CYCLIC GEOLOGIC AND CLIMACTIC PROCESSES IN EASTERN ARABIA TERRA, MARS. R. L. Fergason and P. R. Christensen, Mars Space Flight Facility, School of Earth and Space Exploration, Arizona State University, PO BOX 876305, Tempe, Arizona, 85287-6305, robin.fergason@asu.edu.

Introduction: Eastern Arabia Terra, Mars is currently mantled in a layer of dust, but features viewed beneath the dust layer indicate that this region was not always a region of dust accumulation. This observation implies significant variations in both the geologic processes primarily influencing this surface in its past and the climactic history of Mars. In addition, the study region has the highest concentrations of hydrogen outside the polar regions, as identified by the Mars Odyssey Gamma-Ray Spectrometer/Neutron Spectrometer/High Energy Neutron Detector instrument suite [e.g. 1-7], and is interpreted to be up to ~10% water content in the uppermost surface layer [4-7]. The relationship between the processes that produced the variable features observed in this area, and the nature of the hydrogen signature, and the dust cycle history in this region offers insight into conditions that prompt transitions in geologic environments and climates on Mars.

The study region in Arabia Terra is located from 20 E to 32.5 E longitude and 6.5 S to 13.5 N latitude. A dust mantle masks the underlying surface preventing the identification of composition or thermal inertia of distinctive surface morphologic features observed in these regions. However, this region contains morphologic features, such as layers exposed within craters [e.g. 8-9], dark intracrater material [e.g. 10-15], and evidence for fluvial and volcanic processes [e.g. 16-18] that provide insight into the geologic history of this area. From Viking data, the majority of this area is dissected unit material (Npld) interpreted to have formed during heavy bombardment during the Noachian period. This surface is likely a mixture of volcanic materials, erosional products, and impact breccia, and is highly dissected by channels and channel networks. Ridged unit material (Nplr) is found in the western portion of the study area, and is interpreted to be flood-lava flows and ridges likely due to volcanic processes, and is also Noachian in age. In Henry Crater, subdued crater unit material (Npl_2) fills the crater floor, and is believed to be either thin lava flows or sedimentary deposits; this is the only mapped occurrence of this material in the study region. In addition, there is a small region of ridged plains material (Hr) in the southern portion of the study area that is interpreted to be low viscosity lava flows, and is Hesperian in age. Some craters contain smoother material filling the floors and occasionally central peaks, crater-rim, and crater-ejecta material are present [17]. This work builds upon this extensive Viking-era analysis by incorporating high-resolution and visible datasets to understand the geologic history in this region, and the climactic history of Mars.

Method: To help better understand the geologic and climate history in Arabia Terra, many datasets, including Thermal Emission Imaging System (THEMIS) daytime and nighttime infrared images [19-20], THEMIS and MOC [21; 8] visible images, TES [22-23] and THEMIS [24] thermal inertia, TES albedo [25-26], and Mars Orbiter Laser Altimeter (MOLA) data [27-28] were integrated to create a unit map of the study region (Figure 1). This unit map was used as a basis for determining the relative age and environmental relationships between surfaces, and fostered the interpretation of the geologic history of this area.

Results: The study region was mapped into four units based on differences in the thermophysical and morphological characteristics of the surface: (1) dust mantled; (2) intracrater mounds; (3) intracrater material; and (4) wind streaks (Figure 1).

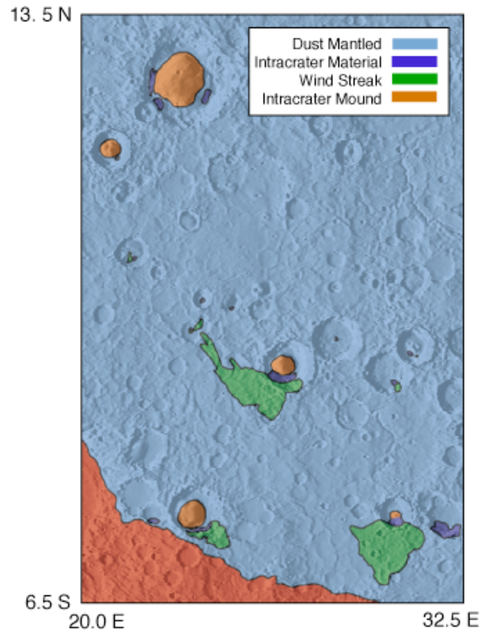

Figure 1. Unit map of study region overlaid onto MOLA 8 pixel per degree shaded relief.

Dust mantled. The dust mantle inhibits identifying the physical or chemical nature of the underlying material, however morphologic features, such as fresh craters, lava flows, channels, and erosional features, are observed through this mantle. Lava flows with variable textures are observed that are separated by distinct morphologic and sometimes topographic boundaries. Wrinkle ridges are often distinguishable as well. There are also layers of material, possibly multiple lava flows, volcanic ash deposits, or cemented dust, in which the overlying material has been eroded exposing topographically and likely stratigraphically lower materials and leaving mesas or islands of remnant material (Figure 2). In addition, channels are observed and occur in clusters that are often separated by expanses of surface material devoid of channels. Within channels or topographic depressions and alongside the base of mesas, low albedo bedforms are observed. These bedforms have wavelengths of several 100 meters, are similar or higher in albedo than their surroundings, and are likely analogous to transverse aeolian ripples (TARs) [e.g. 8; 29].

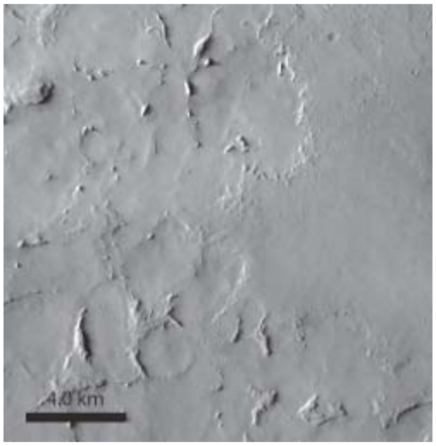

Figure 2. THEMIS visible image V05529007 of layered material in Arabia Terra that is mantled in air-fall dust.

Intracrater mounds. Five craters in this region contain interior mound material (Figure 1), which erodes in a fluted or yardang pattern that occurs on the slopes and often on all sides of the mounds (Figure 3), and are always associated with low albedo, presumably unconsolidated deposits (part of the intracrater material unit). The mounds have variable THEMIS thermal inertia values. The majority of mounds have a low thermal inertia (40-140), indicating that they are mantled by a minimum of a few centimeters of dust or fine sand. However, one mound (centered at 26.5 E, 1.5 N) has a higher thermal inertia (400-435) and is either free of dust or the dust layer is too thin (tens of microns) to considerably lower the thermal inertia, and is likely indicative of the actual thermal inertia of these materials. This mound also has dark material, presumably unconsolidated sand, present along the slopes, and the higher inertia is perhaps due to surface scouring by migrating sand. This sand could also be preventing the accumulation of air-fall dust if it is currently active. All mounds, regardless of their thermal inertia, have an albedo similar to the surrounding dust-mantle surface.

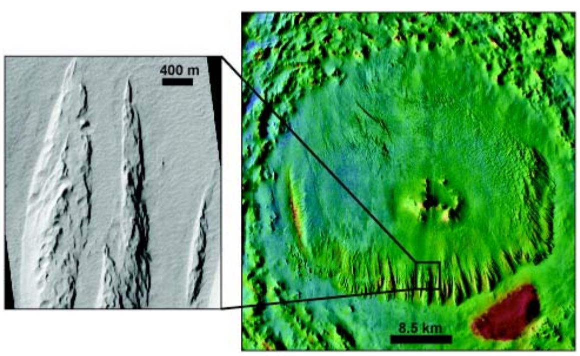

Figure 3. THEMIS nighttime IR mosaic in color and overlaid onto daytime IR mosaic of interior mound material. Black/white image is a portion of MOC-NA visible image M2000102 (NASA/JPL/MSSS)

Intracrater material. Intracrater material is present in 14 craters in the study region (Figure 1). The TES bolometric thermal inertia and albedo of this material is 200-450 and 0.18-0.20, respectively. The THEMIS thermal inertia values range from 140-460, consistent with the thermal inertia derived from TES, and this material is interpreted to be unconsolidated sand. These deposits only occur in craters with raised topography, such as intracrater mound unit material, central crater peaks, or crater ejecta material, in the crater interior. The erosion of this topographically high material may be a potential sand source. These deposits are typically elliptically shaped sheets, and the size of the deposit is unrelated to the crater size. In both THEMIS and MOC visible images, the deposits have a darker appearance in the center, and then lighten towards the edges, suggesting a variable thickness of unconsolidated material or variably-thick veneer of bright dust, and in some cases the deposit is thin enough that the underlying morphology can be observed through it.

The thermally derived particle size, low albedo, and gradational boundaries suggest that this unit consists of unconsolidated sand that has been distributed by wind. The low albedo also implies little to no dust on these surfaces [30], and indicates that these deposits are currently or recently active, remobilizing and removing any dust that settles on them, or incorporating this dust into the sand sheet. The proximity of these unconsolidated materials to raised features that exhibit knobs or outlying structures indicative of erosion, such as intracrater mounds, central crater peaks, or crater ejecta material inside craters, suggests that local material serves as a partial source for the sand or as a topographic trap. Thus in Arabia Terra, aeolian transport is a currently active process, and the intracrater material is evidence for a current aeolian dominated environment and the presence of seasonal winds that are strong enough to mobilize sand-sized grains.

Wind streaks. Five craters have wind streaks that are identifiable in the THEMIS infrared daytime and nighttime data (Figure 1). The TES albedo of these streaks varies from 0.16-0.26. The THEMIS thermal inertia ranges from 115-350, which is more variable than TES bolometric thermal inertia values of 120-170, and lower albedos are correlated with higher thermal inertia values. THEMIS can resolve small crater rims, ridges, and additional features that may have elevated thermal inertia values, which are too small to be resolved by the TES dataset, and is a likely explanation for the higher thermal inertia values derived from THEMIS data.

The majority of streaks occur towards the south-southeast of sand deposits, indicating a current primary wind direction generally from the north-northwest. GCM results in this region indicate a seasonal variation in wind direction, with stronger winds from the northwest in the northern fall and northern winter and weaker winds from the southeast in northern spring and northern summer [31]. The stronger wind direction is consistent with the modern wind streak orientation. In addition, there is one wind streak with minor streaks oriented towards the northwest, which is perpendicular to the prevailing wind streak direction, and is consistent with a seasonal variation in the prevailing wind direction [31]. This wind streak is the largest observed, and the wind streak material may be sufficiently thick to act as the source material for the minor streaks.

Interpretation: Several morphologic features are observed through the dust mantle that provide an indication of previous geologic environments active in this region. There are morphologies suggestive of wrinkle ridges and lava flow fronts, indicating multiple layers of lava flows and an ancient history of volcanic activity. In addition, isolated mesas and knobs are present and are likely remnants of a layer that was previously more extensive and has since been eroded (Figure 2). These remnant materials are evidence that the surface beneath the dust mantle is significantly layered, and that winds strong enough to erode this material did occur in the past. This observation is inconsistent with GCM results, which indicate a low wind shear environment under both current conditions and different obliquities [e.g. 32-33]. Regardless, this remnant material is strong evidence that significant erosion has occurred in this region and that Arabia Terra has not always been a region of active dust deposition or with low wind shear stresses. In addition, channels are present and the tributary organization of some channels suggests that fluvial processes, possibly surface run-off, also modified these surfaces [e.g. 34].

Aeolian bedforms with an albedo similar to the surrounding surface are observed in many channels and topographic depressions and alongside the base of mesas. These bedforms are interpreted to be transverse aeolian ridges (TARs) [8; 29], and likely formed by winds channelized in topographic depressions. The albedo is similar to the surrounding surface suggesting that these bedforms are no longer active and are possibly covered in a mantle of dust. In addition, these bedforms have grooves eroded into their flanks, suggesting that these bedforms may be cemented or indurated, resulting in some resistance to erosion. They may have ceased to be active because the wind regime has changed or because they have been cemented. These dust-mantled bedforms indicate a previous aeolian environment in which mobile material was transported and deposited, but the climate has since changed such that bedform material is no longer active. Because these bedforms occur in channels that were presumably dry, this aeolian environment likely existed after fluvial activity ceased.

The fluted or yardang-like erosional pattern of the intracrater mounds is suggestive of a weakly indurated material. In addition, the association with unconsolidated intracrater material (sand) suggests that the intracrater mound unit is sufficiently indurated to withstand abrasion by wind. The high albedo, which is consistent with dust, suggests that the erosion of this material is no longer occurring, and this surface is mantled in dust. Alternatively, this material may be light toned by nature. However, due to the similarity in albedo to dust and the lowered thermal inertia of many of the mound materials, a dust mantle is more likely. The thermal inertia of the mounds is likely 400 to 435, much lower than bedrock, and suggests a less consolidated material, such as an ash flow tuff or weakly lithified dust. Many of the mounds have a lower thermal inertia (40–140), which is likely the same indurated material but mantled in an unconsolidated dust layer to lower the thermal inertia. Although these materials primarily occur within craters, there are materials north of Henry Crater that have similar erosional morphologic features and fine laminations, suggesting a more extensive deposit.

Geologic History: Arabia Terra has a complex history including volcanic, fluvial, and aeolian processes, which suggests that this region has undergone multiple environmental and climactic changes. First, multiple volcanic lava flows were deposited. Due to the paucity of volcanic constructs, this was likely fissure vent volcanism early in Martian history. Although evidence for these source vents is not observed, they may have been covered by lava flows or obscured by later fluvial or aeolian processes. Overlapping lava flow fronts are observed on the surface beneath the dust mantle, and thus it is likely that there are multiple layers of volcanic material present and that there was an extensive period of volcanic activity in this region. Cratering also occurred during this time.

This region then transitioned into a dominantly fluvial environment, during which channels were incised and additional cratering occurred. It is likely that volcanic activity ceased before this transition, as channels cross-cut wrinkle ridges and possible lava flow fronts, yet there is little indication that volcanic features transect channels. In addition, these channels often form along topographic boundaries or lava flow margins, and are further evidence that this region transitioned from a volcanic to a fluvial environment. Thus, these environments likely did not exist simultaneously, and effusive lava flows were not emplaced after the period of fluvial activity.

Following a volcanic and channel-forming period, there was deposition of consolidated material found in craters that forms the intracrater mound unit. In one instance, sand is saltating over a mound and provides a qualitative assessment of degree of lithification. This material must be lithified to withstand the abrasion by sand, but is likely not strongly lithified. All mound material erodes into fine flutes and yardangs indicating significant modification by erosion and a possible fine-grained precursor material. There are at least two possible scenarios for the origin of this material: (1) deposition of volcanic air-fall ash; and (2) lithification of air-fall dust. First, a pyroclastic deposit or volcanic ash fall may have occurred, but it is unlikely that significant amounts of ash were deposited this far from the potential Tharsis Montes source region [e.g. 35-36]. Alternatively, this material could be multiple layers of ancient dust that have been lithified by some process. This scenario implies that dust was deposited throughout the study region, possibly in a manner and environment similar to the current Martian climate. Then dust became cemented, and these deposits were eroded into their present configuration. This was likely a repeated process, as is suggested by the fine laminations in the intracrater mounds. Alternatively, only portions of the dust may have been cemented, such as within craters by lacustrian processes [37], and the remaining unconsolidated material was removed by wind. The presence of intracrater mound remnants just north of Henry Crater are evidence that cementation of dust occurred over a broader area than just inside craters and may have occurred throughout the entire study region. The intracrater mounds consist of fine laminations at the resolution of MOC images, suggesting repeated cycles of deposition and cementation.

In addition to the erosion of intracrater mound material, erosion of the uppermost layers on the surface beneath the dust mantle occurred, leaving remnant mesas and knobs of this scoured surface (Figure 2). Few remnants of this material are observed in the study area, and there are no superposition or cross-cutting relationships between this layer, channels, and the intracrater mound material to determine its relative age. This layer may have formed at the same time as the intracrater mound material and by the same process, but the thickness of this layer is only ~60 m thick, whereas the intracrater mound material can be over 2000 m thick. It is difficult to assess the erosional nature of this material since it is relatively thin and there is not MOC coverage. In THEMIS visible images, the material shows no evidence of the fluted or yardang erosional patter characteristic of the interior mound material, and this layer thus may have a fundamentally different origin. If it is indeed of a different origin than the intracrater mound material and these surfaces are not related, then a significant amount of material must have been eroded from this area, potentially during different time periods. This erosion could be the source for the unconsolidated material collected in topographic lows forming wind ripples, similar to transverse aeolian ripples (TARs [8; 29]).

Currently Arabia Terra is mantled in a layer of unconsolidated dust ranging from a few cm to 1-2 meters thick, and is likely variable in thickness throughout the region. Although this dust accumulation was a relatively modern event, recent GCM analyses suggest that Arabia Terra may not be currently accumulating dust. Instead, it may be a region of dust deflation [38-39]. This result implies that the atmospheric conditions that control the deposition or erosion of dust in Arabia Terra have changed in the recent past, and may currently be in a state of transition. These results suggest that Arabia Terra may periodically transition from an area favorable for dust accumulation to an area dominated by dust removal, and then back to a region of dust accumulation. This cyclic transition in the dust cycle is also suggested by the extensively layered nature of the intracrater mound material. The source of dust cementation is still unknown.

Conclusions: Arabia Terra has been modified by volcanic, fluvial, and aeolian processes throughout its history. These results indicate that this region has not always been a site of dust accumulation, and that high wind shear events were likely common. Current GCM models do not indicate high wind shear stresses in this region under current atmospheric conditions or those of past obliquities. However, this work presents strong evidence that a significant amount of material, possibly cemented dust, was removed from this area, which requires extensive periods of high wind velocities. This discrepancy indicates that there are processes important to the dust cycle on Mars that are not currently being considered.

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