GEOLOGIC ENVIRONMENTS OF PHYLLOSILICATE DEPOSITS FROM ORBIT J. F. Mustard[1], S. L. Murchie[2], B. L. Ehlmann[1], R. E. Milliken[3], J-P. Bibring[4], F. Poulet[4], J. Bishop[5], E, Noe Dobrea[3], L. Roach[1] [1]Dept. of Geological Sciences, Box 1846, Brown University, Providence, RI 02912 John_Mustard@brown.edu, [2]JHU/Applied Physics Laboratory, Laurel, MD 20723, [3] JPL-CalTech, [4]IAS, University of Paris, Orsay, France. [5]SETI Institute/ NASA-ARC, Mountain View, CA, 94043, [6]University 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'Activitié) 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 by the 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. Analysis of the diversity of phyllosilicates, associated hydrated minerals, and their geologic setting based on integrated OMEGA-CRISM-MRO analysis are described here.

Mineralogy of Crustal Phyllosilicate Terrains: Particular phyllosilicate minerals can be identified based on the cation-OH pairing, which can be distinguished using infrared spectroscopy though more work is needed to increase the fidelity of some identifications, particularly for Fe/Mg phyllosilicates [5]. Two principal classes of phyllosilicate minerals exist on the Mars surface: Al-phyllosilicates and, the more common and spatially dominant, Fe/Mg-phyllo-silicates. 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.

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 [6]. Iron oxides are also present [7, 8]. Sulfates for the most part are absent though a few areas of alunite in association with Al-smectite clays have been found. Importantly, while prehnite has tentatively been observed in a few locations, minerals and assemblages indicative of metamorphism at elevated P/T conditions (T>300 C) such as pumpellyite, epidote, actinolite, and talc are not found.

A new class of hydrated silicate has been identified with CRISM data [9]. 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.

The lack of definitive high-temperature mineral assemblages is a highly significant finding and leads to three possible environments of formation: low temperature hydrothermal alteration in the crust; near-surface/shallow crustal alteration in connection with a hydrologic system; surface weathering in a pedogenic environment. A final possibility is that high-temperature assemblages may have been formed but have been altered to low temperature assemblages in the presence of water over the course of Mars history.

Stratigraphic settings and Environment: In the Murchie et al. [10] analysis of martian environments that host hydrated minerals there are three that focused on phyllosilicate-bearing systems: Massive deposits in crustal settings (e.g. Nili Fossae), layered terrains (e.g. Mawrth Valles), and intricate fan and fluvio-lacustrine units (e.g. Jezero Crater). We structure this abstract around these three.

CRISM has identified phyllosilicate and other hydrated silicates in the intracrater fan and fluvio-lacustrine layered deposits in Holden [11], Eberswalde, Jezero, and Gale craters. Some of these deposits are clearly fluvio-lacustrine in origin (e.g. Jezero [12] while others are less clear and may contain significant sequences of eolian sediments (e.g. Gale). These deposits often show phyllosilicates to be present in the source regions for the sediments, leading to the hypothesis that much, if not all, of the phyllosilicates in these deposits have been transported to the site of deposition. More observations and analyses are needed to resolve the origin and significance of the phyllosilicate in these regions.

The layered terrains in Mawrth Valles show spectacular deposits of Al and Fe/Mg phyllosilicates in distinct stratigraphic sequences (e.g. [13. 14. 15. 16]). The strong association of phyllosilicate mineralogy to specific layers over a large region ($>10^5$ km^2) indicates regional alteration processes of deposition of sediments from source regions alternately rich in Al then Fe/Mg phyllosilicate. In Nili Fossae, laminated and layered phyllosilicate-bearing units are observed in exposures of Noachian basement [17, 18]. However, this region lacks the distinct Al-Fe/Mg phyllosilicate associations among stratigraphic units and coherent units are not as traceable over extensive regions. This suggests a complex evolution of the Noachian crust forming the layered units over an extended period.

Massive phyllosilicate deposits are observed in Noachian basement outcrops near Nili Fossae. They are in direct contact with Noachian-aged olivine-bearing units and establish unequivocal evidence for Noachian formation. Throughout the southern highlands, phyllosilicate-bearing outcrops are observed exposed by erosion and impact craters [18]. They are found in ejecta, walls, floors and central peaks of impact craters. If formed as a consequence of the impact process (e.g. [19]), the deposits would be expected in distinct settings such as along fractures or in floor deposits, and T/P conditions of these environments would results in specific mineralogy assemblages. The ubiquity and uniformity of mineralogy in all elements of the crater deposits argues for the alteration minerals to be present at the time of impact.

Phyllosilicate mineralogy is surprisingly uniform across Mars and apparently with depth [2, 18]. Central peaks in craters as large as 70 km and exposures of phyllosilicate-bearing outcrops near the base of Valles Marineris contain comparable mineral assemblages to those in Mawrth Valles and Nili Fossae [18]. Mineral assemblages expected for high temperature environments (e.g. prehnite, actinolite, talc) are not observed. This indicates that either the environment of phyllosilicate formation was uniform over the upper 5-10 km (e.g. [20]) of the crust, or mixing of basin ejecta incorporated minerals formed in the near surface to depth. More work is needed with the high-resolution CRISM observations to determine if there is a change in phyllosilicate mineralogy with depth.

While the phyllosilicate mineralogy is uniform on the broad scale, there are nevertheless distinct regional variations that may indicate specific processes or environments. The phyllosilicate-bearing outcrops surrounding the northern portions of the Argyre Basin [21] are uniformly chlorite-rich. In the highlands north of Syrtis Major there are three distinct phyllosilicate assemblages that define provinces [6]. Of note, the eastern province has Noachian basement rich in Fe/Mg smectite overlain by regionally extensive but thin and discontinuous kaolinite and carbonate-bearing units. The latter indicates a possible near-surface alteration environment fostered by Late Noachian to Early Hesperian hydrologic processes.

Discussion: Orbital data show a wide range of sheet silicates that occur in diverse geologic settings. However, there is an apparent lack of minerals formed in high temperature environments such as would be expected in some diagenetic, metamorphic, or hydrothermal settings expected on Mars. Exposure of phyllosilicate by impact craters and in the walls of Valles Marineris traverse a large range of apparent crustal depths (5-10 km), yet show a limited range of phyllosilicate variability. Does this indicate a limited range of temperature environments at the time of formation or processes that might have homogenized the mineral compositions with time?

The association of the phyllosilicate 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. In the regions where this has been investigated to date, however, there is little to no evidence for phyllosilicate alteration of Hesperian-aged units, though precipitates of hydrous silicates have been observed in Hesperian units [Milliken et al., 2008].

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