

HYDRATED SILICATE MINERALS AND THEIR GEOLOGIC ENVIRONMENTS FROM ORBIT J. F. Mustard¹, S. L. Murchie², B. L. Ehlmann¹, R. E. Milliken³, J-P. Bibring⁴, F. Poulet⁴, J. Bishop⁵, E. Noe Dobrea³, L. Roach¹, F. Seelos², N. K. McKeown⁶ ¹Dept. of Geological Sciences, Box 1846, Brown University, Providence, RI 02912 John_Mustard@brown.edu, ²JHU/Applied Physics Laboratory, Laurel, MD 20723, ³JPL-CalTech, ⁴IAS, University of Paris, Orsay, France. ⁵SETI Institute/ NASA-ARC, Mountain View, CA, 94043, ⁶University of Calif., Santa Cruz, CA, 95064.

Introduction: Phyllosilicate minerals were first definitively identified on Mars from orbit by the OMEGA (Observatoire pour la Mineralogie, L'Eau, les Glaces et l'Activité) instrument on board Mars Express [1, 2]. Global mapping showed that sheet silicates are widespread but largely found in terrains of Noachian age. Phyllosilicate formation requires moderate to high pH and high water activity [3]. A major hypothesis presented by Bibring et al. [4] is that the conditions necessary for phyllosilicate formation were specific to the Noachian, the earliest era in Mars' history.

High spatial resolution, precision pointing, and nested observations of imaging instruments (Context Imager (CTX), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), and the High Resolution Imaging Science Experiment (HiRISE)) on the Mars Reconnaissance Orbiter (MRO) provide enhanced capabilities to analyze surface mineralogy across the planet and determine the nature and geologic setting of phyllosilicate deposits. Findings from MRO on the diversity of phyllosilicates, associated hydrated minerals, and their geologic setting are described here. Along with [5, 6] we discuss implications for aqueous alteration processes on early Mars. Herein, we focus on well-exposed crustal phyllosilicate environments as potential terrains to be sampled by MSR to establish the conditions of phyllosilicate formation.

Mineralogy of Crustal Phyllosilicate Terrains: Particular phyllosilicate minerals can be identified based on the cation-OH pairing, which can be distinguished using infrared spectroscopy (Fig. 1; see [6]). Two principle classes of phyllosilicate minerals exist on the Mars surface: Al-phyllosilicates and, the more common and spatially dominant, Fe/Mg-phyllosilicates. OMEGA identified the smectites nontronite (Fe-rich), saponite (Mg-rich), and montmorillonite (Al-rich), along with the Fe-rich chlorite chamosite [2]. The increased spatial and spectral resolution of CRISM has revealed an increased diversity of phyllosilicate minerals: kaolinite (Al-rich), illite or muscovite (K-rich), and Mg-rich chlorites (Fig. 1).

CRISM data also show regions with phyllosilicate-bearing units typically have additional alteration minerals. Hydrated silicates such as opal, altered glass, and zeolite, specifically analcime, have also been mapped by CRISM associated with phyllosilicate bearing terrains [7]. Iron oxides are also present [8, 9]. Sulfates are notably absent as are all metamorphic facies typical

of elevated P/T conditions ($T > 300$ C) such as prehnite, pumpellyite, epidote, and talc.

A new class of hydrated silicate has been identified with CRISM data [10]. This is characterized by absorption near 2.2 μm and commonly has associated 1.4 and 1.9 μm bands. This 2.20-2.25 μm band is distinct from that observed with Al-OH phyllosilicates such as montmorillonite in that the absorption is broader and centered at longer wavelengths. These spectral characteristics are consistent with hydrated silica glasses such as opal or volcanic glass.

Mineral Assemblages: With CRISM we find that the spatial distribution of these diverse alteration minerals has a high degree of spatial coherency. Within the most well exposed crustal phyllosilicate deposits, we see, in effect, different "provinces" of alteration where some of these minerals are found and not others. Nili Fossae has at least two distinct provinces, one in the immediate vicinity of the fossae with patchy kaolinite-bearing rock units overlying Fe/Mg smectite bearing rock units. All alteration minerals lie beneath a mafic cap rock extending over a region of thousands of square kilometers. In contrast, west of the fossae and east of Antoniadi crater, Fe/Mg smectite, chlorite, zeolite, and hydrated silica are more common, exposed within heavily cratered terrain [7, 8]. Mawrth Vallis presents a distinctly different regional phyllosilicate view: Fe/Mg-smectite is pervasive and is frequently covered by smaller patches of montmorillonite, kaolinite, opal, mica or mixtures of these. [9, 11, 12, 13]. As CRISM coverage builds we are expecting further distinct provinces of alteration minerals to be identified.

Stratigraphic setting: Bibring et al. [4] showed that phyllosilicate-bearing terrains were strongly associated with Noachian-aged units, but did not detail the implied formation environments represented by these phyllosilicate units. Subsequent analyses [5] define three broad categories of phyllosilicate settings: phyllosilicates in layered deposits, massive units, and in fluvial-lacustrine units such as fans. In many regions multiple environments are observed. For example, in the Nili Fossae Region, massive, layered, and delta deposits with phyllosilicate minerals are observed.

Across the southern highlands, many small outcrops of phyllosilicate, numbering in the thousands are observed, commonly associated with impact craters [14]. Phyllosilicates appear to have been excavated or exposed from deep-seated environments and are found

in the ejecta, walls and central peaks of impact craters as well as in outcrops near the base of cliff walls in Valles Marineris. We have estimated depths of excavation of 4-7 km. A possible explanation is that alteration processes extended to deep within the crust [cite Parmentier abstract?].

Discussion: The CRISM data show a wide range of sheet silicates that occur in diverse geologic settings, apparently from deep crustal to near surface environments. The association of these minerals with Noachian-aged terrains does not require Noachian age of formation and more work is needed to stratigraphically date these deposits. Specifically, the nature of the contact with overlying units (unconformable vs. gradational) and the stratigraphy of phyllosilicate-bearing units with respect to unaltered mafic units will be assessed using combined CRISM-CTX-HiRISE observations.

Nevertheless, it is apparent that sheet silicates are critical indicators of environmental conditions on early Mars. Both altered materials and unaltered precursor materials in phyllosilicate-rich terrains are important targets to consider for sample return. A sample from phyllosilicate terrains would be a great asset for determining the timing and geochemical environment of

alteration. A key point as planning for MSR progresses is that all phyllosilicate-bearing terrains are not equal. MRO data show distinct phyllosilicate settings and mineralogies whose diversity must be better understood in order to establish the geologic environment being investigated and to best target a sample return mission.

References: [1] Bibring J-P. et al, *Science* v307, 1576-1581 (2005). [2] Poulet F. et al., *Nature*, v438, 623-627 (2005). [3] Velde B. in *Origin and Mineralogy of Clays* (ed. B. Velde), Springer, Berlin (1995). [4] Bibring J-P. et al. *Science*, v312, 400-404 (2006). [5] Murchie, S. L., et al., (this meeting) (2008). [6] Milliken, R. E., et al., this meeting (2008). [7] Ehlmann B. et al. 7th Mars Conference (2007). [8] Ehlmann, B. et al., 2008, LPSC 39, #2326. [9] Bishop, J. et al., 2008, LPSC 39, #2124. [10] Milliken, R. E., et al., Opaline Silica in (Geologically?) Young Deposits on Mars (submitted) *Science* (2008). [11] Wray, J. et al., 2007, 7th Mars Conference, #3119. [12] McKeown, N. et al., 2008, LPSC 39, #1400. [13] Noe Dobrea, E., et al., (2008). [14] Mustard, J. F. et al., Hydrated Silicate Minerals on Mars Observed by the CRISM Instrument on MRO (submitted) *Nature* (2008).

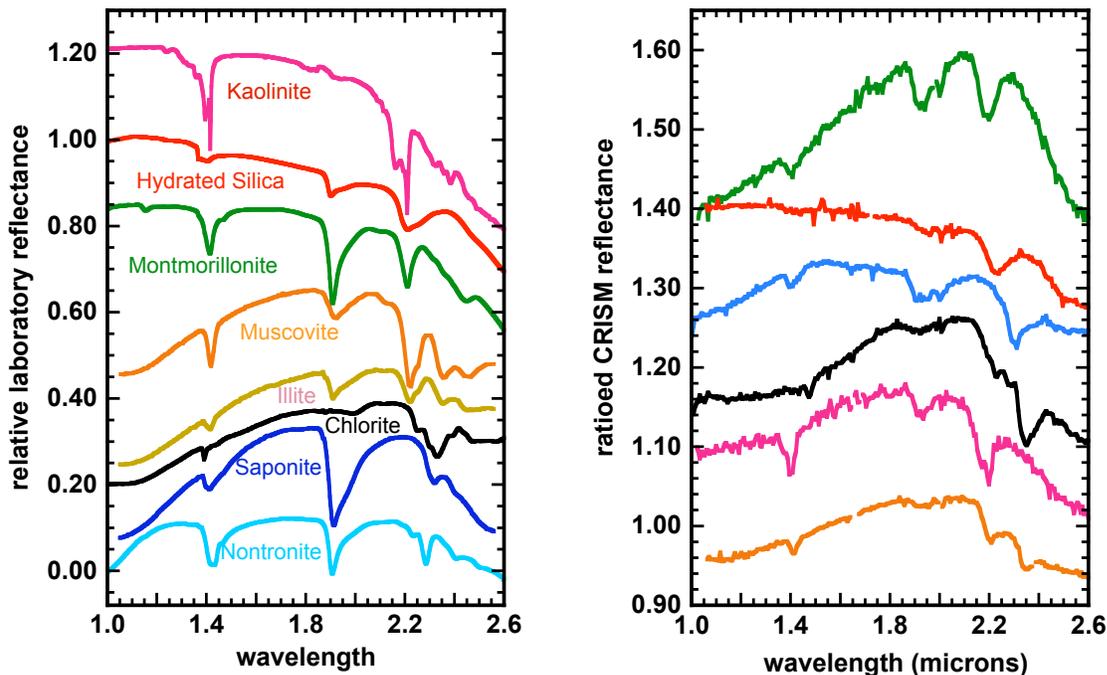


Figure 1. Laboratory spectra (left panel) of pure minerals and CRISM spectra (right panel) showing absorption features diagnostic of phyllosilicate minerals. The colors of spectra in the left panel are tied to the colors of spectra in the right panel to show the mineral identification. The laboratory spectra are offset for clarity. The CRISM spectra are ratios of a spectrum showing a mineral feature to one that is spectrally neutral to remove common artefacts due to imperfect atmospheric removal and instrumental effects.