Signatures of Weathering on Ancient Mars: A Global Spectral Database of Martian Compositional Clay Stratigraphies

A. Klidaras, *Purdue University, USA (aklidara@purdue.edu)*, **B. Horgan, W. H. Farrand**, *Space Science Institute, USA*, **A. Broz**, *Purdue University, USA*, **T. Goudge**, *University of Texas at Austin, USA*, **S. Olson**, **C. Albright**, *Purdue University, USA*.

Introduction:

The climate of early Mars remains a topic of considerable debate. Ambiguity remains around key properties, including: the origin(s), number, and duration of warm intervals, average surface temperatures, the composition and pressure of the atmosphere, and the size of the martian water inventory. Martian compositional clay stratigraphies (CCS hereafter) are ~3.7 Ga deposits where Al-phyllosilicates overlie Fe/Mg-bearing phyllosilicates (Wray et al., 2008). Most authors have interpreted these vertically stratified clay sequences as ancient weathering profiles, therefore these deposits have the potential to provide constraints on the environmental conditions and climate of early Mars. Visible-Near Infrared (VNIR) orbital spectroscopy can be used to investigate these deposits remotely through the detection of diagnostic phyllosilicate cation-OH absorption bands between 2.15-2.35 μm (Bishop, 2019). Specific phyllosilicate phases signify different paleoenvironments, e.g., saponite indicating closed-system, typically subsurface aqueous alteration vs kaolinite indicating open-system intense subaerial leaching. Other secondary minerals e.g., hematite, carbonates, sulfates are indicators for conditions like redox state and acidity. However, detailed investigation of the phyllosilicate phases in CCS and their association with other secondary minerals has so far been limited to small regions, and typically employs qualitative spectral analysis. Following from the description of the spectral analysis pipeline (which maps and classifies CCS phyllosilicate phases) in Klidaras et al. (2025b), we present new preliminary results on the diversity of alteration minerals in the Al-units of CCS, and the diversity of accessory phases in CCS globally.

Methods:

At each of the 124 TRDR CRISM images categorized as containing CCS in Carter et al. (2015), alteration minerals were classified by band center across the 2.14-2.36 μm range. The band center classification system and product is visually depicted in Figure 2. Representative spectra and Viviano et al. (2014) spectral parameters were extracted from pixels with high band depth (to mitigate the influence of noisy pixels). Ratioing was not performed. Further details about the spectral analysis pipeline can be found in Klidaras et al. (2025b).

For each band center group (Figure 2) in each CRISM image, a Region Of Interest (ROI) was automatically generated to isolate high band depth pixels using a statistical threshold of: mean(band depth) + 1 standard deviation. From each ROI, an average spectrum was saved. To explore the diversity of Al-unit spectra, the Al-rich and Al/Si-OH ROI spectra (~250 total) were manually reviewed. For each class of band center/shape observed, a representative spectrum was recorded, and plotted alongside laboratory spectra of relevant minerals in Figure 3.

The spectral parameter results were analyzed by region, as defined in Carter et al. 2015. However, a new region was created to represent the cluster of CCS outcrops exposed at Valles Marineris as well as adjacent exposures to the south in Thaumasia Planum as well as NW Noachis Terra (see Figure 1).

Preliminary Results:

Al-unit Diversity (Figure 3). Considerable diversity in Al-unit mineralogy was found, including absorption bands resembling montmorillonite, kaolinite/halloysite, and potentially amorphous/poorly crystalline phases. Neither beidellite or alunite were detected.

Narrow 2.20-2.21 μm absorptions that resemble the smectite mineral montmorillonite were found to be common and found at all regions.

Kaolinite/halloysite-like spectra were relatively common. These were distinguished by the presence of a sharp 2.20-2.21 μm band accompanied by a weaker absorption at 2.165 μm. The clearest signa-

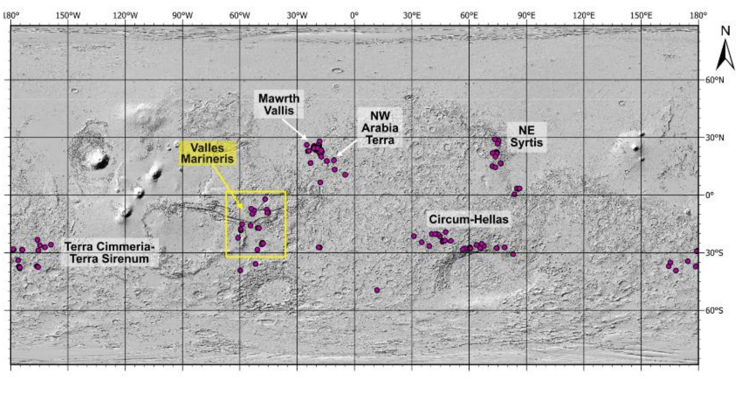

FIGURE 1*: Map of CCS exposures studied.*

MOLA hillshade of Mars, with CCS CRISM images found in Carter et al. (2015) indicated with purple dots. Regions identified in that study are labelled in white, the additional region proposed in this abstract is colored yellow.

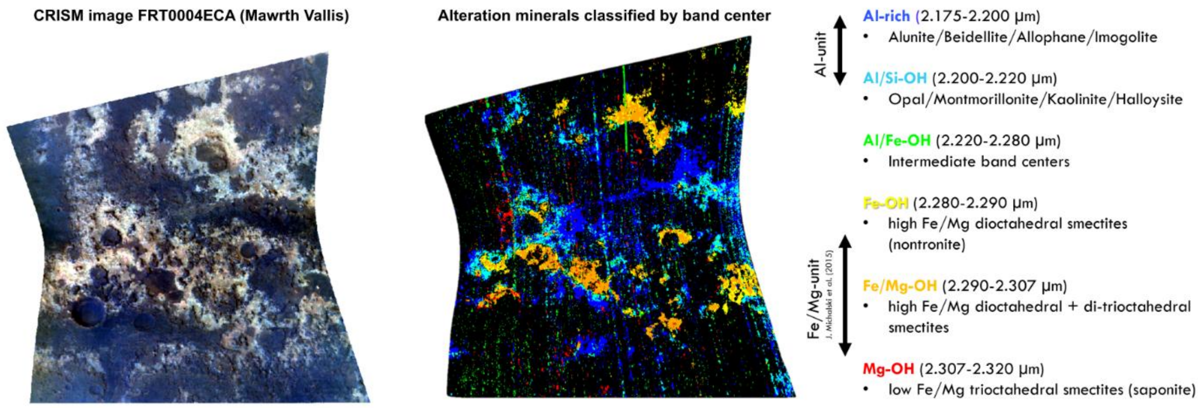

FIGURE 2*: Mapping alteration minerals by band center.*

(Left) CRISM image FRT00004ECA enhanced true color composite (R/R631, G/R527, B/R442) vs alteration mineral map (Right), with key depicting the band center classification system.

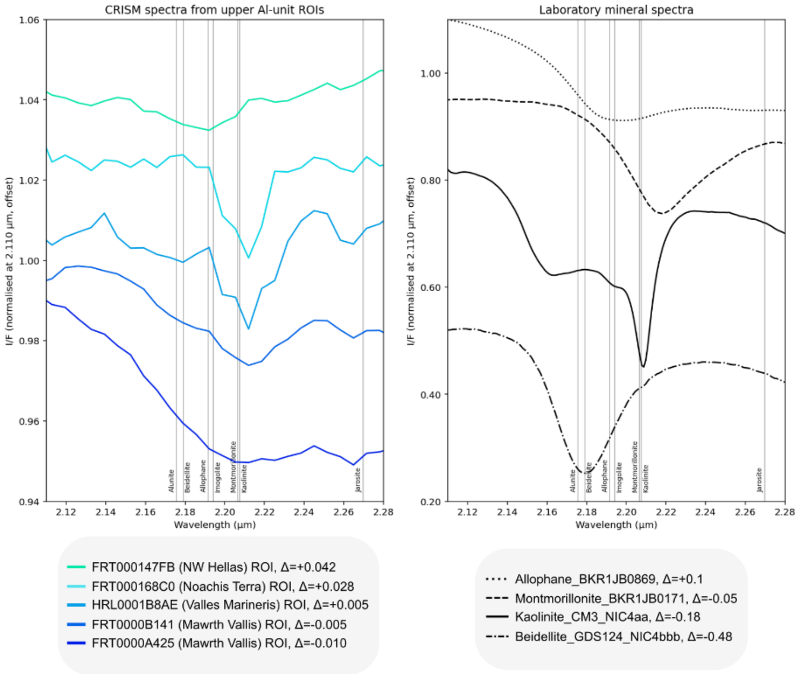

FIGURE 3*: Diversity of Al-unit band shape and center. (Left) Unratioed CRISM spectra from automatically generated high band depth ROIs, normalized and offset for clarity. Vertical lines with labels indicate the mean band center position of that mineral as calculated in Klidaras et al. (2025a, 2025b). (Right) Laboratory mineral spectra of aluminous minerals/mineraloids previously detected in the Al-unit of CCS, normalized and offset for clarity.*

tures were found in the Mawrth Vallis, Terra Cimmeria – Terra Sirenum, and Valles Marineris regions.

Broad absorption bands with 2.20-2.21 µm band centers and a pronounced asymmetry were abundant, especially at Mawrth Vallis. Their asymmetric shape is closer to kaolinite/halloysite than montmorillonite, but lack a well defined 2.165 µm absorption. This could reflect the ubiquitous noise masking this weaker feature, poor crystallinity, or mixture/interlayering with Al-smectites like montmorillonite.

Narrow absorptions with 2.19 µm band centers indicative of poorly crystalline aluminous phases like allophane/imogolite (Bishop and Rampe, 2016) were not common. However, candidate detections were made at Hellas and Mawrth Vallis. Follow up work is needed using close examination of the 1.9 µm band position to confirm the presence of allophane/imogolite.

Narrow 2.18 µm-centered beidellite-like absorptions have not yet been detected. This contrasts with previous detection of beidellite in Mawrth Vallis and NE Syrtis (Bishop et al. 2011), further investigation is needed to confirm if it really is absent or occurs in small exposures that are averaged out by the ROI generation process. Alunite, which has a broad ~2.17 µm absorption feature, was not observed either.

Accessory Mineral Comparison (Figure 4). BD2265 (jarosite/gibbsite/acid-leached nontronite) clearly exhibits stronger values in the Al-unit than the Fe/Mg-unit. Narrow, weak 2.265 µm absorptions are ubiquitous throughout the Al-unit spectra shown in Figure 3. This spectral parameter is strongest in the Al-unit of NE Syrtis.

SINDEX2 (hydrated sulfates) shows the inverse pattern, with a clear enrichment in the Fe/Mg-unit vs the Al-unit. This trend is strongest in NE Syrtis but nearly absent in Valles Marineris

BD1900 (water and hydroxyl-bearing minerals) is usually weak. No consistent enrichment in either unit is observed. The strongest hydration is found in the Mawrth Vallis and NW Arabia Terra regions, which are adjacent exposures.

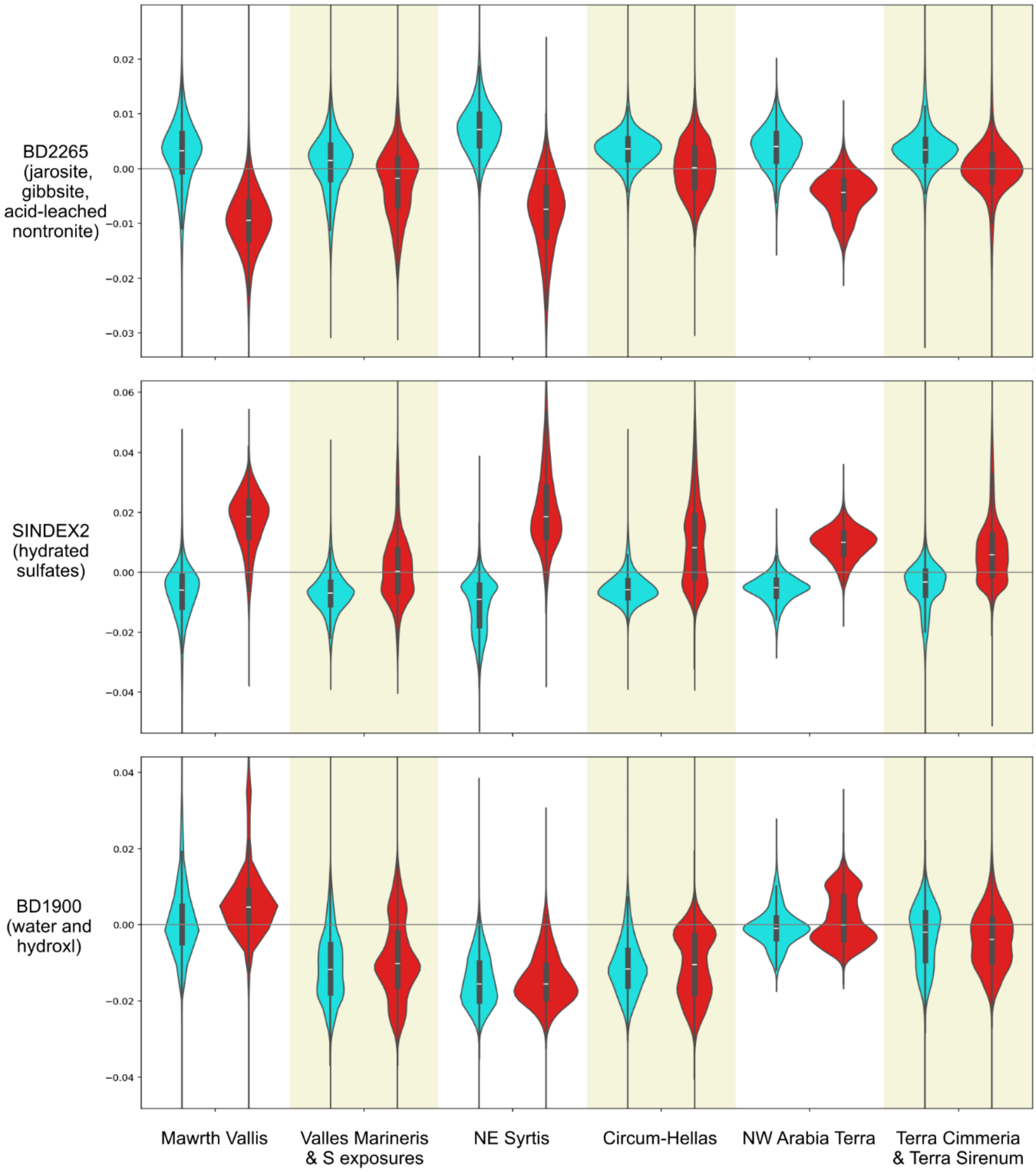

***FIGURE 4**: Spectral parameter comparison across different regions.*

Various Viviano et al. (2014) spectral parameters for every CCS pixel (masked by band depth to exclude noisy/unaltered pixels) in the 124 TRDR CRISM images analyzed, binned by region.

Discussion:

The widespread detection of kaolinite/halloysite-like spectra, as well as asymmetric spectra that lack a well-defined doublet (possibly reflecting poorly crystalline kaolinite/halloysite, or potentially mixture/interlayering between those minerals and montmorillonite), supports previous interpretations that CCS formed through intense subaerial leaching. However, the possible detection of allophane/imogolite at a few CRISM images – in agreement with an earlier discovery of these phases at Mawrth Vallis (Bishop and Rampe, 2016) – implies that some sites experienced only incipient, rather than intense, chemical weathering.

The high BD2265 values found at NE Syrtis is consistent with prior research suggesting a common association between jarosite and Al-phyllosilicates in Nili Fossae (Baker and Ehlmann, 2025). Its widespread detection and preferential enrichment within the Al-unit could be consistent with top down acid weathering, but closer examination is required to explore other controls on jarosite abundance such as spatially varying environmental and redox conditions.

The SINDEX2 preferential enrichment in Fe/Mg-unit is interesting, especially since the BD2265 results show the opposite pattern. This could be explained by an increased diagenetic overprint deeper in the subsurface, perhaps via gypsum/bassanite veins like those seen in Gale crater. Additionally, the abundance of swelling smectitic clays in the Fe/Mg-unit (as opposed to the kaolin-bearing Al-unit) could promote more fracturing, enabling more fracture-filling sulfate to be emplaced.

The stronger BD1900 hydration signatures at Mawrth Vallis and NW Arabia Terra, which are adjacent CCS exposures, could reflect a greater abundance of hydrated/OH-bearing minerals there. Alternatively, it could reflect better outcrop exposure, e.g., lesser dust/coating/regolith cover compared to other regions. This result could also reflect differing degrees of dehydration between regions.

Future Work:

The qualitative analysis of Al-unit spectra reported here will be followed up with a quantitative spectral parameter analysis, utilizing the 2.165 μm kaolinite doublet to map the relative abundance of kaolinite/halloysite-like vs montmorillonite/opal-like spectra.

The inferences from the Viviano spectral parameters reported here must be confirmed with actual examination of spectra, which is important because spectral parameters alone can be misleading. Additionally, careful consideration is needed to disentangle what mineral signatures are primary to the rock and what represent later diagenetic overprint, although orbital-resolution data could be insufficient to distinguish this; ultimately, this may require rover-scale observations to answer, such as those planned by the Rosalind Franklin rover in the phyllosilicate-bearing strata of Oxia Planum.

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