Searching for pedogenic phyllosilicates in ancient martian soils

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Motivation and Goals

- **What is the origin of martian phyllosilicates?** On Earth, extensive phyllosilicate-rich deposits are created through soil formation (pedogenesis). Could some martian phyllosilicates be pedogenic?
- **What do phyllosilicates tell us about ancient environments and habitability?** Paleosol mineralogy and geochemistry record environmental conditions at the time of their deposition, and can be used to constrain past near-surface habitability.
- **Which sites are the best targets for finding ancient organics and signatures of life?** Soils are highly habitable environments, and have excellent preservation potential. Paleosols on Earth harbor the oldest non-marine organics and eukaryote fossils (1).
- **In this study,** we are investigating the mineralogy as well as the near and mid-infrared spectral characteristics of terrestrial paleosols formed under a range of environmental conditions, in order to develop methods to identify paleosols from orbit.
- **Goal:** Evaluate known phyllosilicate-bearing sites on Mars for signs of pedogenesis

Methods

- Collected 25 samples of clay-bearing paleosols with a wide range of mineralogies from units exposed in the John Day Fossil Beds National Monument (2).
- Coordinated spectral analysis on 13 representative samples:
  (1) Room temperature near-IR spectra
  (2) 80°C mid-IR spectra, heated for spectral contrast
  (3) 80°C near-IR spectra to check for changes in hydration
- Compare mineralogies interpreted from near-IR and mid-IR spectra. Do they correlate? What are the discrepancies?
- Verify with XRD, compare to predicted mineralogy/abundances
- Apply lessons to Mars surface spectra: What minerals are found in near/mid-IR at different sites? What variety is there in absorption band strength/positions?

Soil Formation and Mineralogy

- ***Pedogenesis (soil formation):*** All of the chemical processes that lead to vertical chemical differentiation of surface sediments above the shallowest impermeable layer
- The major secondary minerals created during pedogenesis are **phyllosilicates and oxides**.
- The mineralogy of a soil depends on the degree of weathering:

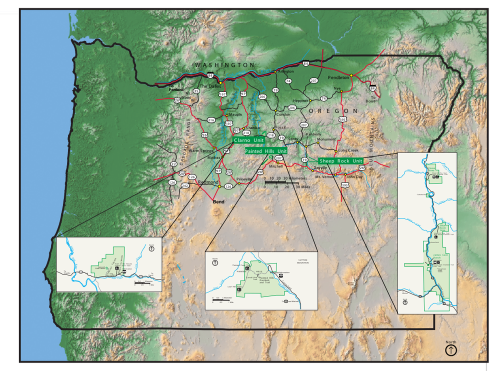
Sample profile:								
Soil type:	Aridisol	Inceptisol	Andisol	Spodosol	Vertisol	Alfisol	Ultisol	Oxisol
Minerals present:	Calcite	Minor clays	Allophane Ferrihydrite	Smectite Allophane	Smectite	Kaolinite	Kaolinite Oxides	Oxides

Al/Fe content, Degree of weathering increasing →

Paleosols as Environmental Records

- ***Paleosols:*** Relic soils preserved in the stratigraphic record when a soil is buried by subsequent units (sediments, lava, etc.), compacted, and lithified, found prior to 2.7 Ga on Earth (3,4).
- Paleosols directly interact with the surface environment, often provide better records of local climate than marine sediments
- On Earth, isotopes, mineralogy, chemical profiles are used to make estimates of climatic variables at time of formation - precipitation, atmospheric composition, temperature, etc. (5).
- **Paleosol sequences can be identified from orbit.** These deposits can be 100's of meters thick and provide records of surface conditions over millions of years (2,6)

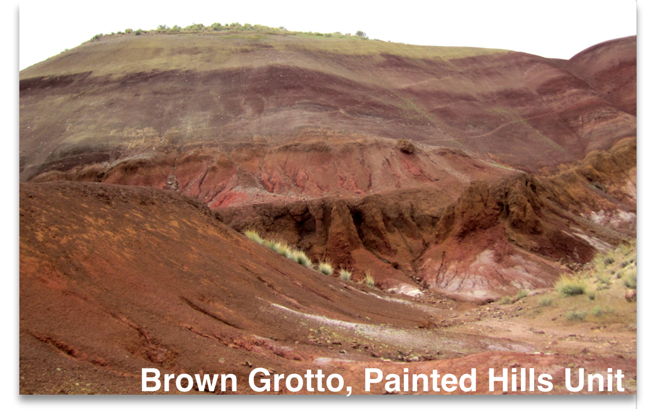
Mars Analog: John Day Fossil Beds



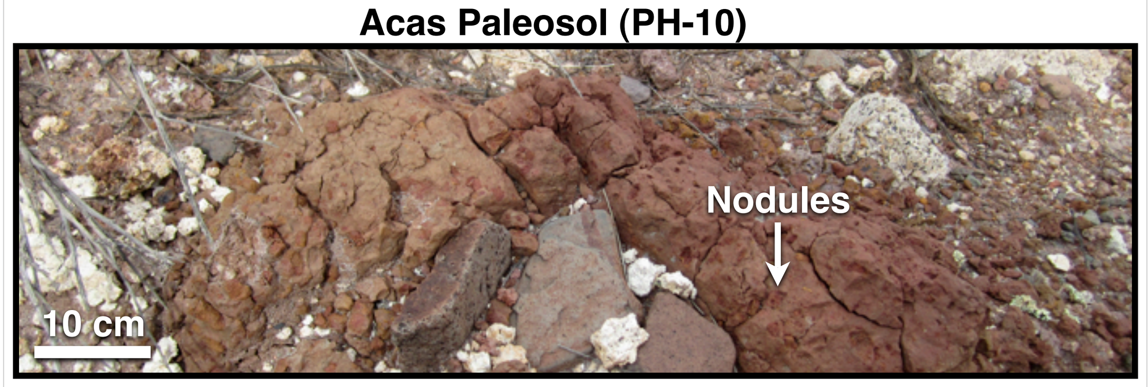
- To identify pedogenic mineral assemblages in orbital near and mid-infrared spectra, first we need spectra of natural paleosol samples.
- **Sample site:** John Day Fossil Beds NM, Oregon, USA (2)
- Volcanic sedimentary sequence on flanks of Cascades volcanic arc. Pyroclastic flows, ash, and fluvial deposition over 14 My.
- Units have experienced ~1km of burial
- 42-28 Ma: Eocene-Oligocene boundary, time of global cooling. **440 meter stack of paleosols transitions upward from highly weathered laterites to minimally weathered andisols.**

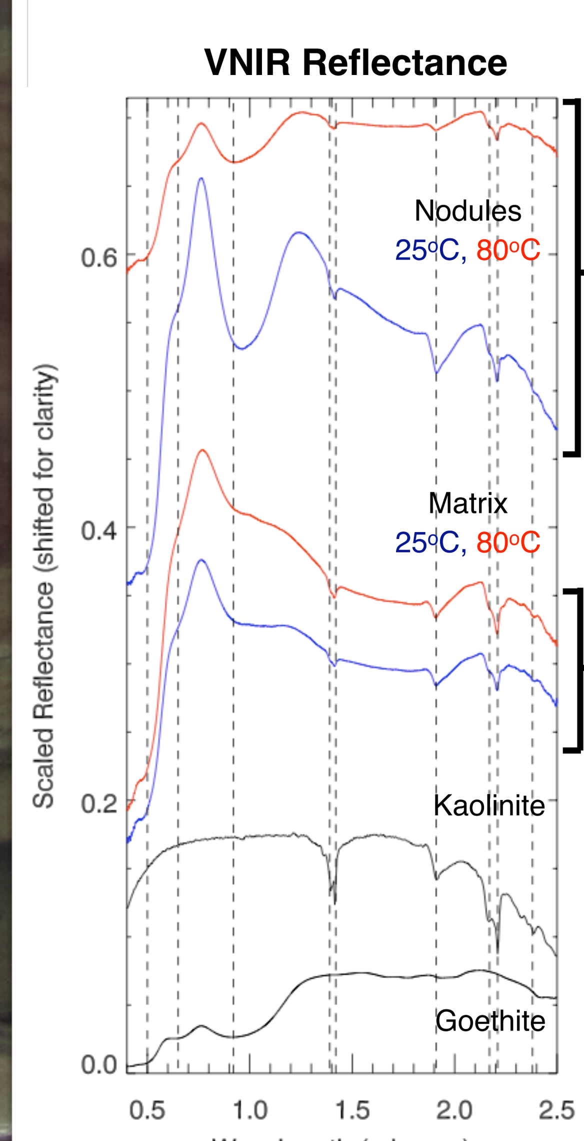
Kaolinite and Oxide-rich Paleosols

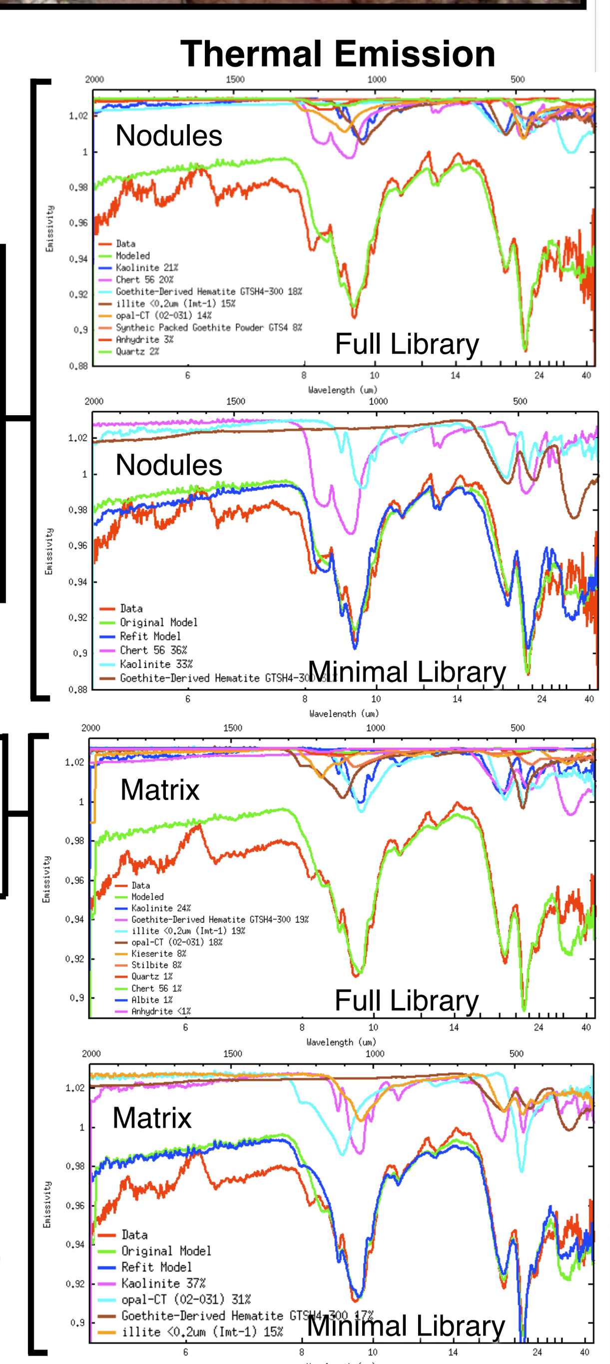
- **Highly weathered soils** formed in a humid climate form over thousands to tens of thousands of years.
- **Acas paleosol:** Ultisol with red detrital nodules derived from mass wasting of older soils (2)



Acas Paleosol (PH-10)

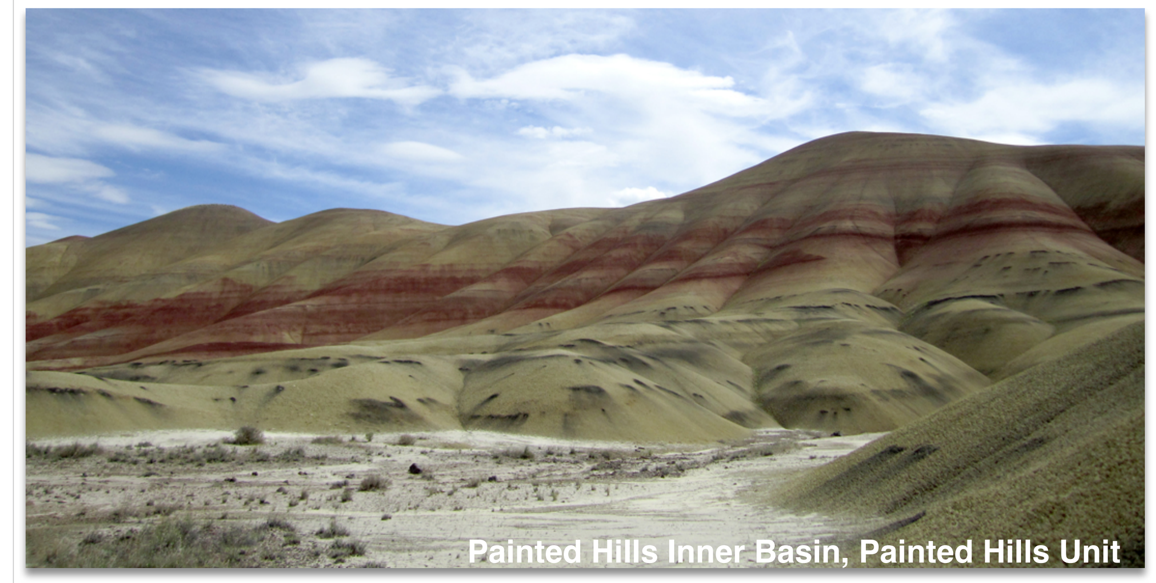






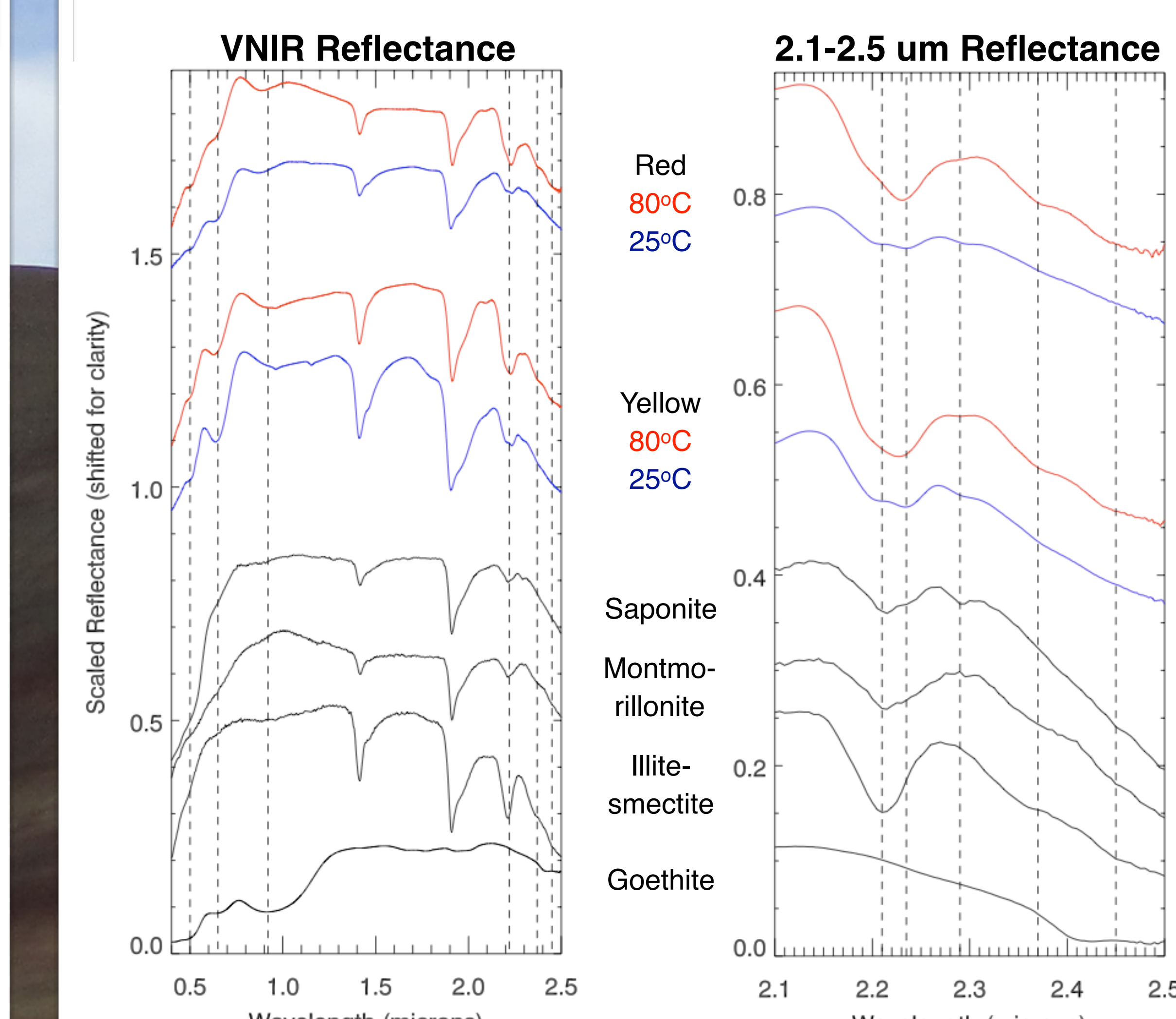
- **VNIR detections:** Kaolinite and goethite, no silica
- **Thermal deconvolution:** Kaolinite (~35%), oxides, and silica
- Only spectral changes on heating appear to be dehydration
- Very little burial alteration evident (no burial reddening or chlorite, minor illite in matrix?)
- **Big surprise:** Importance of poorly crystalline phases in thermal spectra. May be slightly more crystalline in nodules?

Smectite-rich Paleosols

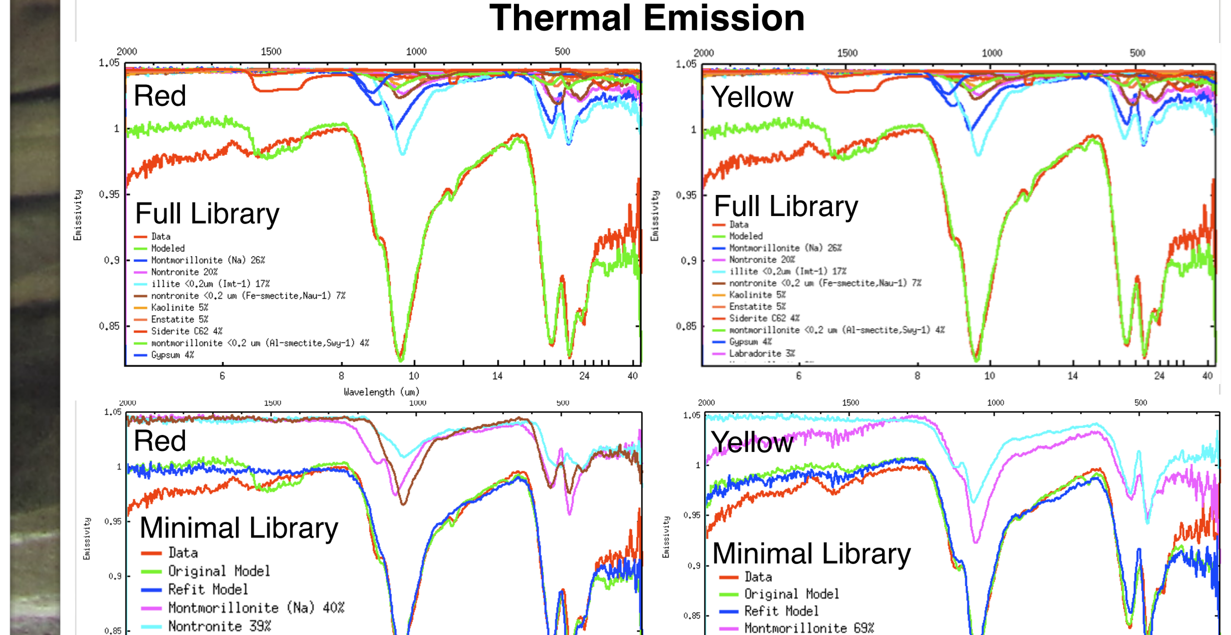


- **Moderately weathered soils** formed in a temperate climate or in poorly drained soils, form over hundreds to thousands of years.
- **Luca and Lakim paleosols:** Alfisols and inceptisols with iron-manganese nodules resulting from organic concentrations (2)

Lucas and Lakim Paleosols (PH-3)



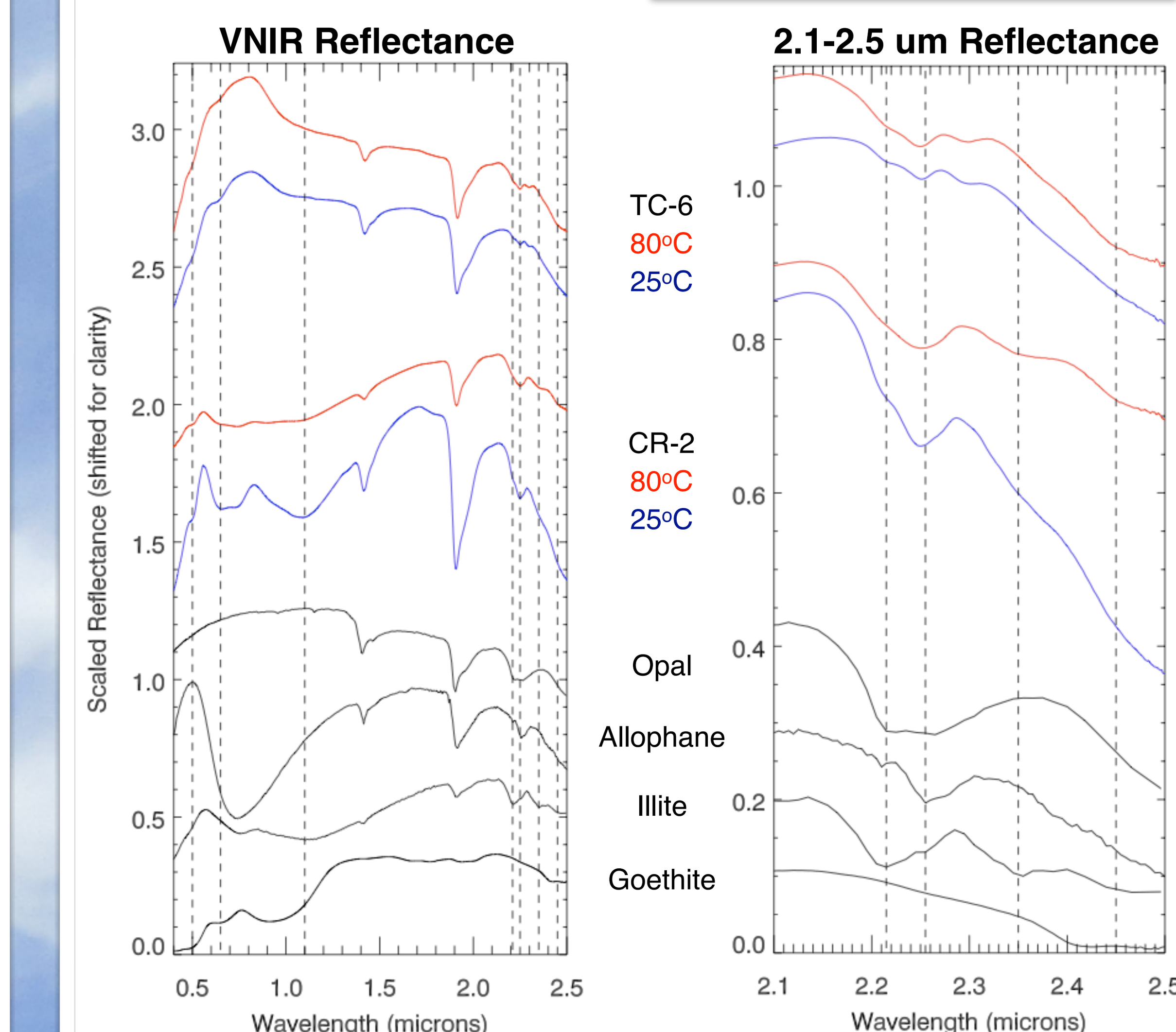
Thermal Emission



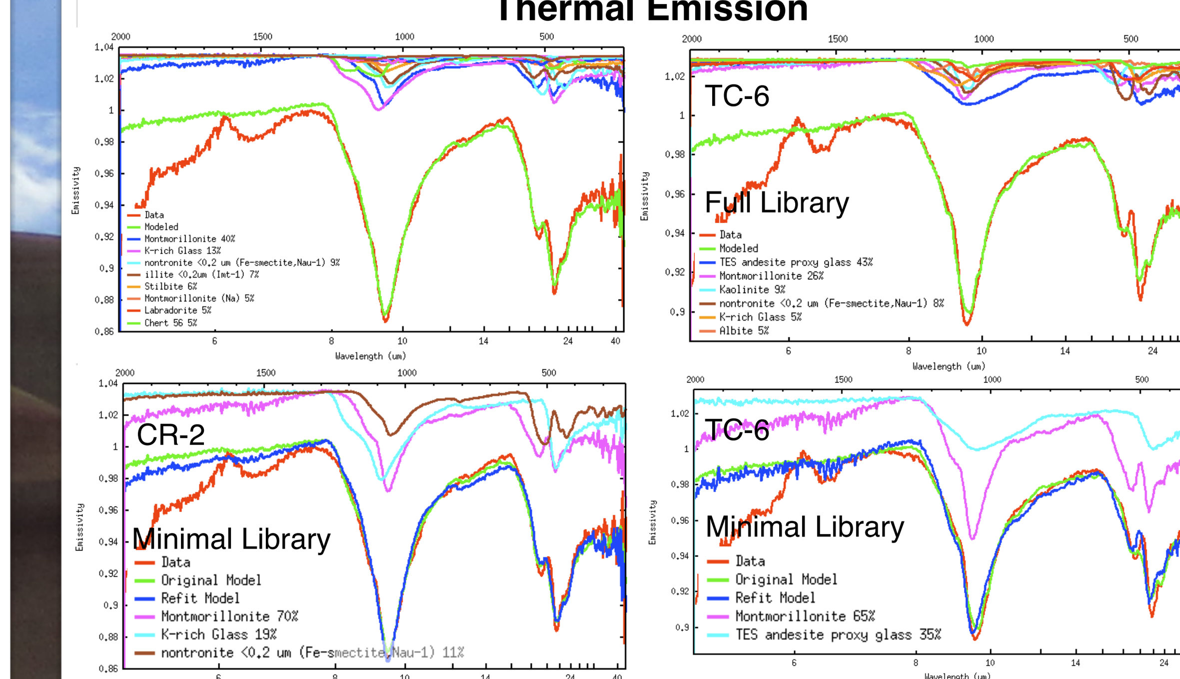
- **VNIR detections:** Goethite and smectites (composition unclear)
- **Thermal deconvolution:** Montmorillonite and other smectites
- Major spectral changes in 2.2 um region during heating - changing crystallinity, illitization? How is this affecting TIR clay spectra?
- Are we seeing evidence for burial illitization?
- **Big surprise:** Smectite absorptions are non-unique in VNIR and TIR ("a big smectite mess"). How often are smectite bands like this in martian surface spectra? Might this indicate pedogenesis?

Poorly-crystalline Paleosols

- **Minimally weathered soils** formed in a cool, arid climate , form over hundreds of years.
- **Micay and Wawcak paleosols:** Inceptisols and entisols (2)



Thermal Emission



- **VNIR detections:** Goethite, illite, and allophane?
- **Thermal deconvolution:** Montmorillonite, poorly crystalline silica
- Minor spectral changes in 2.2 um region during heating
- These units have probably undergone burial illitization
- **Big surprise:** Poorly crystalline silicates - allophane? These are a dominant phase in ash-derived soils (andisols), but aren't expected to persist in paleosols (should become more crystalline)

Conclusions

- VNIR and TIR compositions broadly agree. Well and poorly crystalline clays are detected in VNIR and TIR equally well.
- Pedogenic smectites may be spectrally distinct
- Allophane appears to be preserved and detectable in paleosols
- **Future work:**
  - XRD: Test compositions/abundances interpreted from spectra
  - Mixtures with basalt: Test relative detectability of phyllosillicate and oxide absorptions in near and mid-IR
  - Application to TES/THEMIS (mid-IR) and OMEGA/CRISM (near-IR) at candidate paleosol sites

References: [1] Strother P *et al*. (2011) Earth's earliest non-marine eukaryotes. *Nature, 473*, 505-509. [2] Bestland E. *et al*., (1997) Stepwise climate change recorded in Eocene-Oligocene paleosol sequences from central Oregon. *J. Geol.*, *105,* 153-172. [3]Kimberley M. and Grandstaff D. (1986) Profiles of elemental concentrations in Precambrian paleosols on basaltic and granitic parent materials. *Precambrian Res.*, *32* , 133-154. [4] Driese S. (2004) Pedogenic translocation of Fe in modern and ancient Vertisols and implications for interpretations of the Hekpoort paleosol (2.25 Ga). *J. Geol., 112*, 543-560. [5] Sheldon N. and Tabor N. (2009) Quantitative paleoenvironmental and paleoclimatic reconstruction using paleosols. *Earth Sci. Rev.*, *95*, 1-52. [6] Kraus M. (1999) Paleosols in clastic sedimentary rocks: their geologic applications. *Earth Sci. Rev.*, *47*, 41-70.