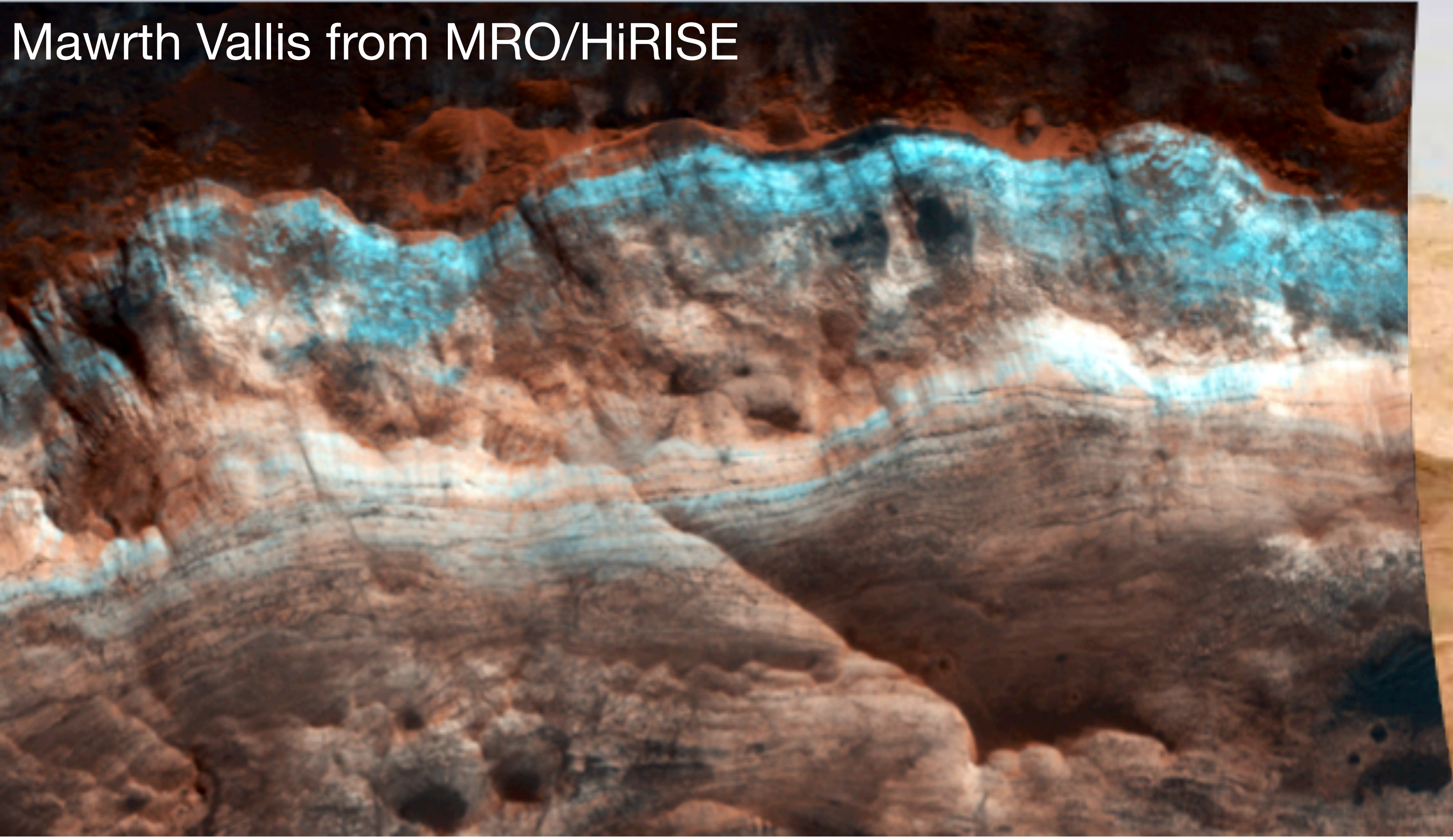

Mineralogical perspectives on Noachian paleoclimate and next steps

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02/09/2021

Presentation to the Decadal Survey Mars Panel

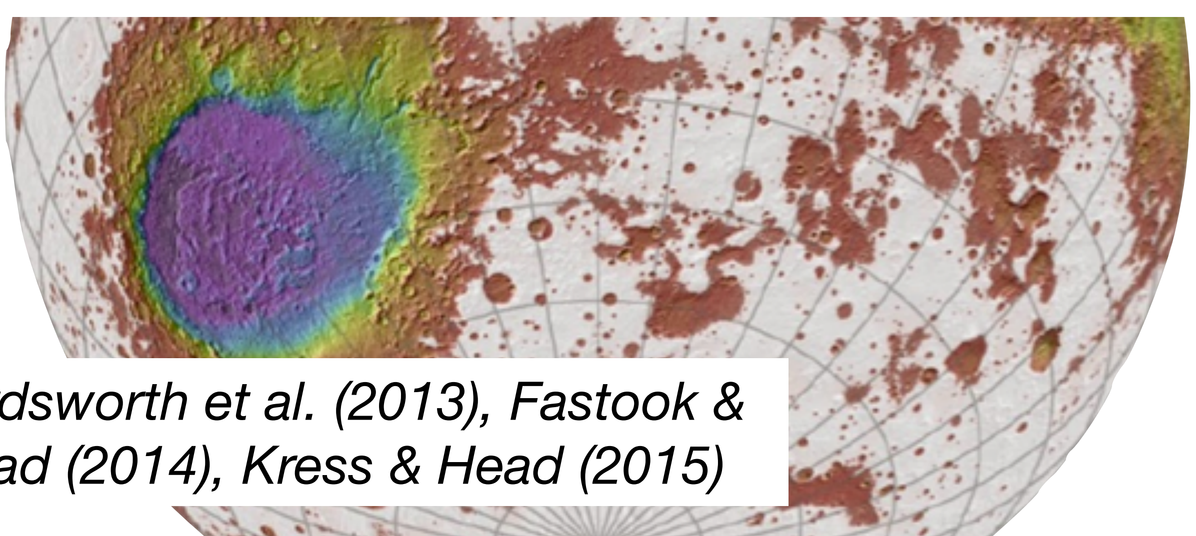
Answering key questions around paleoclimate will require synthesizing climate models, geomorphology, and geochemistry

- *Climate:* How warm or cold was the surface?
  - *Landforms:* What was the coverage and distribution of ice during the Noachian?
  - *Geochemistry:* Was alteration driven by rain or snow/ice melt?
- *Climate:* How did the climate change and on what timescales?
  - *Landforms:* What was the intermittency and duration of wet events?
  - *Geochemistry:* How and why did ancient environments change?

How warm or cold was the surface?

Landforms: What was the coverage and distribution of ice during the Noachian?

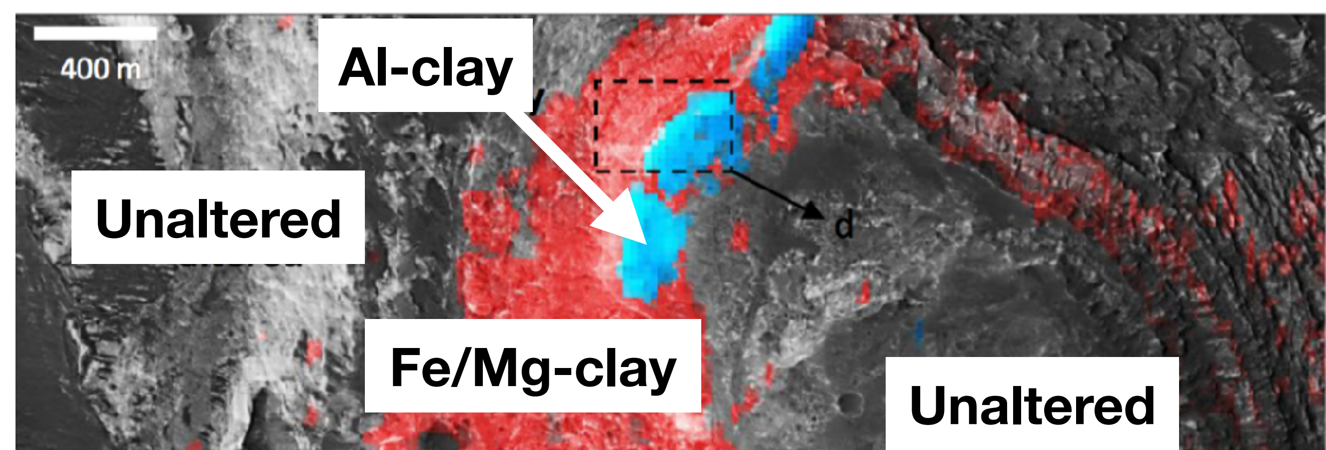
- Key observables (glacial landforms) well understood from Earth
- Currently unclear due to lack of landforms. Can we do a better job searching for these signatures in ancient, beaten up terrains?
- *Inform the search:* Where are the locations where we might expect to see maximum landscape modification? Models, analogs
- *Consider scale:* What resolution do we need to recognize glacial deposits in ancient terrains or the ancient geologic record? Surface vs orbital?

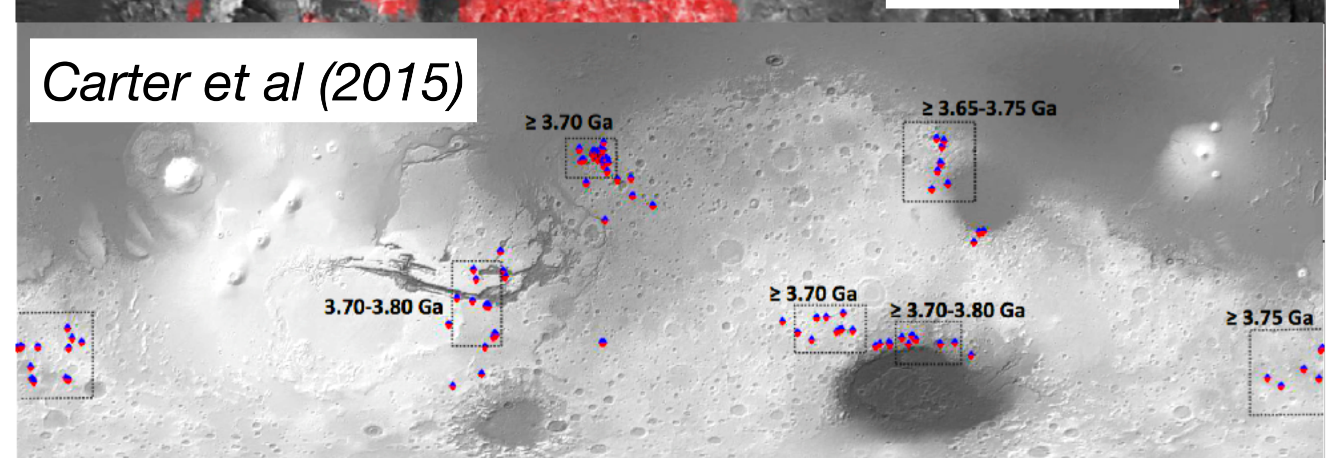


Wordsworth et al. (2013), Fastook & Head (2014), Kress & Head (2015)

Geochemistry: Was alteration driven by rain or snow/ice melt?

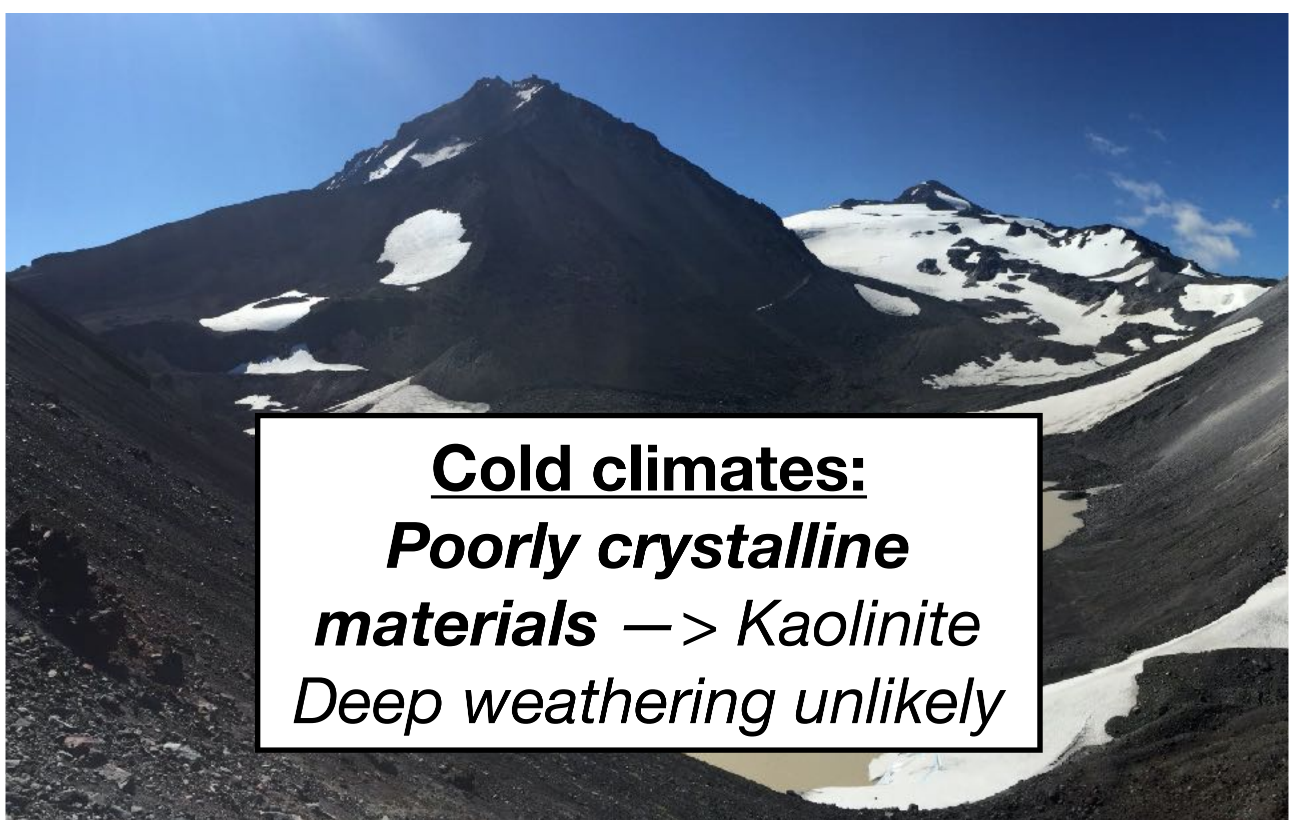
- Noachian mineral distribution on Mars is fairly well understood
- We see outcrops consistent with deep weathering profiles, but how did these form? What is the range of conditions that they *could* form under?
- Currently unclear because key observables (minerals as indicators of climate) are an open area of research

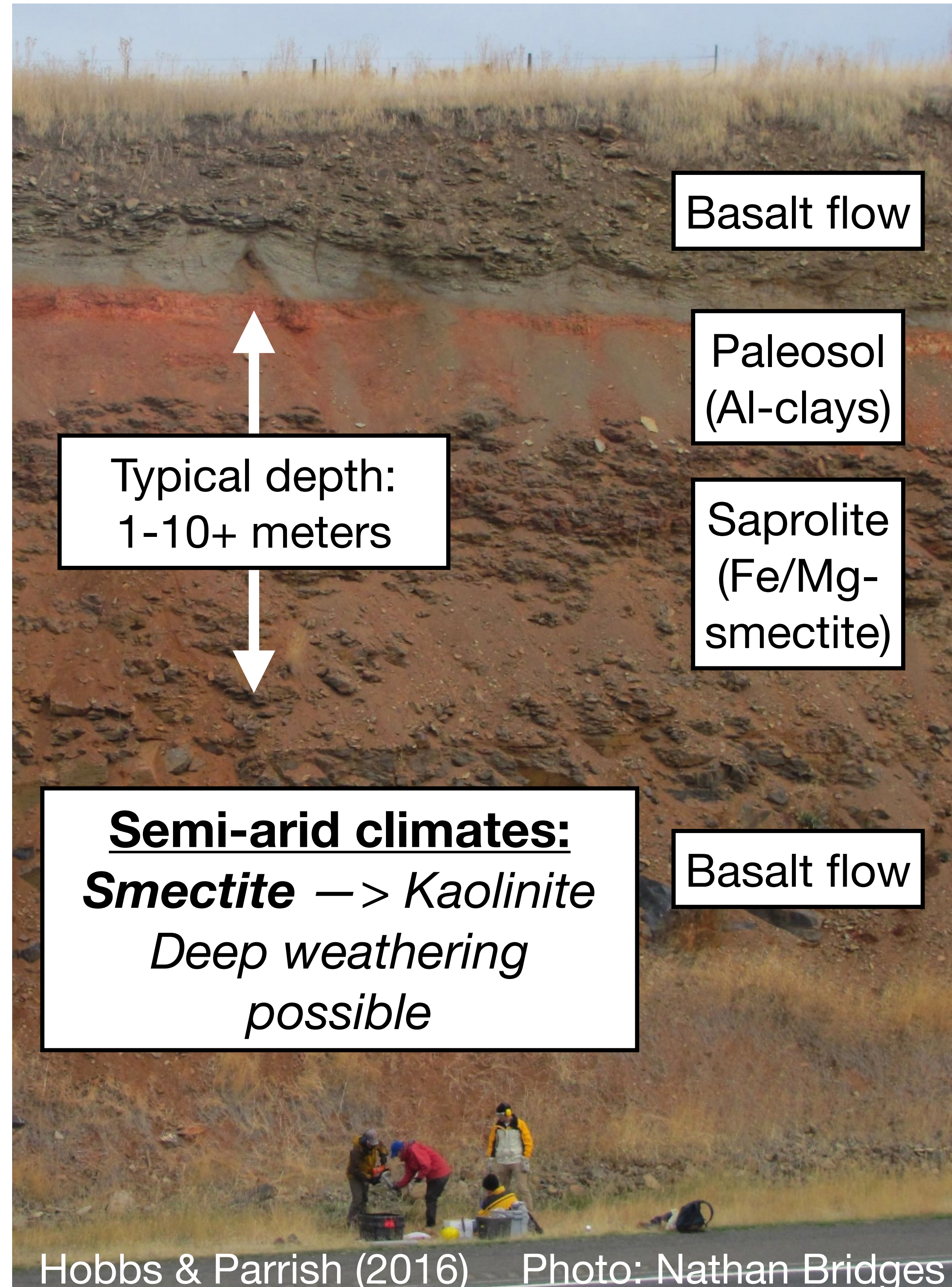




Carter et al (2015)

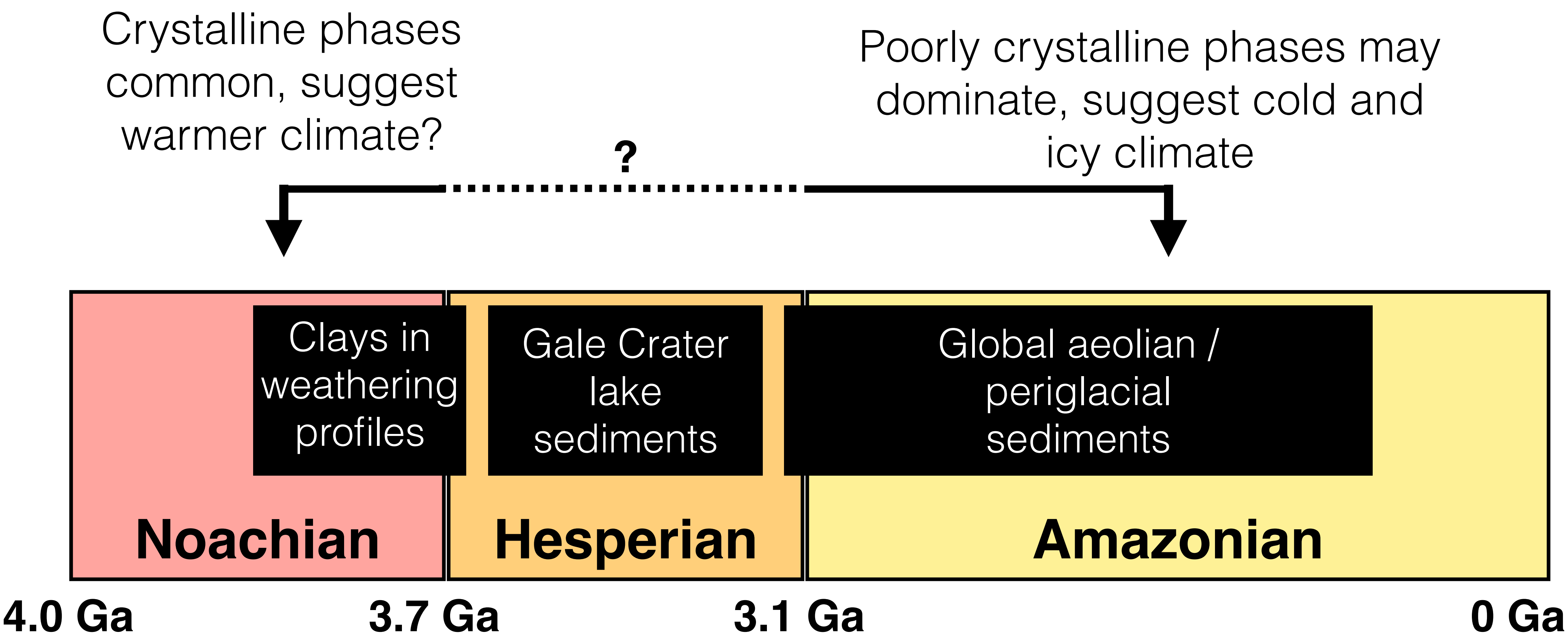
Impact of climate on weathering mineralogy - a framework from Earth analogs





Ziegler et al. (2003); Gaudin et al. (2011); Rutledge et al. (2018); Smith et al. (2018); Smith & Horgan, in review

On Mars, we see a clear transition from Noachian crystalline clay minerals to Amazonian poorly crystalline materials



- Noachian weathering profiles seem consistent with long-term (My+) weathering under an arid to semi-arid and temperate to warm climate
- **Remaining questions:** Does Mars fit into this Earth-based framework? Are there other scenarios that could create these weathering profiles? (e.g., super hot - Bishop et al. 2018; cold - Michalski et al. 2013; acidic - Ehlmann & Dundar, 2015)
- **We may be reaching the limitations of Earth analogs, testing these hypotheses will probably require <u>in situ investigation</u>**

The sedimentary record at Gale crater seems consistent with temperate, semi-arid lakes on Earth

- What do we see?
  - Impressively thick sequence of mudstones consistent with millions to tens of millions of years of lake activity (Grotzinger et al., 2014)
  - Intervals with increased salt (Rapin et al., 2019) suggesting some more arid periods
  - Smectite clays formed due to weathering (Bristow et al., 2018), in some cases at lake shores (Haber et al., LPSC 2020)
  - Much later lake episodes as recorded in deltaic landforms (Palucis et al., 2016)
- What do we not see?
  - Evidence of intense weathering (e.g., kaolinite)
  - Evaporite sequences (yet!) suggesting hot and arid climates
  - Evidence for a cold climate

How did the climate change and on what timescales?

Landforms: What was the intermittency and duration of wet events in the Noachian?

- Noachian erosion (e.g., crater degradation) + aqueous landforms (e.g., deltas vs. alluvial fans) are distinct from later eras
- (early Hesperian?) Lake activity at Gale seems fairly persistent
- Any mechanism for Noachian warming must also be able to explain clement Hesperian conditions and Amazonian wet pulses
- How does possible Noachian intermittency relate to Amazonian water activity and how do we tie the two together through the Hesperian?
- Need more investigation of sedimentary sequences and landforms from all eras, but Noachian is top priority

Geochemistry: How and why did ancient environments change?

- Environmental transitions at a given location may be related to global-scale processes OR they may only reflect local variability
- But how do we work out which is which? Even at Gale this is challenging.
- How representative are past environments at specific landing sites are of Mars during the relevant geologic epoch and how does that moment in time relate to the broader evolution of the planet? *(MEPAG Goal III.A3.1)*
- Need to tie sedimentary sequences + mineralogy/chemistry trends together across <u>regions</u>
- Need to better understand <u>local</u> mineral variability and mineral <u>assemblages</u>

With regard to the history of early Mars with emphasis on paleoclimate, what future measurements or analysis could be game-changing?

- Measurements:
  - High resolution mineralogy (hyper- or multispectral) + chemistry and imaging at scales <10 m/pix (ideally <5 or outcrop scale). *Target weathering profiles, sedimentary sequences - regional integration where possible.*
  - High resolution topographic data at scales <50 m/pix (ideally <10 m/pix). *Target fluvial/lacustrine(/glacial?) landforms.*
  - Better geophysical measurements - paleomag, gravity, ideally linked to these remote sensing datasets. *Target diverse Noachian terrain.*
- Models/Analysis:
  - Better models of weathering processes incorporating thermodynamics, physical transport, and kinetics
  - Continuing laboratory and analog studies to understand how weathering mineralogy and chemistry can be a paleoclimate tool
  - Better linkages between climate models, aqueous landforms, and geochemical signs of weathering

The future of Mars exploration requires missions that can make novel measurements to answer multiple high impact science questions

- High resolution mineralogy/geochem will be hard to justify as a standalone investigation, but could be competitive if paired with other high priority and complementary investigations
- ***Example 1: MORIE PMCS*** high-res imaging/spectroscopy + radar
- ***Example 2: Helicopter survey*** for imaging + mineralogy/chemistry + paleomag, at regional scales. Over the right (Noachian) exploration zone could be a powerful combination.
- But any multi-question mission will face cost/structural challenges
    - Radar pricing by JPL for MORIE was cost-prohibitive (but probably unrealistic)
    - EDL costs may be prohibitive (see MASWG report)