UNRAVELING THE DIVERSITY OF EARLY AQUEOUS ENVIRONMENTS AND CLIMATE ON MARS THROUGH THE PHYLLOSILICATE RECORD. J. L. Bishop[1], L. L. Baker[2], A. G. Fairén[3,4], C. Gross[5], M. A. Velbel[6,7], E. B. Rampe[8], and J. R. Michalski[9], [1]SETI Institute & NASA Ames (Mountain View, CA; jbishop@seti.org), [2]University of Idaho (Moscow, ID), [3]Centro de Astrobiologia (Madrid, Spain), [3]Cornell University (Ithaca, NY), [5]Freie Universität Berlin (Germany), [6]Michigan State University (East Lansing, MI), [7]Smithsonian Institution (Washington, DC), [8]Jacobs-JETS at NASA-JSC (Houston, TX), [9]University of Hong Kong (China).

Introduction: Were Martian phyllosilicates formed on the surface or subsurface? Was early Mars warm or cold? How long was liquid water present on the surface of Mars? These are some of the many open questions about our neighboring planet. We propose that the mineralogy of the clay-bearing outcrops on Mars can help address these questions. Abundant phyllosilicates and aqueous minerals are observed nearly everywhere we can see the ancient rocks on Mars [1,2]. Most bountiful among these is Fe/Mg-smectite. In this study we evaluate the nature and stratigraphy of clay outcrops observed on Mars and the presence of mixtures of other clays or other minerals with the ubiquitous Fe/Mg-smectite.

Subsurface Environments: Subsurface groundwater environments have been proposed for clay formation in some locations on Mars [3]. On Earth, hydrothermal ocean environments tend to produce mixed smectite/chlorite/talc deposits [4]. Thus, phyllosilicate outcrops such as those at Nili Fossae on Mars containing Fe/Mg-smectite, chlorite, serpentine and magnesite [5] or Fe/Mg-smectite/talc [6] may be more likely to have formed in subsurface hydrothermal environments. Characterization of smectite-bearing hydrothermal ocean sediments has shown that these can form as interstratified (mixed layering) nontronite/talc, saponite/talc, nontronite/ glauconite and other forms [7].

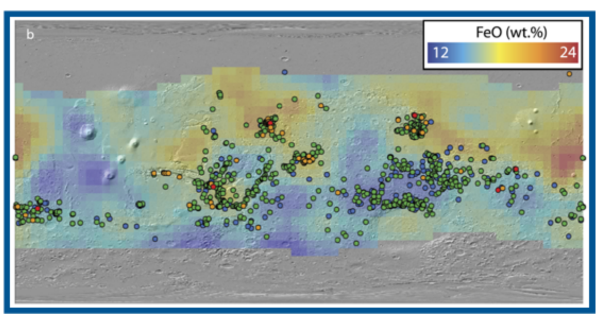

Figure 1. Map of Fe composition in interstratified Fe/Mg-phyllosilicates on Mars compared to GRS data [8]. The majority of Fe/Mg-phyllosilicates on Mars are consistent with Fe/Mg-interstratified smectites/clays (green dots). A small number of occurrences represent high Fe smectites (~8%: orange & red dots), and Mg-rich smectites/clays (~22%: blue dots).

Analysis of the spectral properties of these sediments and the spectral features of Fe/Mg-phyllosilicates on Mars revealed that distinct groups of these clays can be categorized in orbital data [8]. This enabled mapping of specific phyllosilicate compositions (Figure 1): i) high Fe^{3+} notronite, and interstratified smectite/clays with ii) mixed Fe^{2+},Fe^{3+},Mg-cations, iii) high Fe^{2+} and iv) high Mg. Mg-rich smectite mixtures are more consistent with subsurface environments due to their reducing formation conditions. The NE Syrtis region around Nilli Fossae hosts many types of mixed Mg-rich phyllosilicates, positioned as lateral clusters in neighboring environments [5], which is also consistent with multiple, distinct subsurface regions controlled by different chemical environments.

Surface Environments: Clay profiles dominated by smectites on Earth are typically formed in subarid surface environments [3,9]. These temperate to warm climates with alternating wet (~50-100 cm/y) and dry seasons support soil formation with abundant smectites (90% of clay minerals). Fe/Mg-smectites on Mars occuring in wide expanses such as that observed at Mawrth Vallis (Figure 2) are consistent with formation in surface environments [10]. A common phyllosilicate and sulfate stratigraphy is found across thousands of km [11, 12], which is more consistent with deposition or leaching or pedogenesis on the surface [13].

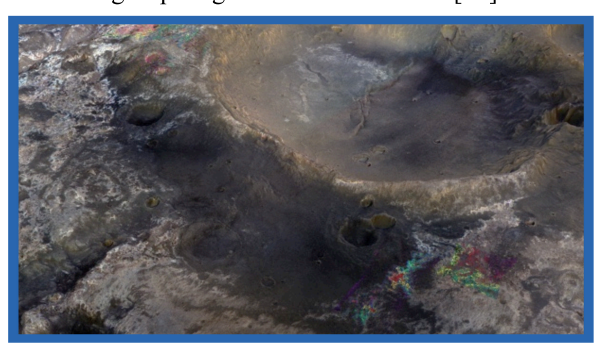

Figure 2. View of light-toned phyllosilicate-rich material at Mawrth Vallis. HRSC stereo mosaic with CRISM parameters overlain. 7X vertical.

Given the difficulties in modeling an atmosphere supportive of long-term liquid water, it is worth considering the existence of liquid water in periodic, short-term, wet environments. Smectites tend to form on Earth from amorphous aluminosilicate precursors in aqueous environments [e.g. 4]. Changes in obliquity, geothermal activity or impacts could have elevated liquid water temperatures for short intervals. In this scenario, warm and wet conditions could have existed on early Mars that enabled faster reaction of amorphous aluminosilicates to form crystalline clays. The possibility of multiple warm events would also be consistent with multiple vertical units in the clay stratigraphy observed at Mawrth Vallis and elsewhere.

Cold and Wet Scenario: Long-term Presence of Liquid Water. Clay minerals can form at temperatures just above freezing in a liquid water environment but the reactions proceed very slowly and the products tend to be impure [e.g. 4,14,15]. Models of nontronite formation (Figure 3) found almost no nontronite production near freezing, but a significant increase in the rate of reaction occurred at ~20 °C [15]. Thus, for liquid water temperatures <20 °C, the ~200 m thick nontronite-rich beds at Mawrth Vallis would have required extremely long-term standing bodies of water.

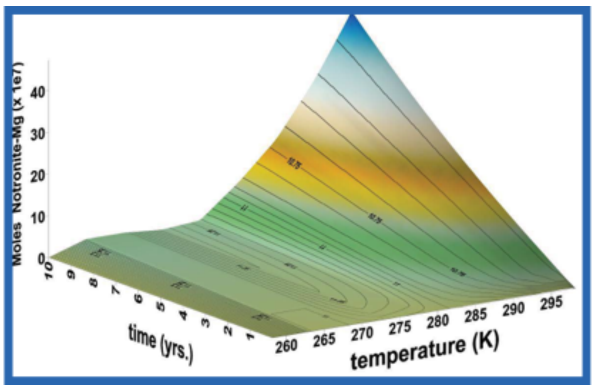

Figure 3. Formation rates of Fe/Mg-smectite on Mars. The rate of formation of Mg-nontronite (Fe/Mg smectite) varies greatly from temperatures near freezing to temperatures elevated only 25 °C [15].

Warm and Wet Scenario: Short-term Presence of Liquid Water. Temperatures of 25-50 °C may have been sufficient to form the ubiquitous Fe/Mg-smectite observed on Mars in geologically short periods of time. Aqueous alteration of olivine in martian meteorites proceeds exceedingly slowly upon exposure to thin films of brine under cold, dry Antarctic conditions; however, olivine alteration and clay formation may occur over durations as brief as centuries or even decades of episodic wetting exposure under more moderate temperatures and under acidic pH conditions [16, 17]. Nontronites synthesized hydrothermally from a gel in air at 75-150 ºC were similar to each other, regardless of the synthesis temperature [18]. Thus, temperatures over 100 °C were not likely necessary for abundant nontronite formation on Mars.

Dry Climate - No Standing Water. Surface regions on Mars bearing poorly crystalline and amorphous materials such as allophane, imogolite, opal, ferrihydrite, and schwertmannite are indicators for environments with limited liquid water on the surface. They tend to form in well-drained aqueous environments, but are preserved only in the persistent absence of liquid water or in cold environments.

Amorphous aluminosilicates similar to allophane have been detected using spectral features from orbit in several locations [19-21]. In the Mawrth Vallis region, this poorly crystalline material is present at 20-30 vol.% for the brighter regions where clay minerals are recognized [21]. An amorphous component is also present at ~20-50 wt.% nearly everywhere CheMin has analyzed samples at Gale crater [e.g. 22]. These poorly crystalline or amorphous components on the Martian surface are likely markers of a dry or cold climate, when formation of clay minerals no longer occurred.

Implications for Mars Climate: Our results indicate that phyllosilicates likely formed on Mars in both subsurface and surface environments and that the mineral record can contribute to constraining the formation conditions. Mixed smectite/chlorite/talc/carbonate occurrences with lateral variations are typical of subsurface phyllosilicate formation, while pure Fe^{3+}-smectite and wide vertical stratigraphies of smectites, clay assemblages, and sulfates are more consistent with formation in surface environments. There is a trade-off between temperature and time such that lower temperatures require longer for phyllosilicate formation. We postulate that short-term warm and wet environments, occurring sporadically in a generally cold and wet early Mars, enabled formation of the observed surface smectite occurrences on Mars without requiring long-term warm conditions. Punctuated, warm environments on early Mars could have arisen from changes in obliquity, geothermal activity or impacts.

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