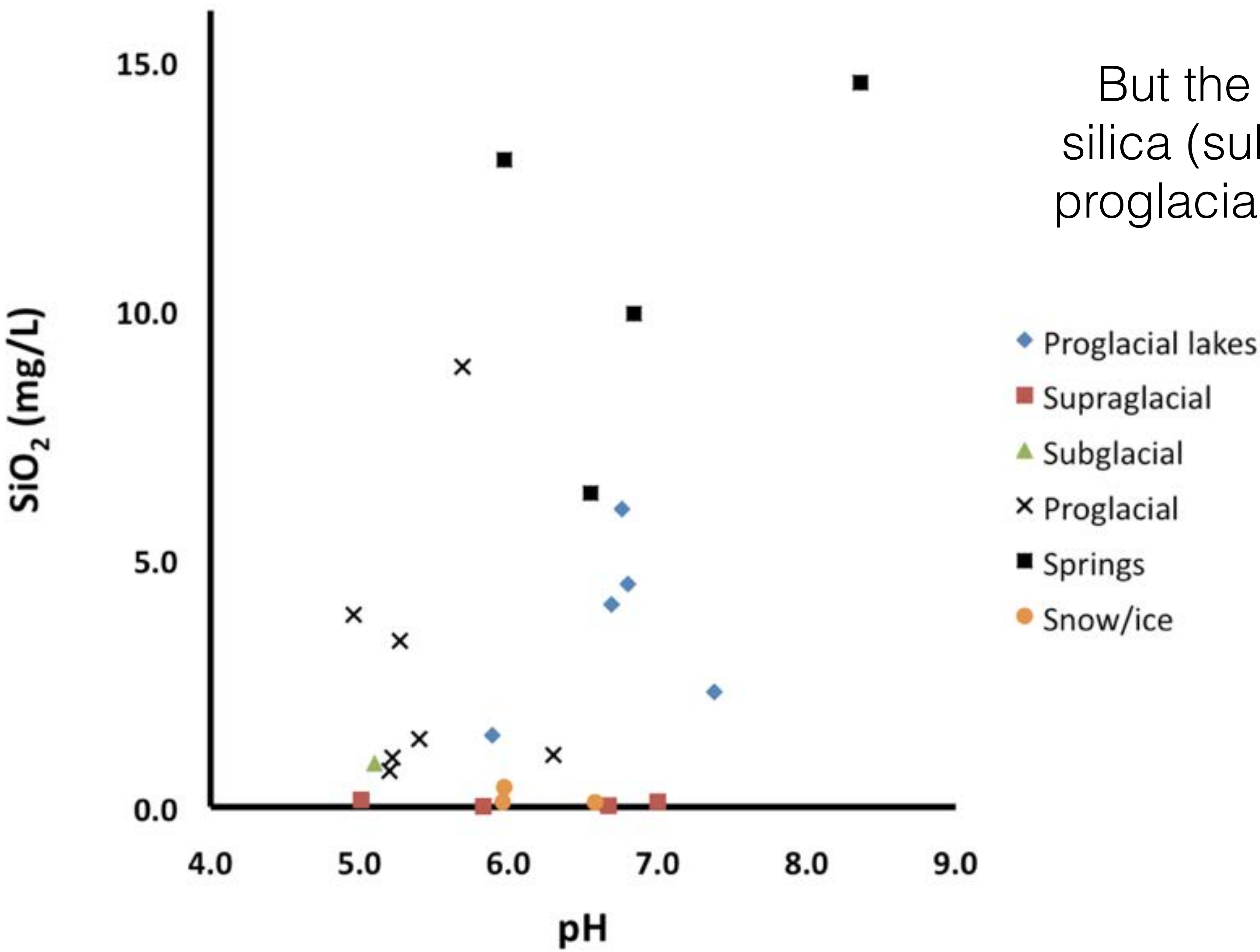




Second question: Can we detect signs of glacial alteration in the field and lab?

(3) Relate alteration processes to aqueous geochemistry
—> Field pH, temperature, silica, etc.
—> Collect water for lab analyses

Silica dissolution is occurring in this glaciated volcanic system independent of meltwater pH.



But the source of silica (subglacial vs. proglacial) is unclear

Mafic glacial systems are unique in that they are appear to be dominated by silica rather than carbonate.

- Previous studies: carbonate dissolution coupled with sulfide oxidation regardless of bedrock, aided by microbial populations *(Sharp et al. 1995; Wadham et al. 2001; Tranter et al. 2002; Anderson et al. 2003; Wadham et al. 2004; Skidmore et al. 2005; Hamilton et al. 2013).*
- Calcite regelation films are well-documented, silica glaze is rarely mentioned *(Hallet 1975,1979; Whalley et al. 1990; Peterson & Morseby 1979)*
- Detailed chemistry/mineralogy of glacial flour has yet to be examined, especially amorphous component: stay tuned!

Glaciers provide diverse microenvironments, and their unique chemistry supports unique ecosystems.

New hypothesis: Poorly-crystalline silicates on Mars may indicate past cold-climate weathering

- Where on Mars would we expect these phases to accumulate?

  (1) Concentration in fine-grained component of distal lacustrine sediments

  (2) Exposure in aeolian sediments

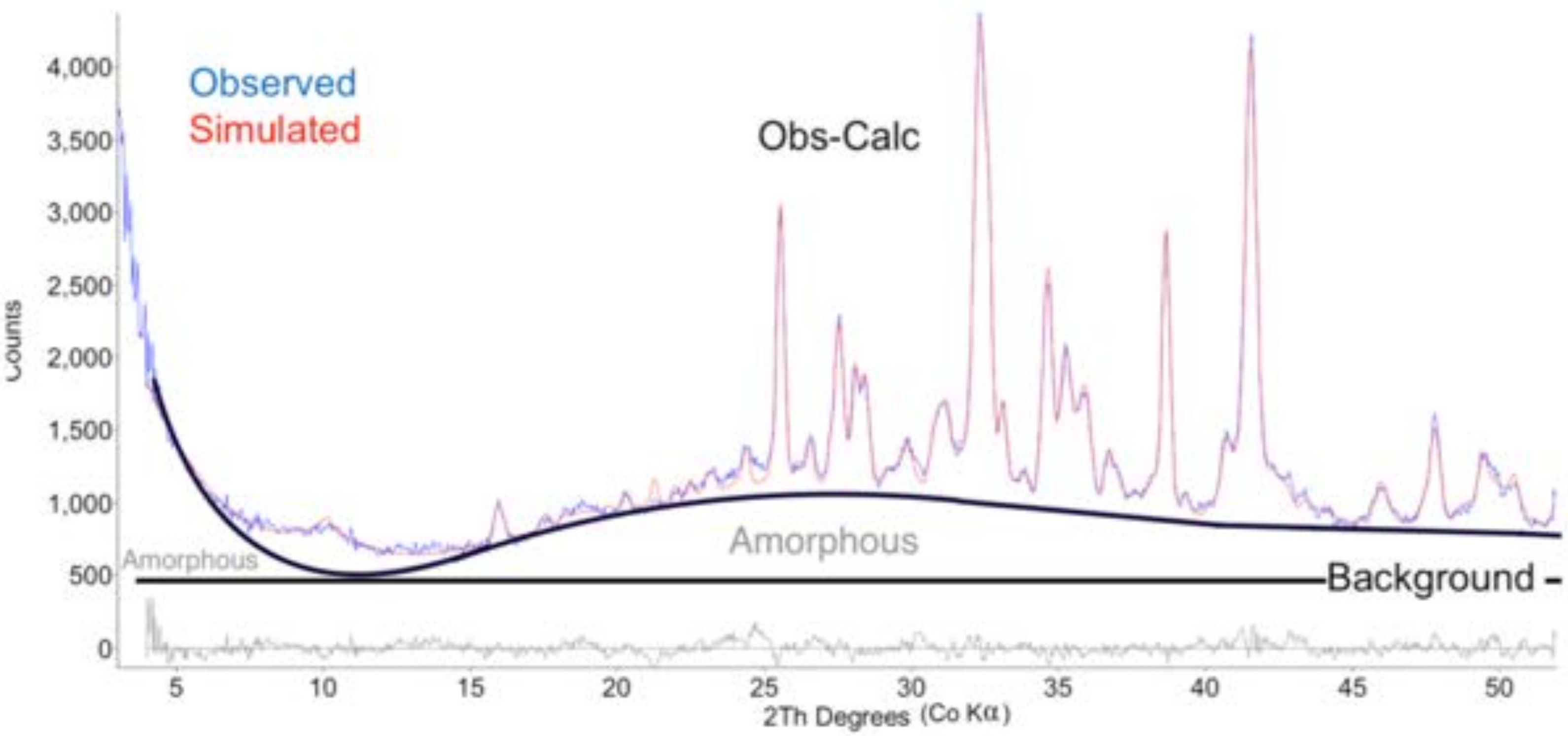
- <u>Locations we can test this hypothesis:</u>

  - Lake sediments in Gale Crater
    (age poorly constrained, late Noachian - mid Hesperian)

  - Possible lake sediments in Gusev Crater
    (age poorly constrained, Noachian - mid Hesperian)

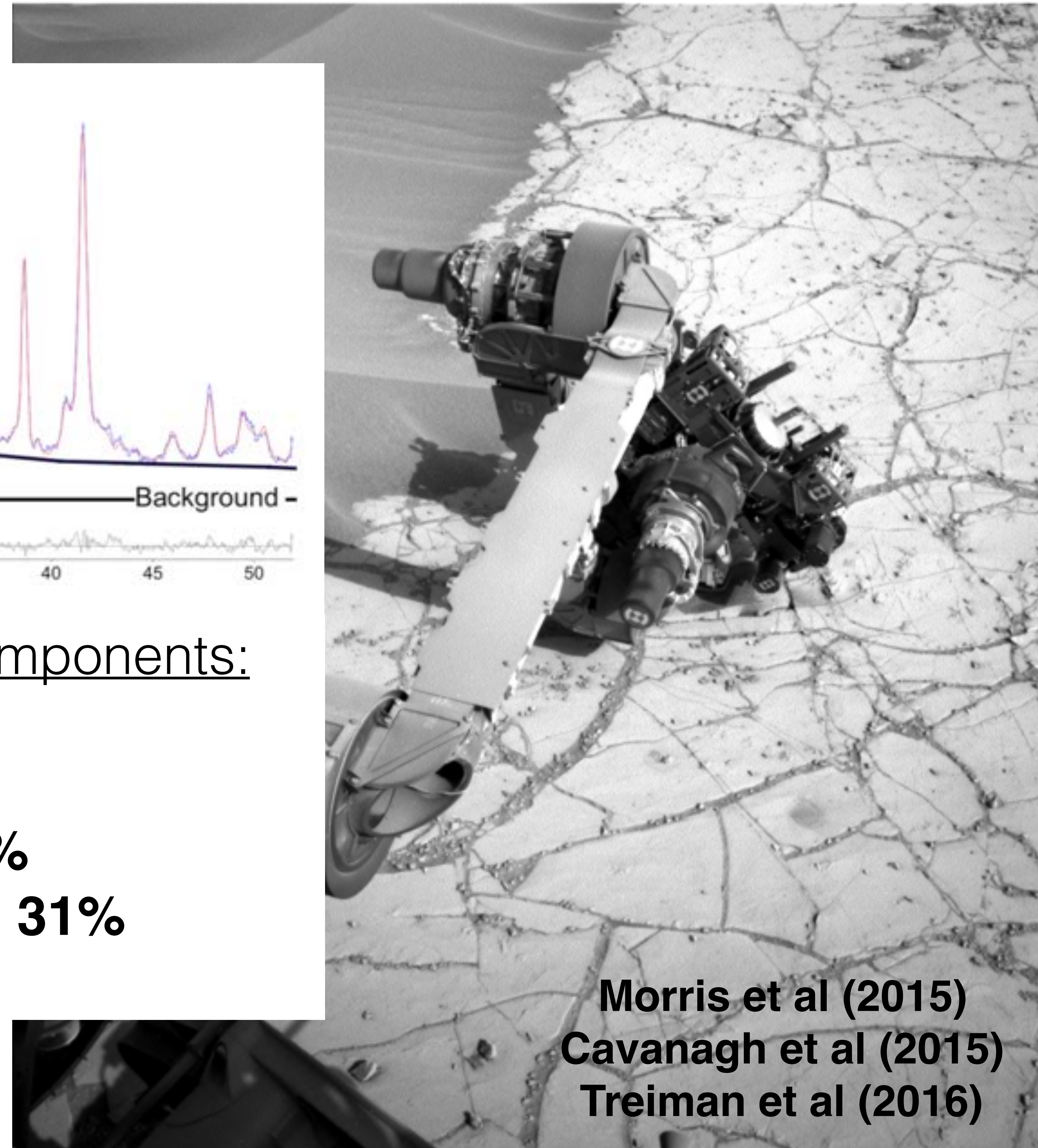
  - Regional aeolian sediments observed from orbit
    (probably Amazonian, but other source eras possible)

Mars Science Laboratory data indicate that poorly crystalline phases are a major component of Gale Crater sediments



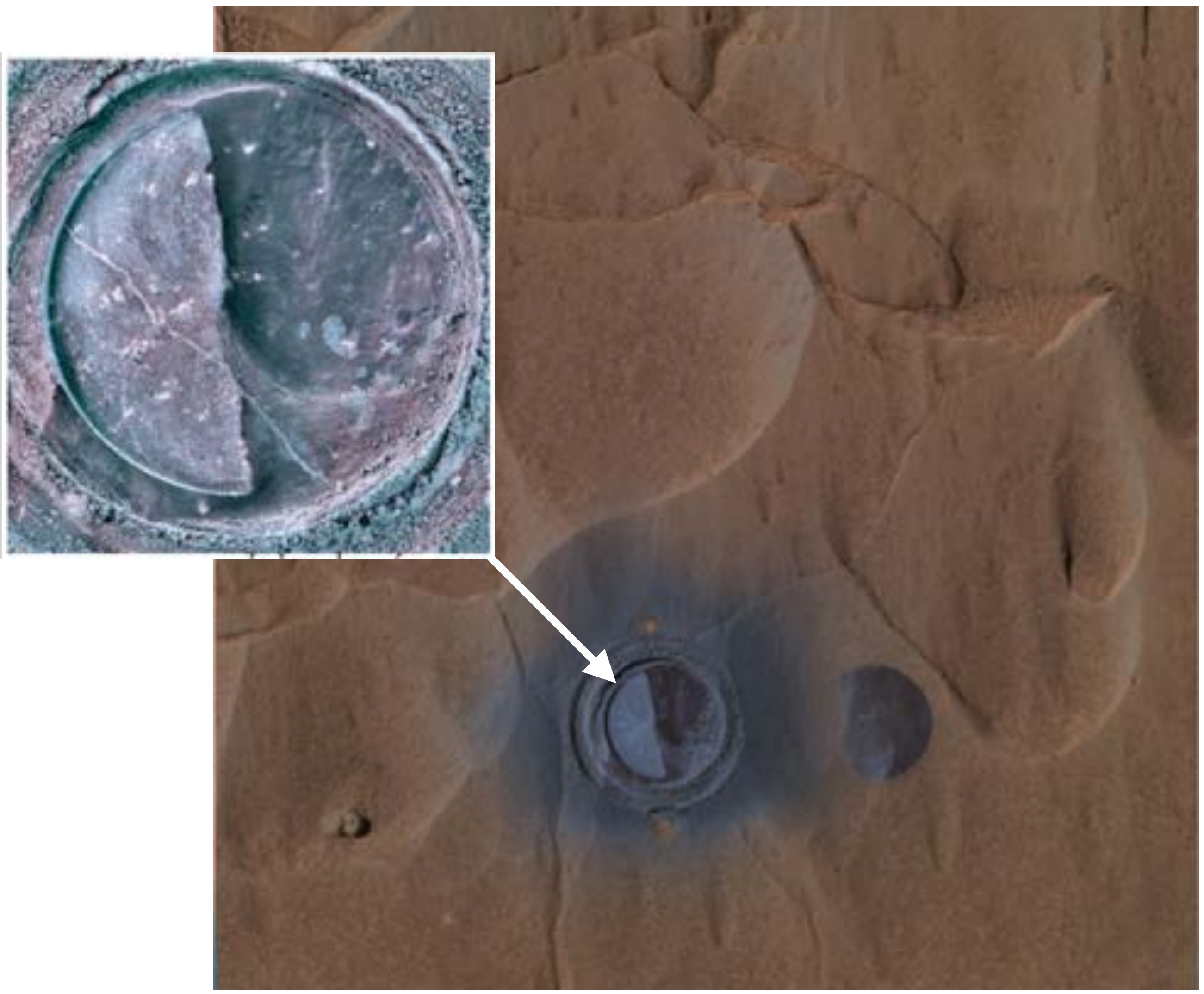
CheMin/APXS Amorphous Components:

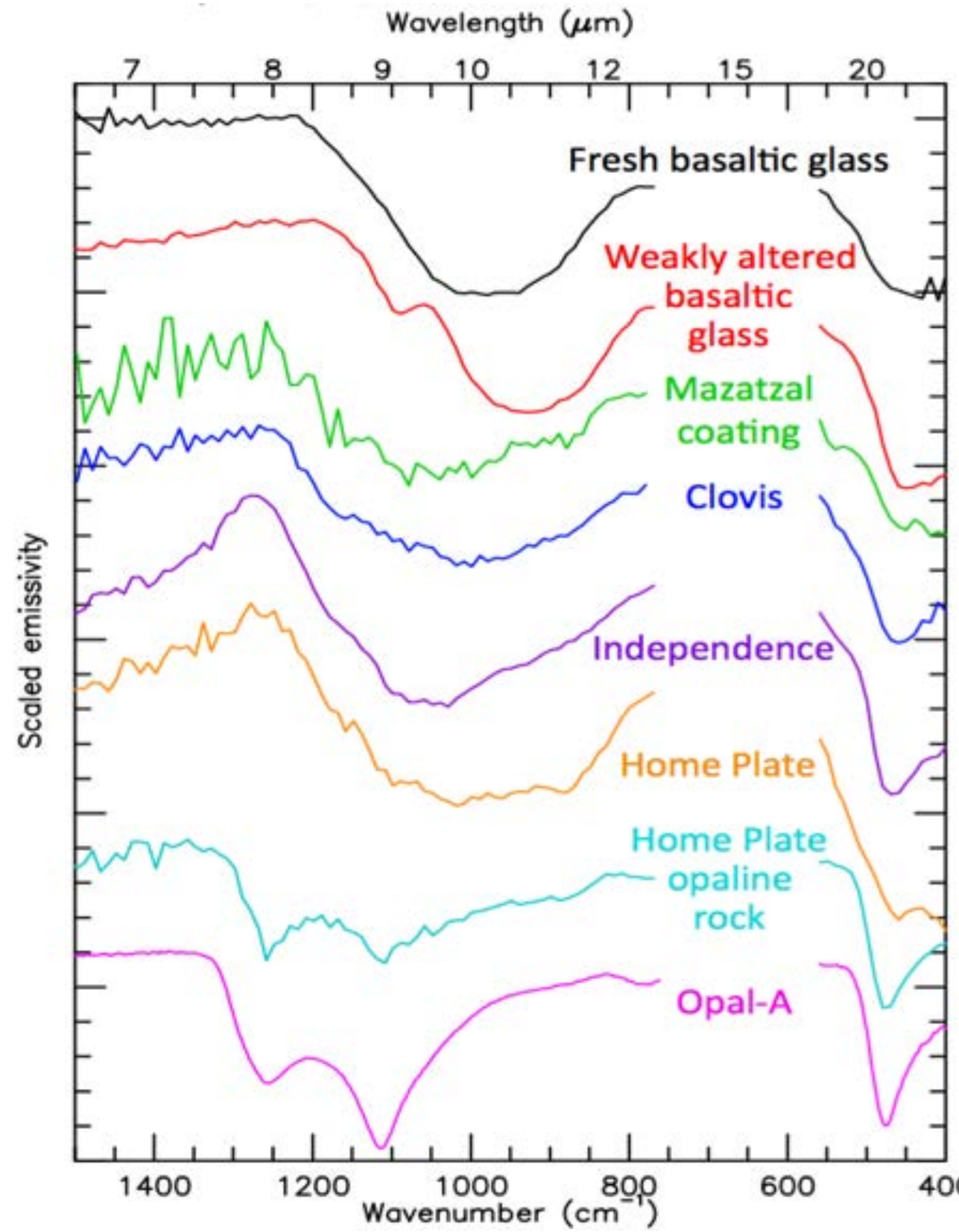
- Rocknest Ripple: **49%**
- John Klein Mudstone: **43%**
- Cumberland Mudstone: **39%**
- Confidence Hills Mudstone: **31%**
- Windjana Sandstone: **25%**



Morris et al (2015)
Cavanagh et al (2015)
Treiman et al (2016)

Spirit rover data indicate that poorly crystalline silicates are also a major component of altered rocks in the Columbia Hills





Ruff & Hamilton (2013)

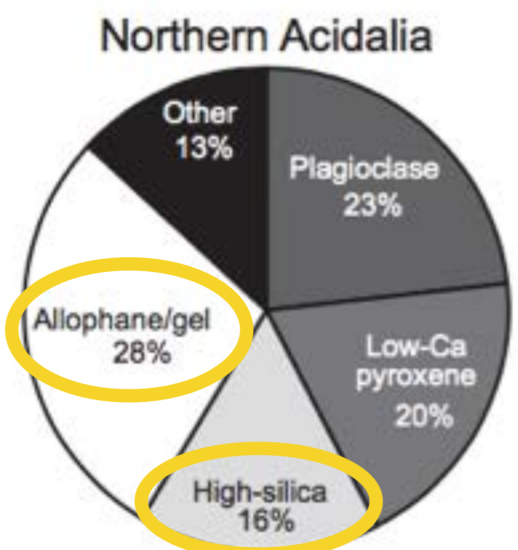
<u>Mini-TES "Glass" Components:</u>

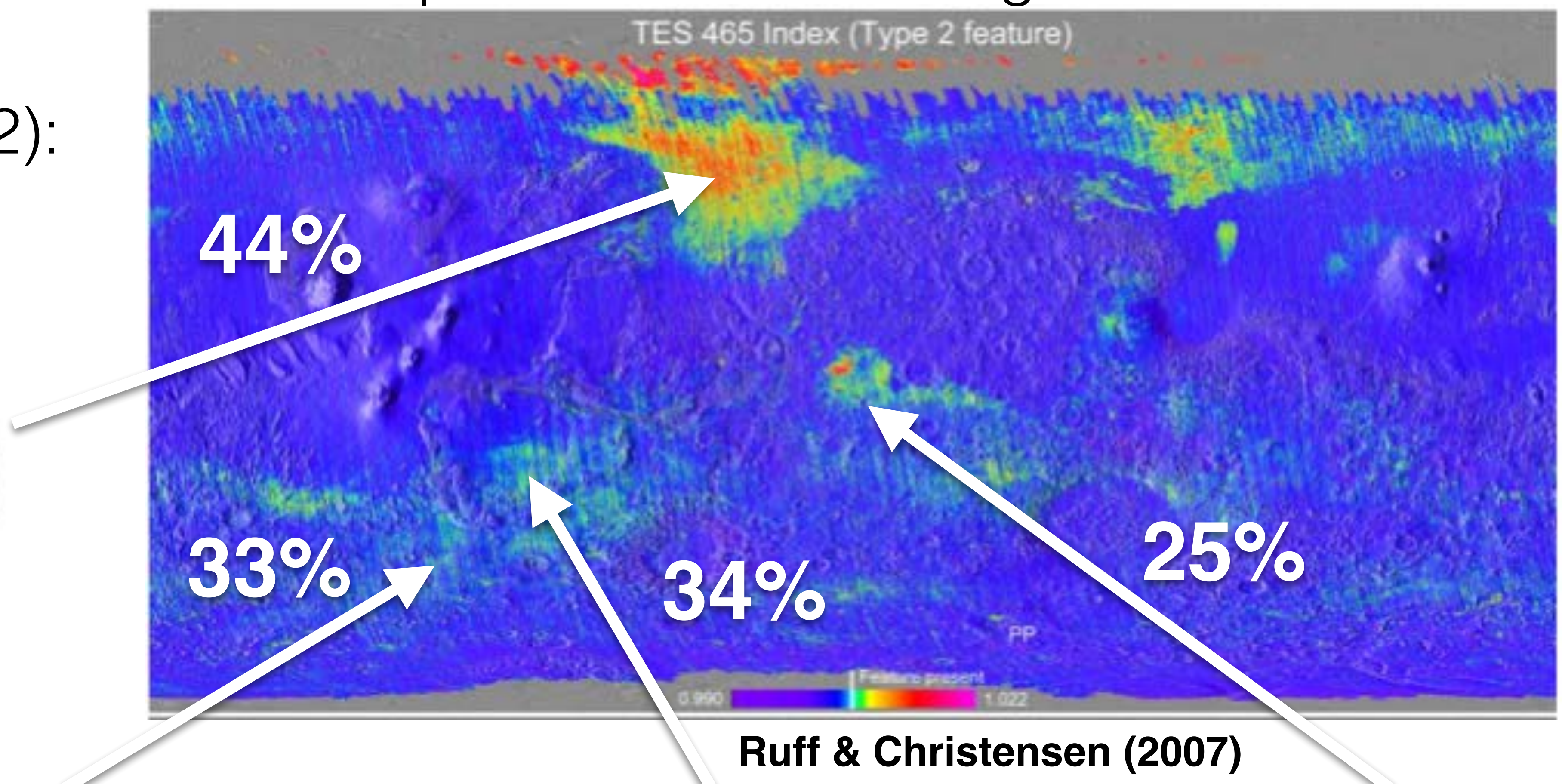
- Mazatzal Rock Coating: **50%**
- Clovis Outcrop: **50%**
- Comanche Outcrop: **33%**

Thermal-IR models of many regions on Mars require a poorly crystalline high silica component

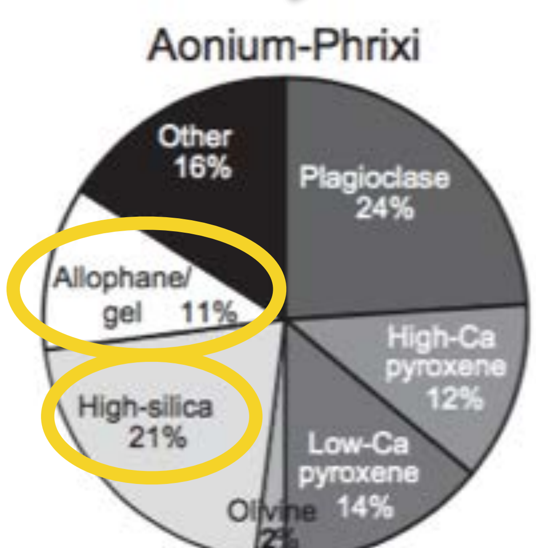
Global map of TES high-silica spectral signature compared to modeled high silica wt %:

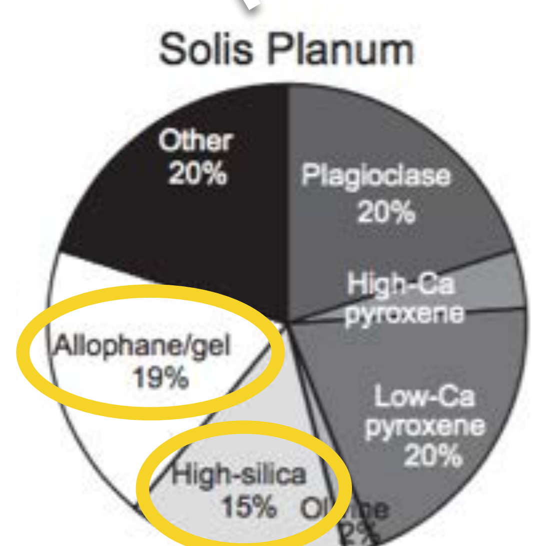
Modeled phases (Rampe et al., 2012):

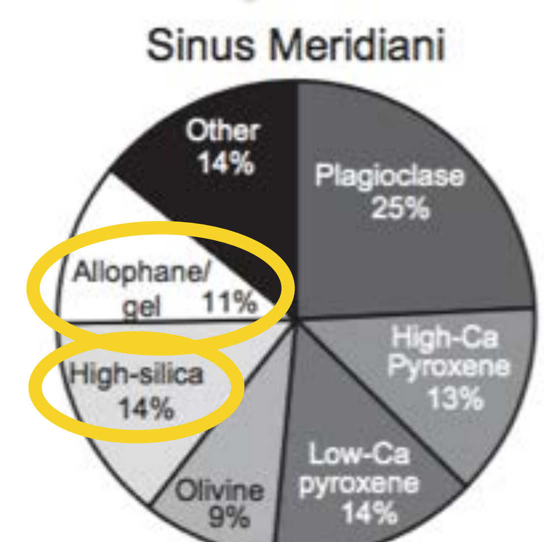




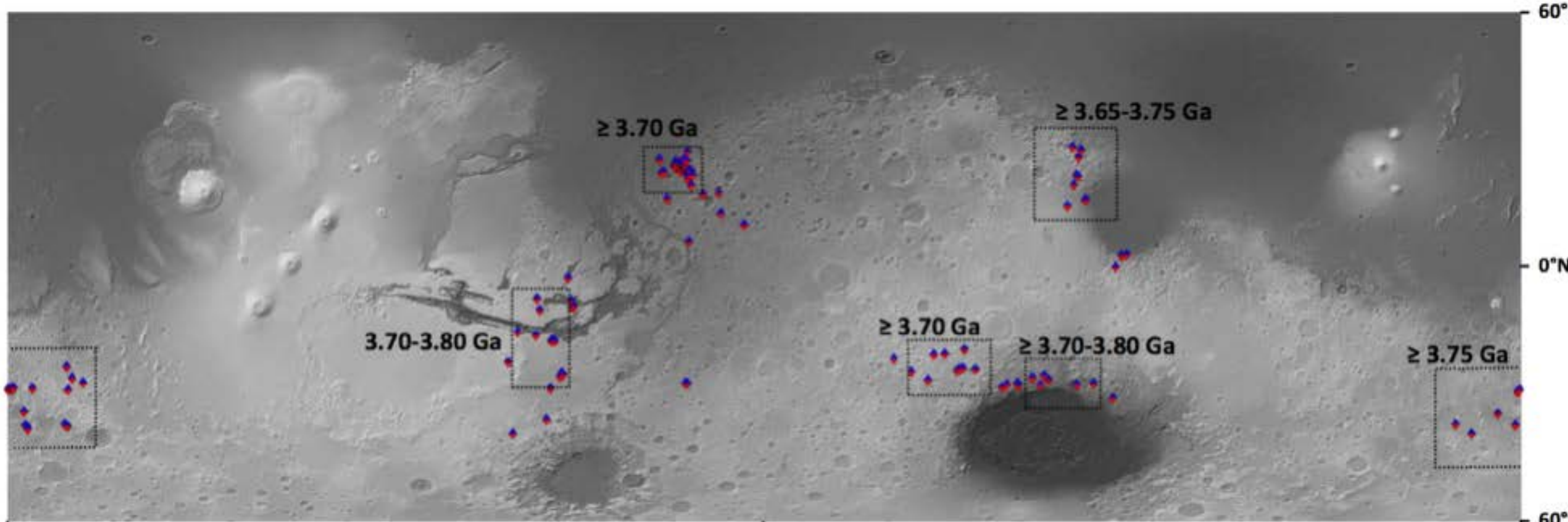
Ruff & Christensen (2007)



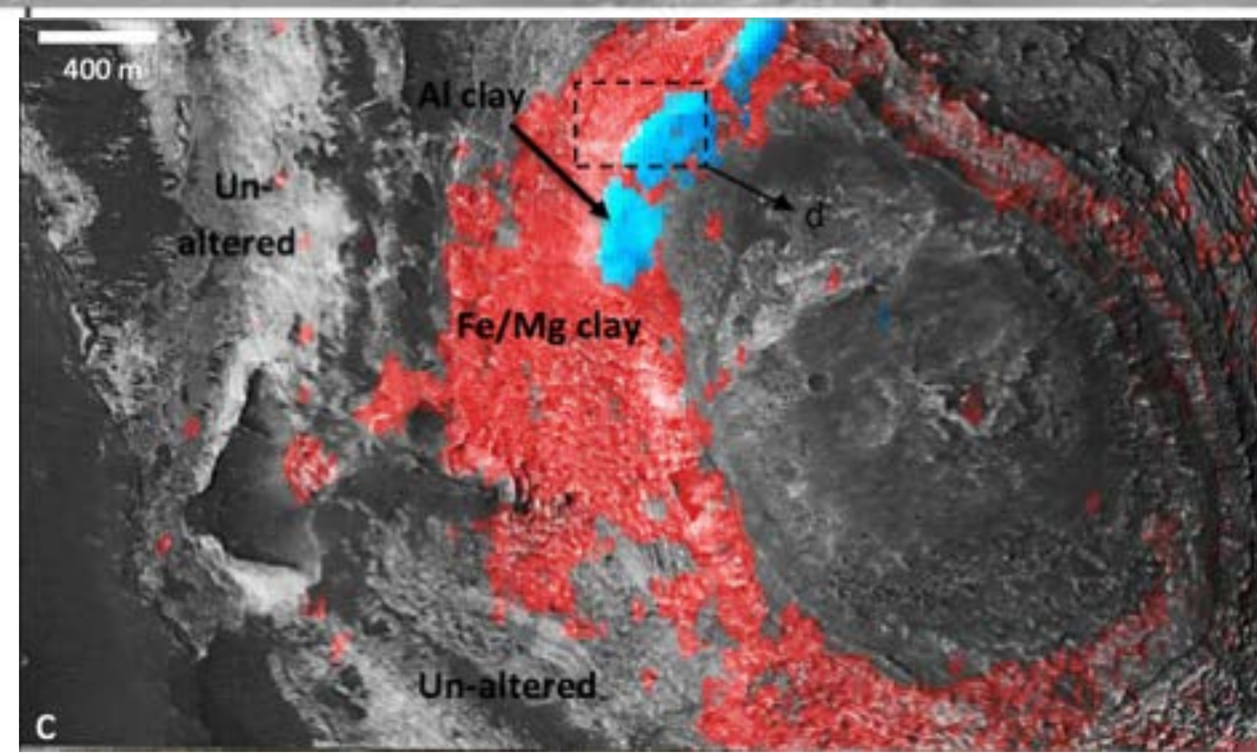




However, Noachian surfaces exhibit clear examples of well-crystalline clay minerals



Many deposits of clay minerals are consistent with deep leaching profiles, suggesting sustained rainfall



<u>Conclusions:</u> Cold-climate melt-driven weathering *could* be the origin for poorly-crystalline phases on Mars

- Based on our new analog work and previous terrestrial studies, cold-climate weathering tends to generate high abundances of poorly crystalline silicates

- Poorly crystalline silicate phases appear to be a common component of martian sediments

- However, we have yet to investigate unambiguously **Noachian** sediments in situ, and Noachian regions exhibit greater degrees of weathering than we can currently explain with cold climates

    - ***Thus, we cannot yet confirm a persistently cold climate on Noachian Mars***

- *Ongoing work:* MSL studies, composition of poorly crystalline phases in diverse climate regimes, experimental precipitation of amorphous phases

Thank you

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