A RECORD OF VOLCANIC AND SEDIMENTARY RESURFACING IN THE MARTIAN HIGHLANDS FROM COMPOSITIONAL AND THERMOPHYSICAL MAPPING AT THE KILOMETER SCALE.

A. D. Rogers[1] C. S. Edwards[2], J. L. Bandfield[3], [1]Stony Brook University, Stony Brook, NY 11794-2100, Deanne.Rogers@ stonybrook.edu, [2]California Institute of Technology, CA; [3]Space Science Institute, USA.

Introduction: One of the outstanding questions regarding the history of the Martian highlands during the Noachian and early Hesperian periods relates to the style and timing of resurfacing. The intercrater plains of the highlands exhibit diversity in compositional and thermophysical properties, providing some constraints on the resurfacing history [*1-4*]. From >5 years of compositional and thermophysical mapping carried out over regions of interest at the ~km scale, we have documented the characteristics and spatial distribution of a class of intercrater surface units that exhibit relatively high thermal inertia (TI) (**Table 1**) and resistant morphologies compared to surrounding lower-TI materials. Common in the southern highlands and not evident in pre-Mars Odyssey data sets, these rock-dominated surface units record evidence of both volcanic and sedimentary resurfacing processes. Below, we outline some of the major findings from these efforts, including new observations, and the possible implications.

Spatial Distribution and Geologic Settings*:* The spatial density of rock-dominated exposures is not uniform throughout the highlands (**Table 1**). Rather, they are restricted to certain locations. These include Tyrrhena Terra, eastern and western (but not central) Noachis Terra, Ladon Basin, and Cimmeria Terra. Most of the units are found within intercrater plains that, from Viking-based imagery, had been interpreted as a mixture of impact, volcanic and sedimentary materials of unknown proportions [*5-6*]. A fewer number of units are found in Hellas concentric graben [4].

Compositional & Morphological Characteristics: Rock-dominated surfaces in the intercrater plains are found exclusively in broad, topographic lows, with individual exposure areas exceeding hundreds of sq km. The units exhibit resistant morphologies; polygonal fracturing and relatively light tones are common. The units are generally mid-Noachian to early Hesperian in age [3-4].

Within the plains, rocky surfaces commonly, but not always (see discussion of Ladon basin below), exhibit olivine and/or pyroxene enrichments of ~5-15% above surrounding low-TI materials [*2-4;9-10*]. Examples of such surfaces are found in E. Noachis Terra, Tyrrhena Terra, and Cimmeria Terra. Some rocky exposures in eastern Noachis show two lithologies in an apparent stratigraphy (**Fig. 1-2**)[*4*]. Both units are massive, have very high-TI (650-1000 J m^{-2} K^{-1} $s^{-0.5}$), and lack the finely layered or friable appearance of other, well known clastic or evaporitic deposits on Mars. In some locations, these units are partially buried by a "rubbly veneer" that exhibits a moderate-TI (~410-480 J m^{-2} K^{-1} $s^{-0.5}$) and is olivine poor and spectrally indistinguishable from surrounding low-TI regolith (**Fig. 2**). The moderate-TI unit was interpreted as weakly lithified material sourced from adjacent low-TI, olivine-poor plains [*4*].

One additional location with relatively high-TI surfaces that has been investigated in this work is Ladon Basin, a likely sedimentary basin of late Noachian age [7]. The characteristics of rock-dominated surfaces in Ladon are somewhat different. Work to characterize rock-dominated surfaces in Ladon Basin is preliminary, but thus far, we find that the olivine-enriched nature found in circum-Hellas settings is not present, and the averaged thermal inertias appear slightly lower (**Fig. 3**). For example, in western Ladon basin, averaged THEMIS thermal inertia values for the highest-TI portions of the basin are ~490 J m^{-2} K^{-1} $s^{-0.5}$. Spectrally, the high-TI portions are similar to surfaces outside of the basin. Slight olivine enrichments are present in portions of the basin, but these tend to correspond with lower-TI units (~360 J m^{-2} K^{-1} $s^{-0.5}$).

Interpreted origin: The high-TI, olivine-enriched exposures are interpreted as effusive volcanic plains on the basis of large areal extent, structural competence, association with topographic lows, distinct mineralogy from regolith, and lack of sedimentary textures or minerals associated with aqueous processes [*2-4*]. Alternative igneous origins, such as shallow intrusions or exposures of primary crust are ruled out on the basis of embayment relationships and ghost craters observed with the units. They clearly represent resurfacing events.

One location that does not exhibit evidence for an igneous origin, thus far, is Ladon Basin, where the lack of spectral distinction and slightly lower TI points to lithified sediments as the most likely origin.

Major implications: 1. Possible spatial control on highlands volcanism (and hydrothermal activity?) from multi-ring impact basins. Because most rocky plains exposures (which are interpreted as flood volcanics) are found basinward of the Hellas concentric grabens, [4] suggested that the Hellas basin may have provided a spatial control on emplacement of these units. They also noted the high concentration of olivine-enriched rocky units in Tyrrhena Terra [*3*], and suggested that perhaps subsurface fractures associated with the Isidis and Hellas basins enabled such a large concentration of volcanism. Units in Cimmeria Terra are outside of the these basin structures, however; thus basin control can explain most, but not all, intercrater rocky surfaces.

Heat and volatiles associated with this volcanism would have contributed to subsurface hydrothermal mineralization and potentially habitable environments. Basin ring structures from the Hellas and Isidis basins overlap in Tyrrhena Terra [e.g. 8]; this may explain the prevalence of high-T phyllosilicate minerals [9,11] in the Tyrrhena Terra region [4].

2. Volcanic and sedimentary stratigraphic sequence in the intercrater plains. The rockiest exposures are commonly discontinuously overlain by moderate-TI surfaces with a resistant morphology, that are spectrally indistiguinshible from surrounding low-TI surfaces. These units are interpreted as poorly-lithified sedimentary materials that post-date the volcanically emplaced, higher-TI units. This full stratigraphy, in turn, is partially buried by crater ejecta and unconsolidated sediment in many places [4]. In E. Noachis Terra only, multiple distinctive high-TI lithologies (interpreted as members of the flood basalt sequence) are observed below the poorly-lithified sedimentary material.

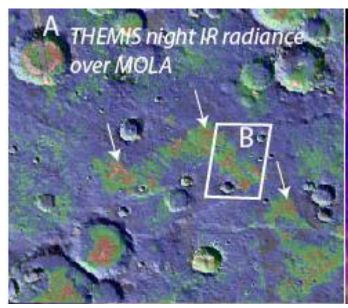
3. Distinctive Noachian-aged volcanism. The thermophysical and compositional properties of the rocky exposures are distinct from known large volcanic provinces such as Syrtis Major and Hesperia Planum. This suggests a difference in material strength and/or post-eruptive modification mechanisms between construct-building styles of volcanism and flood volcanism on Mars. Furthermore, these regions provide rare windows to Noachian-aged volcanic compositions, useful for comparison to younger volcanics and the Martian meteorites. The derived compositions differ from all rock compositions investigated by the MER rovers and from nearly all of the Martian meteorites. One exception is the upper unit mapped in E. Noachis Terra (**Fig. 2**), which exhibits a composition that is broadly similar to the Los Angeles shergottite [4].

Conclusions and Outstanding Questions: Distinguishing igneous rocks from basaltic sedimentary rocks from orbit is critical to reconstructing Martian geologic history. Detailed morphological and spectral analyses have provided some clarity on the origin(s) of intercrater plains, and how bedrock-producing processes vary by geologic setting and/or region. However, many questions remain such as: Are there temporal or spatial trends in composition of in-place igneous materials? Are intercrater plains rocky surfaces in other regions of Mars most consistent with volcanic resurfacing or lithified sedimentary deposits? Are multiple bedrock lithologies unique to eastern Noachis, or observed elsewhere? Further studies of Cimmeria and western Noachis Terra will help address these questions.

[1] Edwards et al., 2009, JGR, *114*, E11001 [2] Rogers et al., 2009 *Icarus*, *200*(2), 446–462 [3] Rogers and Fergason, 2011 JGR *116*(E8), 1–24 [4] Rogers and Nazarian, 2013, JGR *118*, p.1-20 [5] Tanaka et al., 1988 Proc. Lunar Sci.Conf. 18, 665–678 [6] Malin, 1976 Ph.D. diss. Caltech [7] Grant and Parker, 2002, JGR 107, E9 [8] Wichman and Schultz 1989, JGR 94, B12, 17333-17357 [9] Loizeau et al., 2012, *Icarus*, *219*(1), 476–497 [10] Ody et al., 2012, JGR, *118*, 1–29 [11] Carter et al. (2013) JGR, 118, 831-858.

Table 1. Characteristics of rock-dominated surfaces investigated to date

Region	TI range (J m-2 K-1 s-0.5)	Compositional characteristics	Other Notes	Interpretation	Reference
E. Noachis Terra	650 - 1000	olivine and pyroxene	two high-TI lithologies present; overlain by moderate-TI (~410-480) veneer that is spectrally indistinct from surrounding low-TI plains	volcanic, partially overlain by lithified sediments	2, 4
Tyrrhena Terra	280-410	olivine and pyroxene enriched	lower TI, but resistant morphology and compositionally distinct	volcanic	3
Cimmeria Terra	480-500	olivine and pyroxene enriched		volcanic	this work
Ladon Basin	480-500	no olivine or pyroxene enrichment		sedimentary	this work



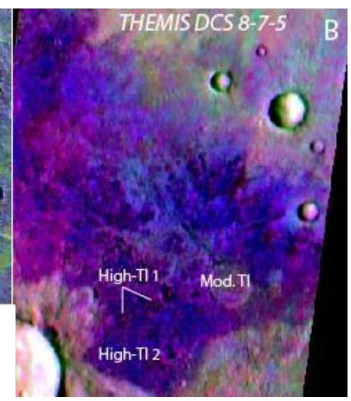


Fig 1. A. Example rocky exposure (arrows) in intercrater plains of Noachis Terra. B. Rocky exposure appears spectrally distinct in near IR(not shown) and thermal IR data sets.

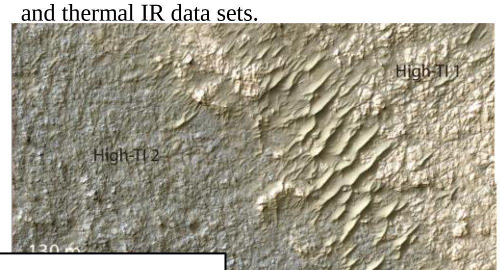


Fig. 2 HiRISE view of multiple high-TI lithologies in E. Noachis Terra.

Fig 3 (right). THEMIS DCS image of high-TI surfaces in western Ladon Basin. THEMIS spectra of high-TI surface are similar to surfaces outside of basin and lack strong 11 micron feature indicative of olivine. Lower-TI surfaces do show olivine enrichment. This trend is opposite of what is observed for most high-TI surfaces studied to date.