Sulfate mineral stratigraphy in Valles Marineris Interior Layered Deposits.

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Introduction: OMEGA (Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité) discovered sulfates in the Interior Layered Deposits (ILDs) in Valles Marineris [1] and those detections have been refined by spectral data from CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) aboard Mars Reconnaissance Orbiter (MRO) [2-5]. Combining mineralogy data with high resolution imagery, such as the HiRISE (High Resolution Imaging Science Experiment) camera on MRO or MOC (Mars Orbiter Camera) on MGS (Mars Global Surveyor), allows us to construct the regional mineral stratigraphy. We can address questions about the environments of formation for these ILDs and the subsequent geologic processes affecting the deposits. Spectral interpretations of observations over ILDs are presented, together with models for the sulfate enrichment of the ILDs.

Although our study addresses broadly the mineralogic stratigraphy of ILDs throughout Valles Marineris, we focus here on a detailed investigation of one exemplar ILD in Eastern Candor.

Datasets: CRISM, a visible-near infrared hyperspectral imager aboard MRO, is capable of multiple mapping modes [6]. It can acquire high-resolution targeted observations at 544 wavelengths from 0.362-3.92 μm and ~20-35 m/pixel, global mapping strips at ~70 wavelengths and 100-200 m/pixel, and emission phase functions of sites for atmospheric study. HiRISE is capable of acquiring co-aligned imagery with CRISM and can resolve details down to ~30 cm/pixel [7]. HiRISE stereopairs can be used to create digital elevations models (DEMs) with 1m spatial resolution and sub-meter relative vertical/horizontal accuracy, an improvement over MOLA-derived DEMs [8].

Background: ILDs have been proposed to be composed of lacustrine (possibly sub-ice) [9,10], aeolian [10], or sub-ice volcanic materials [10,11]. The diverse nature of ILDs suggests multiple formation processes. Testable parameters include bedding thickness, rhythmicity, and lateral continuity; orientation of layers relative to underlying topography and each other, and evidence for post-depositional deformation and tectonic stresses.

Mineralogic Results: Kieserite and polyhydrated sulfates have been previously identified throughout Valles Marineris by the OMEGA team [1,12,13]. Kieserite is identified by its characteristic H_2O and OH vibrational absorption features near 1.6, 2.1 and 2.4 μm. Polyhydrated sulfates (such as epsomite and copiapite) are identified by absorptions near 1.4 and 1.9 μm and a drop in reflectance at 2.4 μm. Sulfates are highly localized and are found in many exposed layered terrains, but not in neighboring dusty regions. Ferric oxides or ferric sulfates are observed in association with sulfate-rich layered deposits in Valles Marineris [2,12,13]. The study area in East Candor has a ferric component within its multiple-sulfate assemblage located in overlying loose dark material that collects at the base of cliffs and in other topographic depressions.

The ILD in East Candor Chasma is one of several examples exhibiting sulfate-rich layers with alternating hydration states [14]. Cliff-forming kieserite-rich layers (which also show polyhydrated absorptions) alternate with slope-forming polyhydrated sulfate layers (Fig 1). Additional minerals including gypsum and/or hydrated silica are also present and appear associated with distinct layers [15].

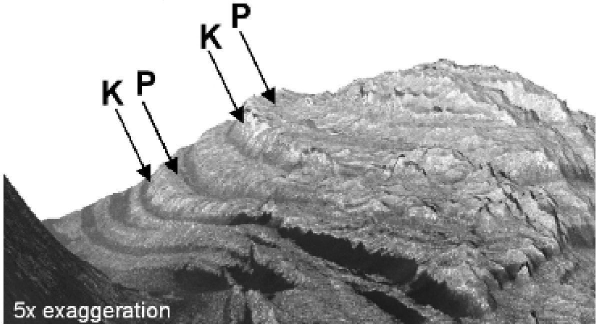

Fig 1. HiRISE image draped on HiRISE DEM. View toward east showing top of layered ILD. Kieserite (K) with some polyhydrated sulfate present on steep slopes and predominantly polyhydrated sulfate (P) on flatter surfaces.

Stratigraphic Results: Stratigraphic mapping of layers show that individual layers are of uniform thickness across the unit and many are traceable for tens of meters until covered by colluvium (Fig 2b). Layering is subhorizontal in the ILD center and outward dipping on the eastern and western exposures. The apparent lack of slumping, channels, cross-bedding or bed truncation at the meter scale supports quiescent water or airfall deposition but is not conclusive.

One section particularly clear of obscuring colluvium shows a repeated sequence of a 3-5m thick resistant layer, ~16m friable layer, 3-5m resistant layer, and a ~20-50m friable layer (Fig 2b). Although this sequence is only repeated ~4 times and may not be enough to claim periodicity, the potential causes of rhythmic layering and their mineralogic implications should be considered. Aeolian, fluvial, or volcanic ash deposition could result in layers of uniform thickness under orbital-driven climate change [16] or uniform repetitive volcanism. Uniform thicknesses of volcanic ash deposits are less likely as they would require repeated eruptions of similar volumes and consistent wind speed and direction. Influx of fresher water into a denser brine may cause rhythmic deposition of thick turbidite sequences that mantle underlying topography [17] and may result in a cyclic evaporite [18]. Future work will put this ILD in context with the regional geology, especially the stratigraphic relationship with the wallrock to the north and other nearby ILDs to allow more useful constraints to be placed on the formation history.

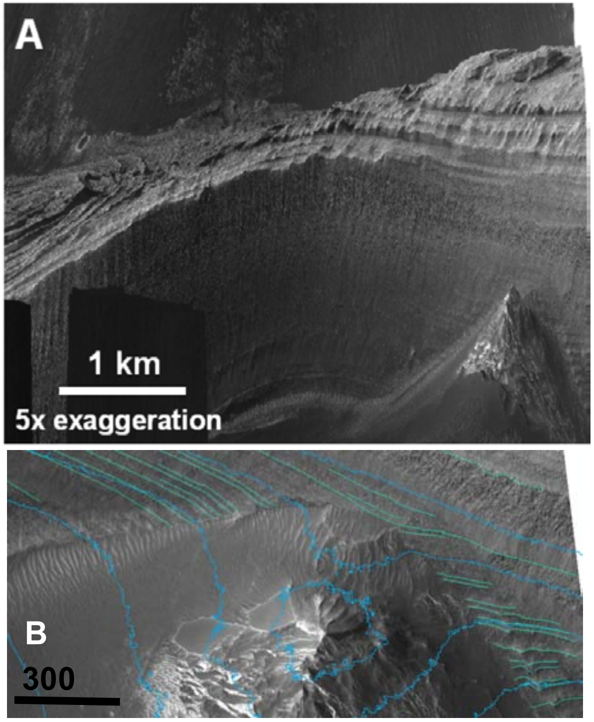

Fig 2. A) Perspective view of East Candor ILD showing top and southern exposure with landslide at bottom right. B) Schematic of rhythmic layering near same landslide. 60 m interval contours in blue. Paired layers (shown in cyan) are 3-5 m thick each and spaced ~16 m apart, which are separated by ~20 to 50 m.

Tectonic Results: An outstanding question is the origin of the northeastern tilt in the eastern part of the ILD and a western tilt in the western part. It could be conformable deposition upon the original curved surface, such as caused by airfall or deep water sedimentation. The bedrock under the ILD is not exposed for examination. Alternatively, post-depositional deformation could create the dips. Terrestrial evaporite deposits ductilely deform under low stresses and temperatures that would not deform other lithologies [15]. Fracturing or faulting is not apparent on the meter scale, nor are significant folding and boudinage observed. The sulfate mineralogy tracks layering, not elevation, which argues against post-deformation diagenesis. Further structural modeling will identify possible tectonic stresses acting on the ILD.

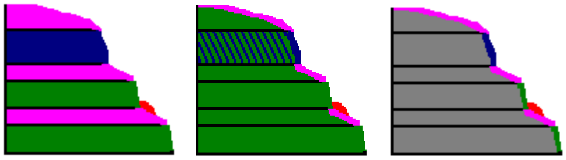

Fig 3. Cross-section models of sulfate in ILDs. (left) Evaporite sequence; (center) Groundwater evaporation to form uniform mineralogy that hydrates with later atmospheric exposure; (right) Capillary wicking of sulfate to surface, with different sulfates exposed on different layers.

Discussion: Two models are consistent with the mineralogic, stratigraphic, and tectonic results for the study ILD in East Candor Chasma (Fig 3) – a complex evaporite sequence, or groundwater deposition of uniform monohydrated sulfate mineralogy that hydrates upon later atmospheric exposure. In the first case, cyclic basinal deposition of diverse sulfate-bearing materials could form the ILD; in the second, perhaps brine chemistry only permitted kieserite evaporite formation, or later groundwater alteration converted all sulfate present to kieserite. Later exhumation under current climate conditions or in periods of high obliquity would compel hydration to polyhydrated sulfate forms [19]. Hydration rate might be partially controlled by a layer's grain size and type and porosity. The first model is more consistent with our preliminary evidence for cyclic layering, and it will be tested by acquiring further spectral data over the area with rhythmic bedding to search for a mineralogic association. A third model, that the sulfate forms via efflorescence due to capillary wicking, cannot explain the repeated alternation of sulfates with different hydrations states on the order of 10s of meters.

Acknowledgments: We wish to acknowledge the CRISM, HiRISE, and OMEGA science teams for all their dedication and hard work.

References: [1] Gendrin, A. et al. (2005) *Science 307*, 1587-1591. [2] Murchie, S.L. et al. (in press) *Nature*. [3] Bishop, J.L. et al. (2007) *7th Mars,* Abst #3350. [4] Parente, M. et al. (2007) *AGU Fall Meeting*, Abst P23A-1091. [5] Murchie, S.M. et al. (2007) *AGU Fall Meeting*, Abst P21C-04. [6] Murchie, S.M. et al. (2007) *JGR 112*, E05S03. [7] McEwen, A.S. et al. (2007) *JGR 112*, E05S02. [8] Smith, D.E. et al., (1999) *Science 284,* 1495-1503. [9] McCauley, J.F. (1978) *USGS Map I-897*. [10] Nedell, S.S. et al. (1987) *Icarus 70,* 409-414. [11] Komatsu, G. et al. (2001) *LPSC XXXII,* Abst #1048. [12] Bibring, J.-P. et al. (2005) *Science 307*, 1576-1581. [13] Bibring, J.-P. et al. (2007) *Science 317*, 1206-1210. [14] Roach, L.H. et al. (2007) *7th Mars*, Abst #3223. [15] Roach, L.H. et al. (2007) *AGU Fall Meeting*, Abst P21C-05. [16] Head et al (2003) *Nature 426*, 797-802. [17] Rimoldi, B. et al. (1996) *Sedimentology 43*, 527-540. [14] Warren, J.K. (1989) Evaporite Sedimentology, Prentice Hall, 251p. [18] Schreiber, B.C. and M.L. Helman (2005) *J. Sedimentary Research 75*, 525-533. [19] Vaniman, D.T. and S.J. Chipera (2006) *American Mineralogist 91*, 1628-1642.