UNDERSTANDING LATE NOACHIAN SURFACE ENVIRONMENTS ON MARS THROUGH ANALYSES OF BASIN-FILLING BEDROCK UNITS.

A. D. Rogers[1] and J. W. Head[2], Stony Brook University, Geosciences Dept. 255 ESS Building, Stony Brook, NY. 11794-2100 (Deanne.Rogers@Stonybrook.edu), [2]Brown University, Department of Earth, Environmental and Planetary Sciences, Providence, RI 02912 USA.

Introduction: Processes operating on Mars during the Noachian clearly include impact gardening of regolith, volcanism, and surface runoff. However, the environments and mechanisms by which the runoff occurred are uncertain. Models for the early climate history of Mars include those that invoke warm conditions, with precipitation-driven surface runoff [e.g. 1-2], to cold and icy, with surface runoff from glacial melt [e.g. 3-5], possibly driven by lava heating [6] and/or short-lived episodes of atmospheric warming driven by impacts [7] or punctuated volcanism [8]. In any case, peak valley-forming episodes occurred during the late Noachian / early Hesperian [9-10].

Distinguishing between environment scenarios for Noachian Mars can be aided by analysis of morphologies, context, composition and stratigraphy of surface units that formed during or prior to the valley-forming episodes. The Terra Cimmeria (TC) region of the martian highlands contains valley networks and predominantly Noachian units [11], and, under the icy highlands model of [3-5], would have been covered by ice sheets of variable thickness [12]. In this work, we describe new observations using infrared and high-resolution imaging data sets and discuss these observations in light of predictions made for the Noachian highlands under warm/wet [1, 2] and cold/icy [3-6] scenarios.

Overview of units and stratigraphy: Similar to the eastern Noachis [13] and Tyrrhena Terra [14] regions of the highlands, TC basins contain physicochemically distinct units (**Fig. 1**) that exhibit higher thermal inertia values and enrichments of olivine and pyroxene compared to surrounding terrain. The unit occurrences are estimated to be <200 m thick, based on the diameters of superposed craters with olivine-poor ejecta blankets, and form the flattest parts of the study area, with low ~600 m baseline roughness [15]. Olivine-poor basaltic, low thermal inertia materials are associated with the highest-standing portions of the area (typically the early Noachian highlands unit [11]), dissected terrain, large crater ejecta, and the slopes leading into the flattest parts of the basins (**Fig. 1**). In some locations on the basin floors, exposures of the olivine-poor unit appear embayed by the olivine-bearing unit (**Fig. 2**). The proposed stratigraphy (**Fig. 1**) is that the olivine-bearing unit overlies the older olivine-poor terrain. Around the margins of the olivine-bearing unit, portions of the olivine-poor terrain have been eroded and remobilized to overlie and obscure the olivine-bearing unit. In some locations, valleys dissect this superposed olivine-poor material (but not the olivine-bearing rocky units) (**Fig. 3**), and thus post-date the olivine-bearing unit. This is consistent with buffered crater count statistics that suggest the last valley-forming events in this region occurred during the Hesperian period [9].

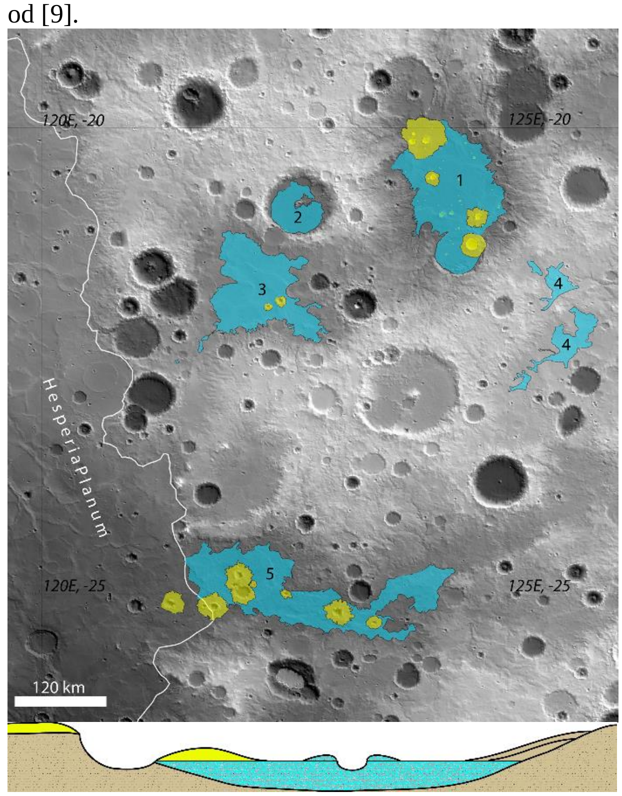

Figure 1. Physicochemically-distinct units ("olivine-bearing units") exposed within western Cimmeria are shown in cyan. Yellow: ejecta from large craters that overlie the units. Numbers designate areas discussed. Lower panel shows generalized stratigraphy.

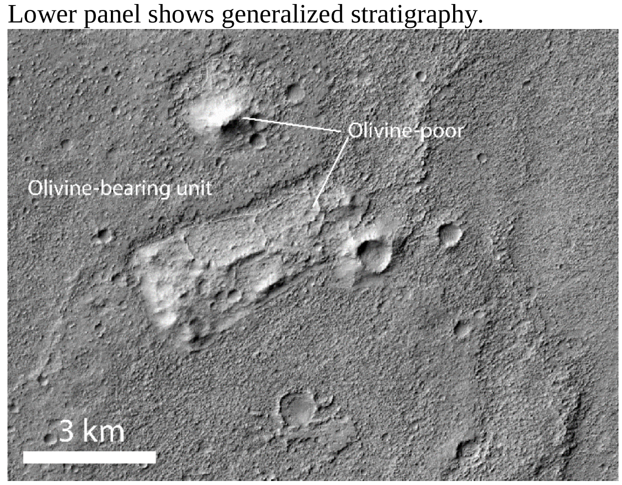

Figure 2. Example of olivine-poor material embayed by olivine-bearing unit on the floor of Area 1. Location shown on Figure 3.

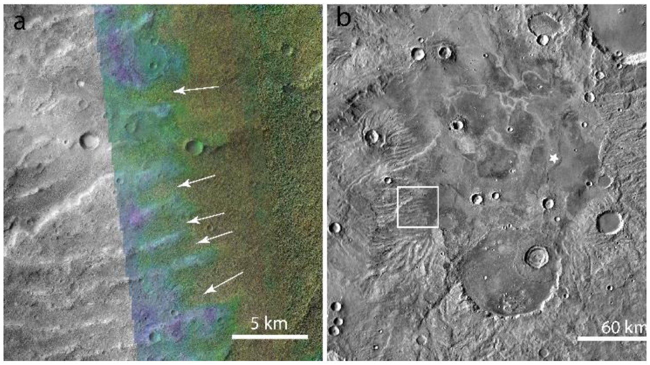

Figure 3. Area 1. **(a)** Olivine abundance over CTX. Arrows point to flat-floored valleys that cut into olivine-poor material. Location shown in **b**. (**b**) THEMIS day IR showing closer view of Area 1 and location of **a**. Star shows location of Figure 2.

Morphology and textures of the olivine-bearing units: The highest-TI portions of the olivine-bearing units exhibit a rugged appearance that varies from one location to the next, with polygonal jointing (**Fig. 4a**), ridges (**4b**), and boulder-strewn surfaces (**4c**) commonly observed. These surfaces are interpreted as modified lava flow surfaces. Boulders suggest that some reworking has likely occurred. Fine-scale layering is not observed.

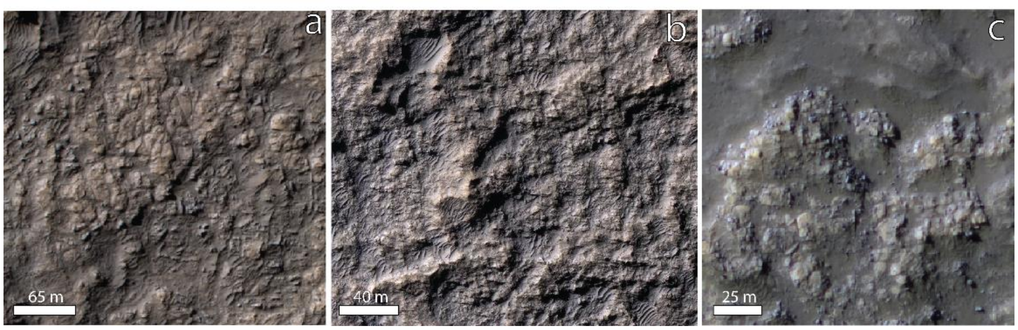

Figure 4. The highest-thermal inertia portions of the olivine-bearing units exhibit rugged morphologies, sometimes with boulder-strewn surfaces. (**a-b**) Area 5; (**c**) Area 1.

Evidence of exhumation: Inverted craters, exhumed crater fill, and isolated mesas/mounds of friable-looking material are present throughout most of the olivine-bearing units (less so in Area 5), suggesting that they have been partially/fully buried and then exhumed.

Aqueous mineralization: Chloride-bearing units are observed in association with the olivine-bearing units. In most places, they appear in swales of the rugged surface, and appear to have been preserved under a layer of dark-toned, friable material (Hesperia Planum volcanic sands, in one location). Other "aqueous" minerals are not observed, including in impact ejecta that expose olivine-poor materials from below the olivine-bearing units, as well as olivine-poor materials on the basin floors that have been embayed by olivine-bearing units.

Interpreted history: Early Noachian highland (eNh) basaltic regolith was relatively olivine poor (see also [12-13], consistent with meteorite observations [15]). Mid-Noachian to late-Noachian volcanism produced low viscosity, olivine-bearing lavas in topographic lows of the eNh unit, including some craters. Significant reworking of some of the volcanic units occurred in the mid- to late-Noachian, possibly through freeze/thaw processes. Fluvial or glaciofluvial activity also occurred during this time, bringing olivine-poor basaltic regolith from the eNh units and depositing it near the margins of those units. Later dissection carved U-shaped valleys into this friable material; the flat floors of these valleys might be partially attributed to the more impervious surface below (the olivine-bearing materials). Waters transported from the valleys were short-lived on the surface, depositing salts and relatively unaltered sediment, with little chance for chemical alteration. Later modification of the olivine-bearing units and overlying sediment occurred through wrinkle ridge formation and aeolian deposition and erosion, which heavily overprint the volcanic textures.

Implication: TC basins contain clear evidence for volcanic resurfacing in the late Noachian. Evidence for prolonged lacustrine acitivty in TC basins, such as fine-scale layering and aqueous mineralization, both prior to and after volcanic resurfacing, is not observed. These observations do not support a warm/wet late Noachian Mars scenario. The proximity of volcanic units to dissected terrain (e.g. Area 1, **Fig. 2**) lends support to the punctuated warming hypothesis for ice sheet melting [8]. Additional work is needed to test and develop these interpretations.

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