METER-SCALE MORPHOLOGY AND STRATIGRAPHY OF PHYLLOSILICATE-RICH OUTCROPS IN MAWRTH VALLIS.

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Introduction: Phyllosilicates on Mars were first detected definitively by the OMEGA spectrometer [1]. OMEGA-based studies have identified phyllosilicate spectral signatures scattered across the lower martian latitudes, usually in Noachian outcrops of light-toned, layered materials [2,3]. The phyllosilicates detected by OMEGA have spectra consistent with those of aluminum, iron, and magnesium smectite clays.

On Earth, clay minerals form most commonly at the planet's surface, through interactions with liquid water in an alkaline-to-neutral environment sustained over a geologically significant period of time [4]. Martian phyllosilicates may have formed in a similar environment, which may have been more Earth-like than either the present, late Amazonian arid climate or the acidic environment likely present when sulfate minerals formed in the late Noachian or Hesperian [3,5,6]. Alternatively, the phyllosilicates could have formed through subsurface aqueous alteration of initially anhydrous Noachian layered deposits, which would permit a range of possible surface conditions. Determining which mechanism(s) formed the martian phyllosilicates could have significant implications for our understanding of the planet's early climate.

OMEGA spectra have been used to identify—and CRISM spectra have confirmed—two distinct phyllosilicate mineralogies in light-toned layered outcrops in and around Mawrth Vallis: Fe/Mg-rich smectite consistent with the spectrum of nontronite, and Al-rich smectite consistent with montmorillonite [2,7]. Mawrth Vallis is an outflow channel that cuts through Noachian cratered terrain in Western Arabia [8] before debouching into the Chryse basin at 26° N, 340° E (Figure 1). Several studies have interpreted the phyllosilicate outcrops there as part of an ancient sedimentary deposit predating the formation of Mawrth Vallis [7,9]; alternatively, it has been suggested that this deposit may post-date Mawrth Vallis [10].

Methods: The 25-32 cm/pixel resolution of the HiRISE camera on MRO [11] enables detailed stratigraphic studies of layered deposits on Mars. Combining HiRISE images with mineralogical data from the CRISM spectrometer [12] is an approach well suited for studying chemical variation across a stratigraphic column. In Mawrth Vallis, such variation provides evidence for changing environmental conditions when the phyllosilicate-rich layers were deposited.

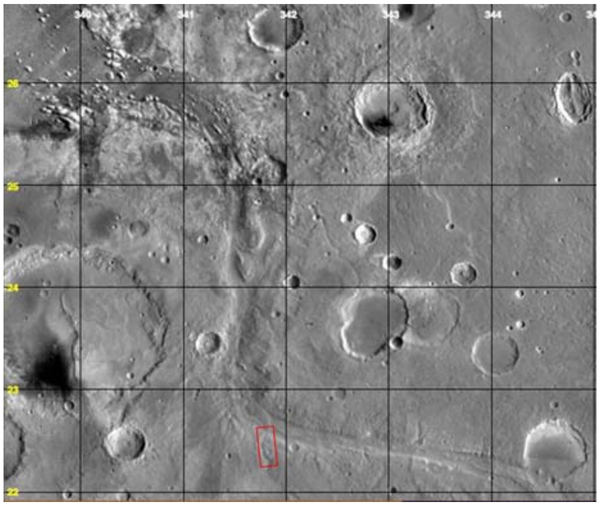

Figure 1. Viking MDIM regional view of Mawrth Vallis. Box highlights the area shown in Figure 2.

As of this writing, HiRISE has imaged eight areas in the Mawrth Vallis region, with stereo coverage for three. Coordinated CRISM observations exist for most of these targets, mostly at half-resolution or mapping resolution (~36 m/pixel or ~100 m/pixel, respectively). One full-resolution (~18 m/pixel) CRISM observation (FRT_3BFB) covers a tributary channel of Mawrth Vallis, for which HiRISE stereo imaging is also available (PSP_2074_2025, 2140_2025; box in Figure 1).

Simple atmospheric and photometric corrections were applied to CRISM data using the procedures in [13,14]. A subset of the image data from 1.0 to 2.6 µm was used to construct maps of the depths of the absorptions at 2.2 and 2.3 µm (BD2200, BD2300) typical of smectites according to (b1+b2+b3+b4)/(2*(b5+b6)), where b1 to b4 are nearby bands outside and on either side of the absorption and b5 to b6 are bands whose wavelengths are within the absorption. Surfaces with absorptions produce values >1. To assess hydration, the band depth at 1.9 µm (BD1900) was mapped according to [15]. A band depth threshold was chosen to include only spectra with obvious bands (based on visual analysis). In figures that follow, red indicates hydration from BD1900, blue indicates Al-smectites from BD2200, and green indicates Fe/Mg-smectites from BD2300. Residual vertical striping in some locations is due to an uncorrected instrument artifact.

These three indicator maps have been manually overlain on HiRISE PSP_2140_2025 (Figure 2), using albedo features in a CRISM color composite to align it with HiRISE. Both datasets have been projected using corrected MRO geometry, and only slight manual stretching of the southern edge of the CRISM image relative to its northern edge gives agreement to better than a CRISM pixel throughout the image.

Results: Figure 2 reveals a spatial separation of the Fe/Mg-smectites (green) from the Al-smectites (blue to pink). The color variation in the latter may reflect variability of hydration state, as indicated by the strength of the 1.9-µm water band (red). There are also some regions in which hydration is evident, but no strong metal-OH bands are observed. These regions may contain a different hydrated phase, or may simply have a lower abundance of phyllosilicates in the bedrock. Only the relatively light-toned portions of the HiRISE image have a phyllosilicate signature detected by CRISM; phyllosilicates are not detected in the darker unit that fills the tributary channel and forms resistant mesas overlying the light-toned bedrock. Note the lateral continuity (at a scale of decameters) of clay signatures across the light-toned outcrops in the scene.

Stratigraphy. Using the full resolution of HiRISE, at least four stratigraphically distinct units are visible in Figure 2. Figure 3 shows a portion of the image containing all four units, and Figure 4 shows full-resolution HiRISE samples from each unit, revealing differences in albedo and meter-scale morphology. The upper and lower units (1 and 4 in Figure 3) each contain Fe/Mg-rich phyllosilicates. Separating these are an Al-rich phyllosilicate unit (2) and a hydrated unit with negligible metal-OH absorptions (3). This stratigraphic interpretation is supported by the HiRISE stereo data.

The same four stratigraphic units can be identified elsewhere in the CRISM-HiRISE overlap region, and each unit also has distinctive color in HiRISE images (Figure 5). This observation suggests that these units may be mappable using only HiRISE images, perhaps allowing the stratigraphic study to extend beyond the region in which CRISM coverage is available. Indeed, Figure 6 shows a small valley in PSP_2140_2025, along the walls of which units 1-4 can be tentatively identified based on HiRISE color and morphology. Figure 6 also shows layering in which color variations are visible over scales of meters, implying a complex depositional history for the Mawrth Vallis region.

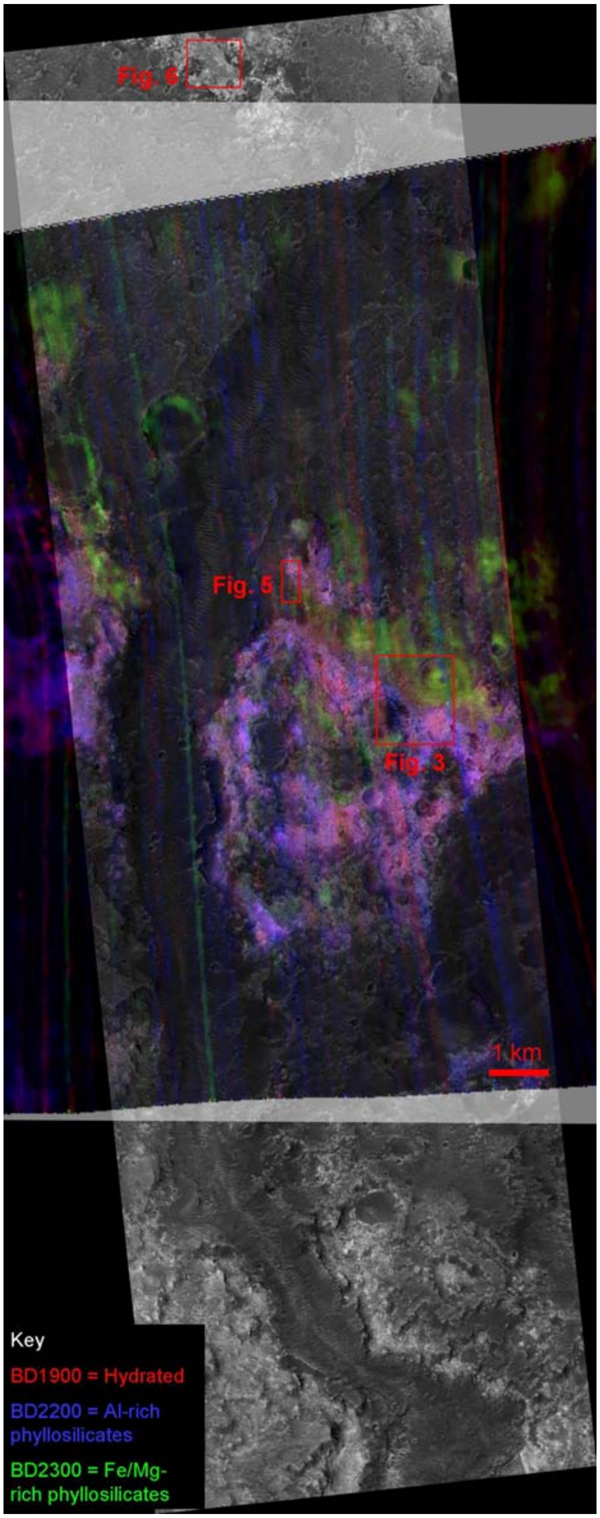

Figure 2. CRISM mineral indicator maps derived from FRT_3BFB overlain on HiRISE PSP_2140_2025. See text for details on map production.

Fracture Morphology. As Figure 4 shows, the uppermost phyllosilicate-rich unit (1) is only sparsely fractured. Polygonal fractures are present in unit 2, and are larger (typically 5-10 m across) in units 3 and 4. Another HiRISE image (PSP_1454_2030) covering a large light-toned outcrop on the floor of the main channel of Mawrth Vallis shows angular fracture polygons up to hundreds of meters across. This apparent increase in polygon size with depth in the stratigraphic section may be related to previous depth of burial, if these fractures formed from stresses associated with compaction and subsequent expansion when the overlying layers were eroded away. But this interpretation is complicated by the distinctive morphology of the polygons observed in the Al-rich unit (2). These polygons appear relatively equant and homogeneous in size, in comparison to the more angular blocks seen in units 3-4 and at the bottom of the main channel. In PSP_2140_2025 and elsewhere in the Mawrth Vallis region, the small, homogeneous polygons alternately display either raised rims or depressed rims, perhaps reflecting variable induration caused by fluid-induced alteration along polygon-bounding fractures. At any rate, the diverse fracture patterns observed in the phyllosilicate-rich deposits of this region may have formed through more than one process.

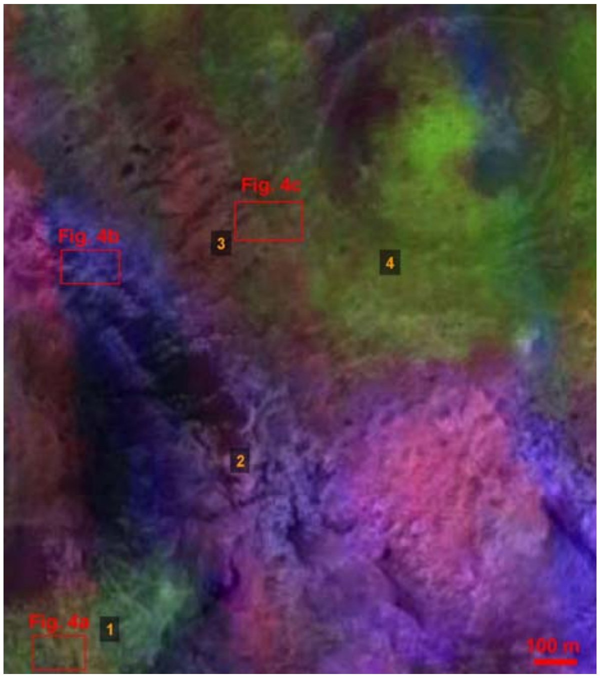

Figure 3. Close-up of a region in which four stratigraphically distinct units can be identified, from the top down: 1) Fe/Mg-rich; 2) Al-rich; 3) Hydrated but with no strong metal-OH absorptions; 4) Fe/Mg-rich. Orange numerals identify each unit.

Discussion: Fractured, light-toned layered deposits have been observed in other areas of Mars, including the portion of Meridiani Planum explored by the Opportunity rover. Detailed *in situ* studies have concluded that some decimeter-scale polygonal fractures observed in Meridiani rocks may have formed by desiccation [16,17]. The sub-meter-scale polygons observed by HiRISE in Mawrth Vallis, although slightly larger, may similarly have formed through desiccation of phyllosilicate-rich sediments. As for the larger, angular fractures discussed previously, the difference in size (a factor of 20 or more) between fractures on the main channel floor and those in the surrounding plains may constitute evidence against the hypothesis that all light-toned materials in the Mawrth Vallis region are part of a single drape deposit [10]. If, however, the drape deposit hypothesis is correct, then the morphology implies that post-depositional modification varied across the deposit.

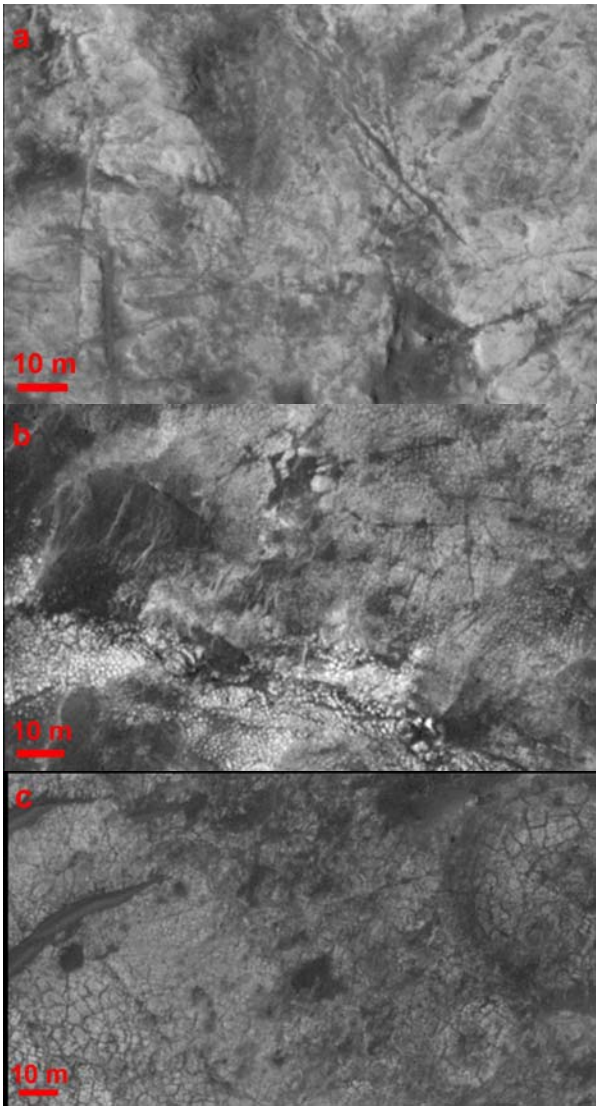

Figure 4. Full-resolution samples of the stratigraphic units identified in Figure 3. a) Unit 1 has sparse fractures, and is intermediate-toned. b) Unit 2 is the lightest-toned, with uniformly meter to sub-meter size polygonal fractures. c) Both units 3 (left) and 4 (right) are fractured into 5-10 meter size angular blocks. Unit 4 is relatively dark-toned. Figures a-c are displayed with the same photometric stretch.

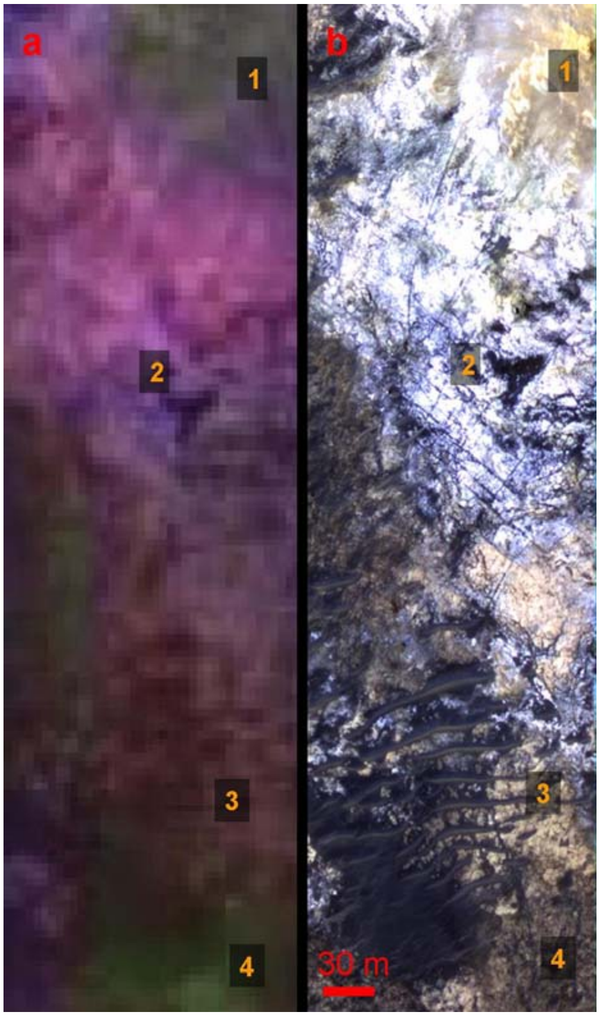

Figure 5. a) Close-up of another region containing all four hydrated units identified in Figure 3. b) HiRISE false color for the same region, showing that the units can be distinguished by color in HiRISE images. For the given stretch, (1) is yellow, (2) is blue-white, (3) is tan, and (4) is brown.

On Earth, *in situ* alteration at or beneath the surface typically results in a heterogeneous mixture of altered and unaltered rocks [4]. Thus, the lateral and stratigraphic continuity (at decameter scales) of the clay-rich units in Mawrth Vallis, and the lack of mafic spectral signatures in these units [7], may suggest that they formed in a subaqueous depositional environment. The alternating mineralogies—from Fe/Mg-smectites to Al-smectites and back again—may imply that water chemistry and/or sediment source changed over time.

As more CRISM full-resolution images of the Mawrth Vallis area become available, additional CRISM-HiRISE comparisons may yield further insight into the question of formation process. Digital elevation models to be derived from HiRISE stereo pairs will enable measurement of strike and dip angles, which can be used to constrain depositional processes and to aid in correlation of units between spatially separated outcrops. Comparing the results of this study to those of other phyllosilicate-rich regions on Mars [e.g., 13,14] may illuminate regional and global climatic conditions during the planet's early history.

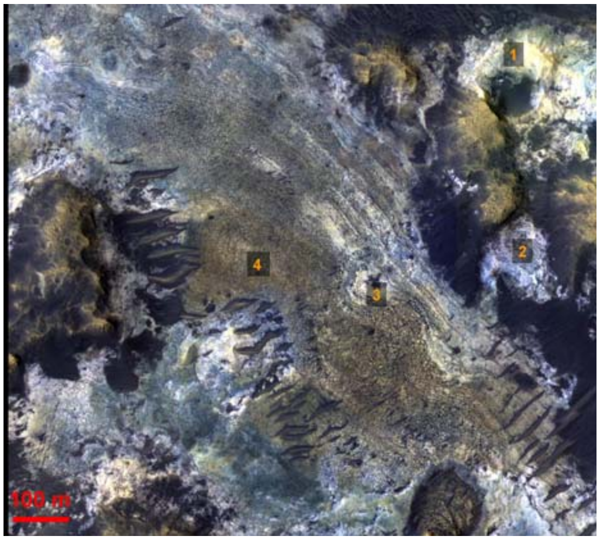

Figure 6. False color (same stretch as Figure 5) of a small valley outside the CRISM-HiRISE overlap region, where color and morphology reveal that the same four stratigraphic units are present here as well. Many sub-units of distinct color are also visible.

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