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Key Points:
- Unusual thermophysical variations are present on lava flows in Daedalia Planum that are not easily explained by observed thermal inertia
- A multi-instrument, multispectral approach is used to identify the potential subpixel distribution of lava outcrops, sand, and dust
- Rough surfaces with a low day and high night temperature response contain the greatest percentage of exposed lava outcrops in the flow field

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The Unusual Thermophysical and Surface Properties of the Daedalia Planum Lava Flows

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Abstract Daedalia Planum contains numerous young lava flows with diverse flow morphology. Previous thermal infrared studies avoided this region because of the moderately high visible albedo, assumed to be caused by optically thick dust, and overall low thermal inertia. The Daedalia Planum flows, however, have some of the roughest surfaces on Mars and display an unusual thermophysical behavior that most likely indicates different areal percentages of dust, sand, and lava outcrops. Recent studies suggest that these surfaces contain significant proportions of lava outcrops rising above low-lying regions of sand with a spatially discontinuous dust layer. A multi-instrument, multispectral approach combined with prior morphological mapping is applied here to discriminate between individual flows and determine the variation of thermophysical units on the surface. High-resolution ConTeXt Camera and High-Resolution Imaging Science Experiment data are used to investigate the flow surfaces and degree of mantling. Thermal Emission Imaging System and Thermal Emission Spectrometer thermal infrared data are analyzed to quantify the thermophysical variations between flows, identify surfaces with minimally mantled lava outcrops, and apply a thermophysical classification to differentiate the surface units. The results demonstrate that the observed thermal variations are due to different distributions of blocky lavas and sand infill. A majority of lava flows with rough surfaces display a diurnal and thermal inertia response indicative of a larger areal percentage of those outcrops versus that of sand and dust. This approach identifies surfaces with more exposed lava outcrops, promising targets for future composition analysis, in regions previously thought to be too dusty for such studies using thermal infrared data.

Plain Language Summary Daedalia Planum contains some of the youngest and most abundant volcanic activity on Mars. The lava flows exposed here were considered too dusty for previous thermal infrared studies, but our analysis suggests that the dust is not uniform and these surfaces contain significant proportions of lava outcrops rising above low-lying regions of sand with a discontinuous dust cover. The presence of different areal distributions of dust, sand, and lava outcrops on these flows is further supported by the unusual temperature behavior between flows as well as other studies showing that these flows have the roughest surfaces on Mars. Visible data are used to investigate the flow surface morphology and potential degree of dust cover. Thermal data combined with a thermophysical classification are used to evaluate the temperature response between. These temperature variations are due to different distributions of lava outcrops, sand infill, and dust mantling. Most lava flows with a rough surface display a temperature response suggesting the presence of a larger percentage of lava outcrops versus sand and dust. These surfaces, identified as having minimal dust or more exposed outcrop, represent promising new targets for future compositional analysis.

1. Introduction

Mantling of the Martian surface by dust and sand hinders remote spectral investigations of surface properties, particularly in the dusty Tharsis region (Malin et al., 2007). Therefore, it is vital to identify the degree of eolian mantling that may obscure a study site in order to perform an accurate analysis of surface processes or bedrock spectral signature(s). One approach to this is using thermal infrared (IR) data to investigate the degree and distribution of the mantling material before focusing on the composition of the underlying rocks. Thermal properties are used to identify particle size based on the grain-size dependence of thermal conductivity (Presley & Christensen, 1997). Modeled thermal conductivity measurements under Martian conditions suggest that low thermal inertia (TI) regions, such as those seen at Daedalia Planum, may not be due solely to an optically thick layer of dust (Mellon et al., 2014).

Recent studies have focused on using high spatial resolution image data to investigate geomorphological surface features in Daedalia Planum (Crown et al., 2015; Crown & Ramsey, 2017; Ramsey et al., 2015; Warner & Gregg, 2003). The likely basaltic extrusive volcanism in this region (Lang et al., 2009; Warner & Gregg, 2003) shows flow morphologies similar to those of terrestrial pahoehoe and a'a flows with complex overlapping relationships (Crown & Ramsey, 2017). Age estimates using crater counts demonstrate that this region has numerous young lava flows (Berman & Crown, 2019). Furthermore, analyses of apparent surface emissivity and temperature collected by both the Thermal Emission Spectrometer (TES) and the Thermal Emission Imaging System (THEMIS) led Bandfield (2009) to conclude that this region has some of the highest RMS surface roughness on the planet, further suggesting a relatively young age. However, there has been limited work using thermal IR data due to the perceived degree of dust cover. Ruff and Christensen (2002) derived a dust cover index (DCI) for Daedalia Planum ranging from ~0.97 near the southern boundary to ~0.94 in the north, approaching the higher elevations of Arsia Mons, whereas the TES-derived visible albedo spans a range from 0.22 to 0.28, both considered moderate to high for dust cover (Christensen et al., 2001).

Despite the DCI and albedo, the most interesting thermal IR data of this region are the unusual thermophysical properties of individual flows. At the higher spatial scales of THEMIS, it is clear that it is not a uniformly dusty region. Neighboring lava flows display thermal diurnal responses that are distinct from one another, which led Ramsey and Crown (2010) to initially investigate this region for the possibility of using thermal IR spectral analysis. THEMIS decorrelation stretch data and spectral analysis of small portions of individual flows (e.g., levee versus channel, rough flow versus smooth flow) revealed subtle spectral and thermophysical differences, leading to the conclusion that the region has a complex interplay between surface roughness, albedo, mantling, and the underlying lava composition. However, the specific relationship(s) between these components remained unresolved.

The initial methods and observations (e.g., decorrelation stretch and surface temperature) of those prior TIR studies helped to define the thermal properties of some of these flows and provided the groundwork for this study. These approaches were examined in greater detail and at a higher level of qualitative analysis that combined new approaches to determine the cause of the observed thermophysical differences between the flows. The small-scale thermophysical variations appeared to be caused by eolian infilling of lava flows in Daedalia Planum (bounding coordinates: longitude 120.4–127.5°W, latitude 22.0–26.8°S). Here we develop a classification approach to identify areas that consist of different mixtures of large lava outcrops, sand, and dust. We show that these flows may have localized regions of minimal to no dust cover with a checkerboard (linear mixture) style of rock plus sand/dust.

2. Background

2.1. Geologic Setting

Arsia Mons (~120°W and 9°S), the southernmost of the three Tharsis shield volcanoes, is aligned along the Tharsis rise and has a prominent summit caldera (Crumpler et al., 1996; Head et al., 1998a; Head et al., 1998b; Mouginis-Mars, 2002). It is approximately 20 km high and 450 km in diameter. It has produced some of the youngest and most profuse lava flows on Mars (Crown et al., 2015; Crumpler et al., 1996; Garry et al., 2018; Lang et al., 2009). Large flow fields originate from the NE and SW flanks; these postdate and surround the main shield (Bleacher et al., 2007; Garry et al., 2014; Scott & Zimbelman, 1995). The SW flow field extends from the base of Arsia Mons and forms Daedalia Planum, a sparsely cratered lava plain within the Memnonia and Phoenicus Lucas quadrangles of Mars (Figure 1). Prior spectral investigations focused primarily on the southern portion of the region because of the lower TES-derived visible albedo and DCI of Ruff and Christensen (2002). For example, analysis of Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA) spectral data revealed the presence of two classes of tholeiitic basalts in the SW portion of Daedalia Planum with varying abundances of Ca-pyroxene (Giacomini et al., 2012; Lang et al., 2009). Giacomini et al. (2009, 2012) used Mars Orbiter Laser Altimeter (MOLA) and THEMIS image mosaics to develop a unit map and identify inflation features based on surface texture similarities and stratigraphic relationships. However, some of the most recent flows are located in the NE portion of the Arsia Mons SW flow field, which is the focus of this study. These have estimated ages of only a few 100 Ma (Berman & Crown, 2019; Crown et al., 2015). Crown et al. (2015, 2010) have completed detailed mapping of the flow boundaries

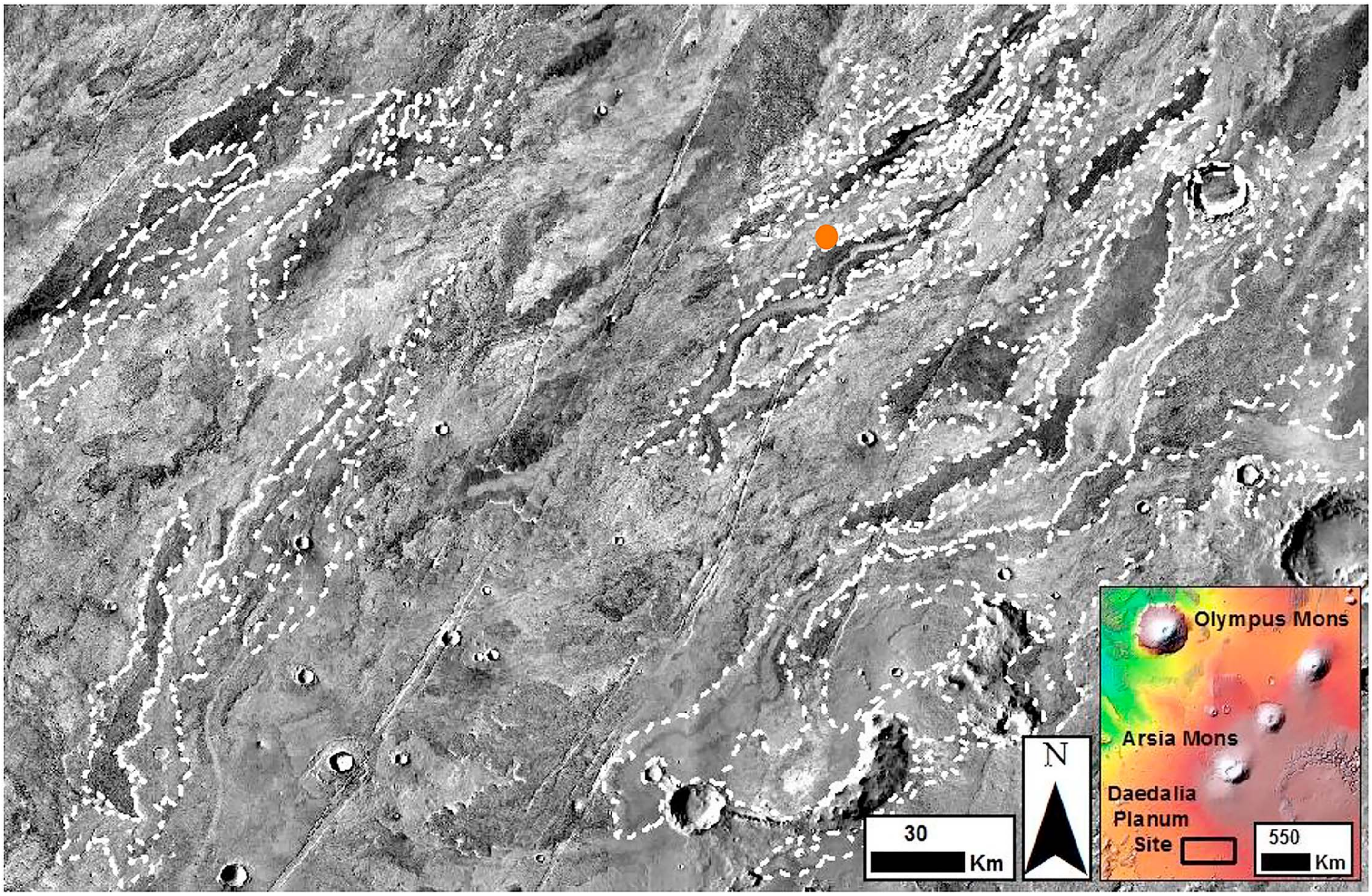

Figure 1. THEMIS daytime thermal IR brightness temperature mosaic by Edwards et al. (2011) with lava flow margins (white, dashed) by Crown et al. (2015). The orange dot signifies the center location of Figures 2a–2c. The MOLA color inset for regional context shows the study area denoted with the black rectangle. Bounding coordinates: longitude 120.4–127.5°W and latitude 22.0–26.8°S.

and superposition relationships documenting intricate flow patterns and complex overlapping and interfingering relationships.

2.2. Thermophysical Response and Thermal Inertia

Thermal IR remote sensing is a powerful tool to investigate surface geology, providing data on the mineralogy, temperature, and thermophysical properties. Two main methods by which the surface particle size distributions can be estimated using thermal IR data are analyzing the diurnal temperature response or modeling the thermal inertia (TI).

Surface temperature at the time of data acquisition is derived directly from thermal IR data. The temperature of the surface measured over the course of a day comprises the diurnal curve, which provides unique information about the material properties (e.g., particle size distribution, the presence of water, ice and/or cemented crusts). In general, for material with the same composition, smaller grain sizes will reach the highest maximum daytime temperature and have the fastest cooling rate over the diurnal cycle compared to larger particle sizes, or rocky surfaces, will have a lower maximum daytime temperature and the smallest diurnal change. Thus, the temperature from multiple collection times can be used to constrain the distribution of particle sizes or thermophysical units on the surface (Kieffer, 2013).

TI represents the resistance of a material to changes in temperature over the diurnal cycle and is used to derive specific surface properties such as block and particle size distribution, moisture content, and degree of cementation (Hardgrove et al., 2009; Pratt & Ellyett, 1979). Thermal inertia ($I = \sqrt{k\rho c}$) is calculated directly from the thermal conductivity (k), thermal capacity (c), and bulk density (ρ) of the material, in units of J m^{-2} K^{-1} s$^{-0.5}$. Prior studies show that the variation in TI is dominated by thermal conductivity and, under Mars atmospheric conditions, particle size is the most influential factor in conductivity measurements (Fergason et al., 2006; Jakosky, 1986; Kieffer et al., 1972; Neugebauer et al., 1971; Presley & Christensen, 1997). Therefore, for material with the same composition, small grain sizes, such as dust, have low thermal inertia values, sand size grains have intermediate values, and larger sizes, or rocky surfaces, have the highest values. All TI data presented here are derived from Mars Odyssey THEMIS nighttime temperature data (Fergason et al., 2006).

2.3. Dust Cover

The primary complication of using thermal IR data for the study of the lava flow fields in Daedalia Planum is the presence of varying levels of surface dust. Even though some sand or dust deposits may have a local origin and therefore preserve the compositional signature of the source bedrock, it is difficult to determine the source using orbital data alone (Edgett & Lancaster, 1993; Johnson et al., 2002). Typically, Martian dust is spectrally bland and globally homogenized. Results by Johnson et al. (2002) demonstrate that thin coatings of dust 10–20 μm thick significantly reduce the spectral contrast of the underlying bedrock and increasingly thicker coatings intensify this contrast reduction until no spectral information of the bedrock is detectable. Prior laboratory studies also show that for different mixtures of a material with various grain sizes, the fine particles will dominate the thermal conductivity and therefore affect the TI values to a greater degree (Mellon et al., 2014). Because the diurnal brightness temperature response of bedrock is significantly influenced by a thin coating of dust (Putzig & Mellon, 2007), identifying the amount and location of that dust is beneficial to determine areas of exposed (or minimally mantled) lava flow surfaces. Mars Orbiter Camera analysis of wind streaks in Daedalia Planum by Edgett and Malin (2000) show the presence of a thin cover of fine-grained sand in some areas rather than an extensively thick dust deposit. This suggests that the mantling by dust may not be uniform spatially. Therefore, it should be possible to identify the general distribution and possible locations of minimal to no dust cover on the flow surfaces, sites that ultimately could be targets of subsequent spectral/compositional analysis.

2.4. Mixed Surfaces

Although TI is a valuable tool, various complex surfaces and instrument limitations arise, which can hinder thermophysical studies (Fergason et al., 2006). For example, analysis must take into account compositional and particle size mixing (horizontal/checkerboard mixing) and/or mantling (vertical layering) at scales below the spatial resolution (pixel size) of the instrument. With limited in situ observations (especially at sites similar to this study location), the material properties within a single pixel (e.g., ~100 m for THEMIS; Christensen et al., 2004) are commonly assumed to be uniform. This assumption, coupled with the dust cover previously defined by TES data, lead to the consideration that Daedalia Planum is too dusty for thermal IR spectral studies. However, these data are composites of complex mixtures of surficial units with possible horizontal mixing and vertical layering, some with drastically different thermal responses such as dust and bedrock.

Certain lower thermal inertia areas may be explained by small-scale horizontal mixtures and/or vertical layering of coarse- and fine-grained material. Therefore, previous spectral analysis at the 3 km spatial scale of TES could very well overestimate the amount of dust and overlook any small-scale surface variability. At the higher spatial resolution of THEMIS, the ability to detect these smaller-scale variations becomes possible. Additionally, recent studies have begun to examine subpixel temperature variations on pit craters and sinuous rilles on Arsia Mons (e.g., Lopez et al., 2012). If larger/blockier portions of these lava flows rise above the low-lying regions filled with sand, a horizontal (linear) mixing scenario arises. Furthermore, if these lava blocks have minimal dust coverage, the data will represent a linear mixing scenario between lava outcrops and sand with minor/variable scales of vertical layering on certain flows. Here we examine THEMIS-derived thermal properties in detail to identify possible locations of these rocky surfaces.

2.5. Previous Work

Crown and Ramsey (2017) examined the rugged and smooth flow types in the northeast Daedalia Planum flow field to determine the applicability of IR data for compositional analysis. Using a combination of image processing techniques and geomorphic analysis, subtle spectral variations were identified (Crown &

Table 1
Summary Description of Data Sets, Including Any Instrument Limitations, Used to Conduct This Study

Data		Resolution (m/pixel)	Wavelength (μm)	No. of stamps	Usage
MRO ConTeXt Camera (CTX)[a]	VIS	6	0.5–0.8	184	Identify lava flow boundaries and surface morphology
MRO High-Resolution Imaging Science Experiment (HiRISE)[b]	VIS	0.30	0.4–1	40	
Mars Odyssey Thermal Emission Imaging System (THEMIS)[c]	VIS	18	0.425–0.86	8	Identify variation in albedo
	TIR	100	6.78–14.88	121	Identify thermophysical variation in the lava flow field
THEMIS-derived Thermal Inertia (TI)[d]	TIR	100		70	Identify particle size on surface
Thermal Emission Spectrometer (TES) Dust cover index (DCI)[e]	TIR	3000	6–50 (TES)	Map	Measures the presence of spectrally obscuring surface dust

[a]Malin et al. (2007). [b]McEwen et al. (2007). [c]Christensen et al. (2004). [d]Fergason et al. (2006). [e]Ruff and Christensen (2002).

Ramsey, 2017; Ramsey & Crown, 2010). With nearly complete coverage by ConTeXt Camera (CTX) images, these data were used by Crown and Ramsey (2017) to classify the flows into two categories, smooth or rough. Flows with a smooth surface morphology are defined as having lower albedo, being less defined and similar in morphology to terrestrial pahoehoe flows. Conversely, rugged flows (similar to a'a morphology) have a higher albedo with an irregular surface morphology containing flow ridges, prominent channels, and levees. These flows display locally high standing, bright, rugged outcrops of lava with transverse eolian ridges and sand visible in the adjacent low-lying regions. Nearly half of the area of these flows was identified as having the rough surface morphology.

The work by Ramsey and Crown (2010) and later Crown and Ramsey (2017) also identified the presence of unusual thermophysical variability. They concluded that the thermal emission from these flow surfaces was the result of a complex interplay between surface roughness, albedo, dust mantling, and the underlying lava composition. However, the specific relationship between these components remained unresolved. With this preliminary information and the geologic mapping completed by Crown et al. (2015), our study uses multiple data and more detailed thermal IR analysis to determine the thermophysical variability at the individual flow scale.

3. Methods

3.1. Data

An integral part of the project is using multiple spatial and spectral resolution data: (1) Mars Reconnaissance Orbiter CTX and High-Resolution Imaging Science Experiment (HiRISE) images, (2) Mars Odyssey THEMIS IR and TI images, and (3) Mars Global Surveyor TES data (Table 1; Figure 2). The benefits and limitations of each relate to the spatial/spectral resolution and/or the areal coverage. HiRISE data, with the highest spatial resolution, provide the most detail but with limited coverage. These data are used for specific detailed observations of surface morphology, with CTX data providing complete coverage at a slightly lower spatial resolution. THEMIS data have a lower spatial resolution than the visible instruments, but span the visible and thermal infrared regions, providing both compositional and surface morphology information.

3.2. Decorrelation Stretch

To determine if thermophysical variations in the thermal IR data are due to compositional differences between the flows versus mantling of optically thick dust, a decorrelation stretch of the THEMIS data is performed using the standard band combinations (6-4-2, 8-7-5, 9-6-4), following the methodology of Hamilton et al. (2007) (Figure 3). If the flow surfaces contained different compositions, distinct color patterns would appear in these band combinations specifically correlating to surface features.

3.3. Geomorphologic Analysis

To examine the observed thermophysical diversity in this region, 43 lava flows ranging in length from ~6 to 170 km are analyzed (Figures 3a–3c). These well-defined flows include both the smooth (11 flows) and rough

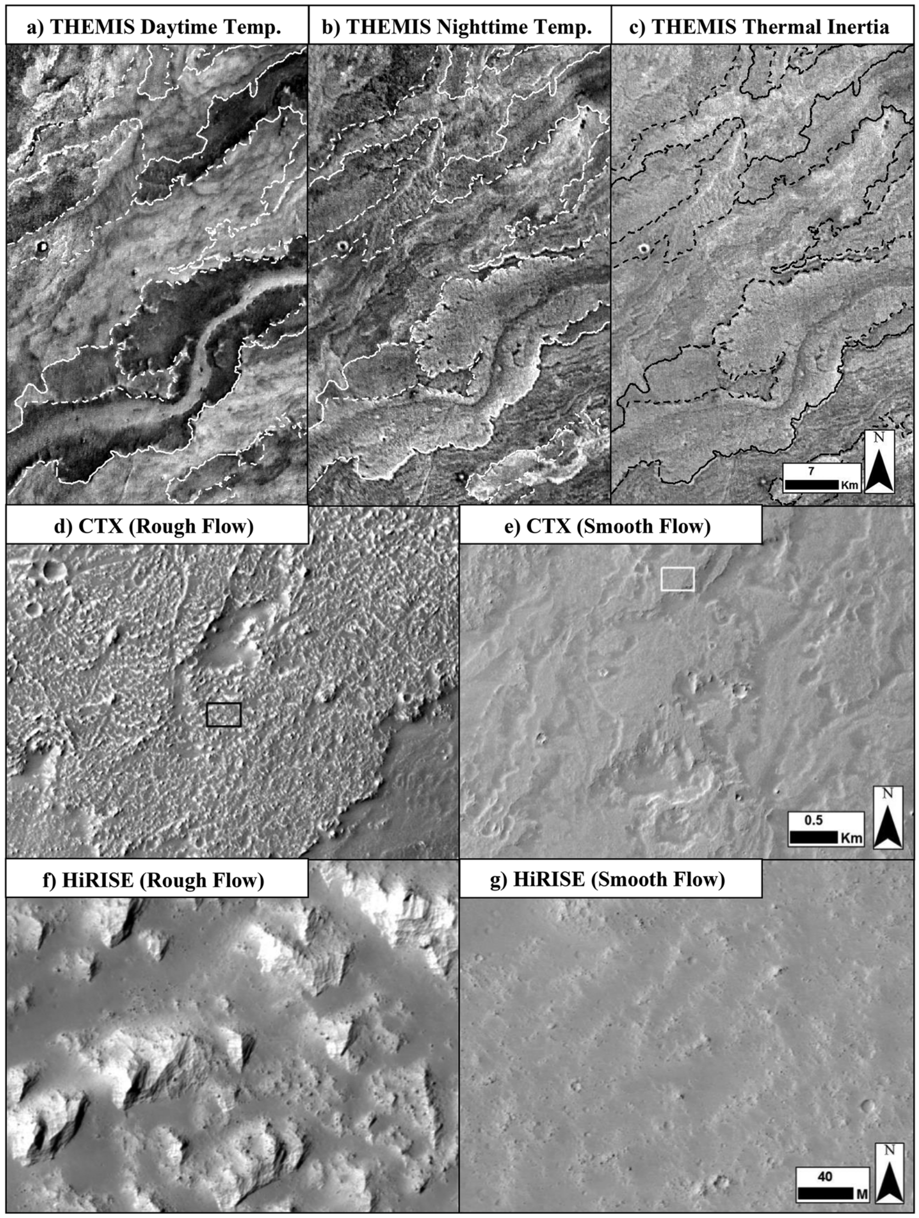

Figure 2. The lava flows in Daedalia Planum shown at various spatial scales: (a) daytime brightness temperature mosaic (Edwards et al., 2011) with the flow boundaries (white, dashed) of Crown et al. (2015), (b) nighttime brightness temperature mosaic (Edwards et al., 2011), and (c) thermal inertia (Fergason et al., 2006) showing the thermophysical variations (the center of this region is shown as the yellow dot in Figure 1). CTX images of representative (d) rough (P01_001590_1567) and (e) smooth (P18_008038_1544) surface morphologies (black and white boxes, respectively, indicate the areas shown in (f) and (g)). Representative HiRISE images showing the (f) rough (ESP_036731_1570) and (g) smooth (ESP_036586_1560) morphologies.

(32 flows) surface morphologies of Crown and Ramsey (2017). CTX and HiRISE data are used to investigate the detailed flow morphology, boundaries, and surface roughness. Only small portions of 20 flows are analyzed at HiRISE resolution due to the limited coverage. CTX data serve as the primary source to examine all the flows for the surface morphology, identify the degree of visible mantling (noting any obvious portions of the flows that appear minimally mantled or not mantled), and estimate the potential of horizontal mixing. For this study, three main surface units are defined (dust, sand, and lava outcrop) with the assumption that Daedalia Planum is dominantly basaltic (Giacomini et al., 2012; Lang et al., 2009). Following definitions established by Putzig and Mellon (2007), these units are chosen based on

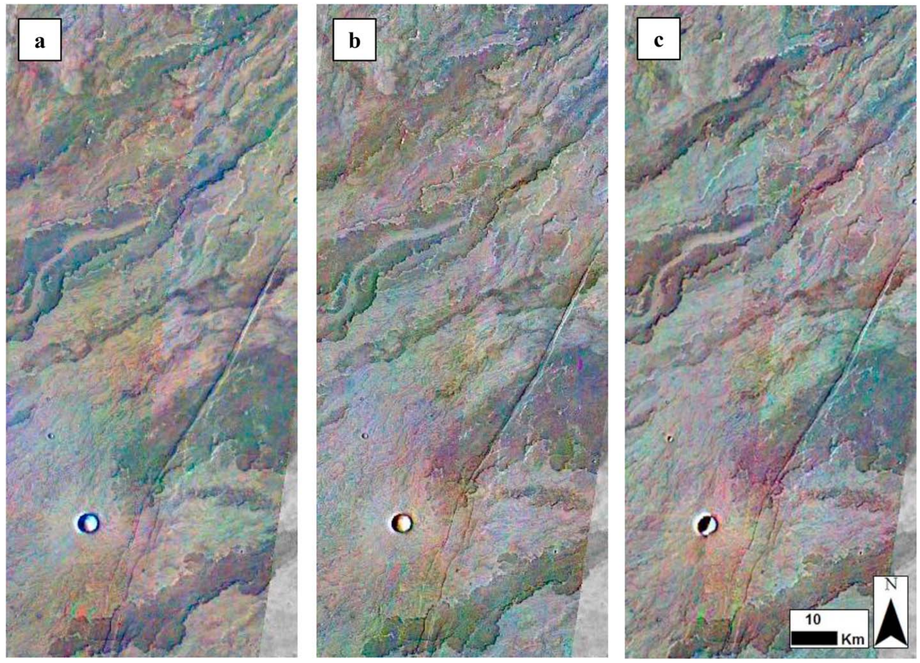

Figure 3. THEMIS IR decorrelation stretch (DCS) of a mosaic of stamps I52299002, I51737003, and I50713002 using bands (a) 6-4-2, (b) 8-7-5, and (c) 9-6-4. The minor color variations (and the consistency of color between the images) indicates that significant compositional variability is likely not present.

natural layering systems found in terrestrial analogs and Mars observations. The degree of vertical layering is estimated by identifying the coverage of locally high-standing, high-albedo, rugged outcrops of lava, transverse eolian ridges, and sand.

3.4. Thermophysical Analysis

To understand the thermophysical variation across the flow field, specific limitations are placed on the THEMIS IR data search (Simurda et al., 2016). THEMIS daytime and nighttime IR data are selected based on the following criteria: (1) all IR bands (1–10) are acquired, (2) data are collected between 15:00–18:00 (day) and 2:00–6:00 (night) local time, and (3) surface temperatures between 225 and 350 K are present in the daytime data. Selecting for all the IR bands allows discrimination based on possible compositional variations. The chosen local time captures the peak variation in thermophysical responses, which improves differentiation between fine-grained material and rock. Specifically, these time periods capture the greatest thermal difference between the rock, sand, and dust. The daytime data temperature requirement minimizes noise to ensure the maximum discrimination in the thermophysical response. Data that meet all constraints are then atmospherically corrected using the approach of Bandfield et al. (2004), spatially registered and processed to radiance and brightness temperature values (Christensen et al., 2004). Data are assessed for quality and any oversaturation or instrument anomalies are removed. The projected brightness temperature data are used in this study to assess the daytime and nighttime thermophysical variation within the flow field (see Figures 2a–2c) and for direct comparison to TI values derived from THEMIS IR nighttime data (Christensen et al., 2001; Fergason et al., 2006). All THEMIS data are cropped to the study area boundaries.

3.5. Regions of Interest

More than 1250 regions of interest (ROIs), each with an area of 500 m × 500 m (25 THEMIS pixels), are defined to avoid sampling bias within individual flows and to quantify the variability of TI and brightness temperature within and between individual flows (Figure 4). Using both CTX and HiRISE data, each ROI is carefully placed at 3–4 km intervals apart and contains a single lava flow surface, either rough or smooth. All flow edges, levees/channels, and impact craters on the flows are avoided as they may have different surface properties. Flow edges will contain shadowing throughout the day, for example, that limits the maximum temperature reached by the surface material, resulting in an inaccurate representation of the

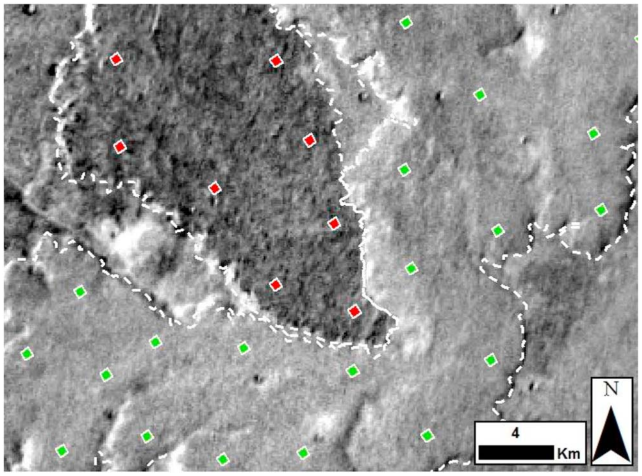

Figure 4. Representative ROI distribution (category colors defined in Table 2) overlain on the daytime brightness temperature mosaic (from Edwards et al., 2011) with flow boundaries in white (dashed) by Crown et al. (2015). Location within the study area designated by the white arrow in Figure 6.

thermal response. Additionally, depending on the observation time and solar incidence angle, shadowed flow edges have a lower albedo in visible data. During flow emplacement, channels, where present, would have continued to feed erupted material down flow. Thus, material on the nonchannelized portion of the flow and adjacent material in the levees and channels will have different emplacement times and conditions. Furthermore, shadows may also affect the thermal response of the levees and channels. Craters and any significant ejecta could have a different thermal signature compared with the target material, either exposing deeper material or scattering surface material.

A complete statistical analysis of the THEMIS temperature and TI data sampled by the ROIs within the study area is performed, including the mean and standard deviation. A look-up table contains the variation between the pixels in each ROI and the variation between flows. Analysis of variance, a statistical test used to determine the degree of variation between identified groups (Sheskin, 2011), is also conducted on these data. This allows for an assessment of the variance between the flows and the determination of whether multiple thermophysical responses are present. In order to compare the responses between flows, two simple calculations are performed for the temperature and TI data: (1) the average of each ROI mean for an individual flow and (2) the difference between the average for each individual flow and that of the average for the THEMIS stamp within the study area boundaries. The goal is to determine the response of each flow in comparison to the flow field.

3.6. Defined Categories

The results of the statistical analysis defined four flow categories based on daytime and nighttime THEMIS IR brightness temperature data relative to the study area mean. These classes depict the diurnal temperature response differences between the flows and show the potential variation in surface materials. To define these categories, the average values of all the ROIs for each flow are compared with the average value of the study area to determine whether the response was high or low. The four categories (labeled A–D) are identified based whether the flow displayed a high or low (i.e., warm or cold) daytime and nighttime temperature response (Table 2). The difference between each ROI mean and the flow area mean (ΔT and ΔTI) is also calculated to compare the variation between the stamps and identify any changes along the flow length. Finally, the THEMIS defined category, brightness temperature values, TI values, surface texture, and flow morphology (as defined by Crown et al., 2015) are compared for each flow. This allows us to identify the correlation between the thermophysical response and surface features.

4. Results

In agreement with the previous work, no major compositional differences are easily identified in the decorrelation stretch products (Figure 3). Because a major compositional difference is not apparent and the age estimates from crater counts reveal a relatively small range in ages (Berman & Crown, 2019), the variation in thermophysical response is most likely due to material properties of the surface, specifically the distribution of dust, sand, lava outcrops coupled with albedo. If the area was completely covered with an optically thick layer of dust, the brightness temperature and TI should vary based only on local topography, which creates shadowing and limits the maximum surface temperature. In this scenario, the greatest variation should only occur on the flow margins, which is not the case. In fact, neighboring flows demonstrate easily seen variations (Figures 2a–2c).

Table 2
The thermophysical Response of the Four Flow Categories Based on Daytime and Nighttime Brightness Temperature Differences

Category	IR daytime temperature	IR nighttime temperature	Thermal inertia	Assigned color
A	High	High		Red
B	High	Low	Low	Green
C	Low	High	High	Blue
D	Low	Low		Purple

The assigned color of each category correlates to Figures 4 and 6.

4.1. Thermal Inertia of the Flow Field

Generally, for material with the same composition, the finer grain sizes will have very low thermal inertia units (tiu) of ~56, whereas sand will have intermediate values (~223 tiu), and larger rocks, or rocky surfaces, will have values as high as ~2,500 tiu (Putzig & Mellon, 2007). If the surface properties are uniform at the pixel scale, the THEMIS-derived brightness temperatures are expected to have a greater variation over a day for low TI materials (e.g., high daytime and low nighttime brightness temperatures). High TI surfaces would display a low daytime and high nighttime brightness temperature with a more limited variation in temperature over a day. However, the TI in Daedalia Planum does not change dramatically and displays a more subdued variation, ranging from 170 to 332 tiu with a maximum ΔTI of ~55 tiu. These TI values are indicative of intermediate particle sizes, which likely means that the dust cover is heterogeneous and less than the optical thickness. Moreover, CTX and HiRISE images show distinct surface variations and the presence of horizontal mixing and vertical layering scenarios. The TI values on this flow field may not represent the true complexity of the surface, however. The limited range of values may be the result of using only THEMIS nighttime data to derive TI values, which would not depict the full extent of the thermal response. In fact, even though the flows display moderate TI values, there are numerous combinations of vertical layering and horizontal mixing of dust, sand, and lava that could produce these values. Therefore, understanding the thermal response over the diurnal cycle may reveal more nuanced differences requiring further analysis.

4.2. Unique Diurnal Signatures of the Flow Field

To assess the diurnal responses of the flows, the ΔT variation was first investigated. This analysis showed that different diurnal responses do exist between flows with four unique types of responses. The maximum variation in ΔT of individual flows is ~5 K, with some being less than the THEMIS uncertainty of 2 K. These changes in temperature show that the variance between flows is not due to instrument noise and that, in general, the flow field is not completely covered by dust. It is more probable that the data are detecting different proportions of lava outcrop and eolian infilling of sand, all of which are mantled to some degree by dust. This suggests that flow surfaces with low daytime and high nighttime brightness temperatures that also have a high TI should have the greatest exposure of lava outcrops.

4.3. Thermal Response of Categories B and C Flows

Two dominant trends in THEMIS brightness temperature data are present (Table 2), representing the likely thermophysical end-members of this flow field. Category B flows, with high daytime and low nighttime brightness temperatures, display a lower TI value and are therefore presumed to be surfaces with the greatest amount of dust coverage. Category B flows show the greatest variation in temperature over the diurnal cycle and the highest heating and cooling rates, all indicative of a finer particle size dominated surface. Whereas category C flows, with the inverse temperature relationship, have higher TI values and the least variation over the diurnal cycle with the lowest heating and cooling rates. These are indicative of a surface with comparatively greater amount of higher thermal inertia material. The ability to separate the flows into these categories demonstrates that the areal percentages of lava outcrops and sand in low-lying areas are significantly different on some of the flows. For example, a pixel on a category B flow would be dominated by sand, minor amounts of rocky outcrops, and covered with appreciable dust (Figure 5c). A pixel on a category C flow will have a higher areal distribution of lava outcrops than sand in low-lying regions and quite possibly less dust (Figure 5d).

4.4. Thermal Response of Categories A and D Flows

The two remaining categories, A and D, likely represent a more specific distribution of horizontal mixing and vertical layering scenarios (Table 2 and Figure 6). Eleven flows have unchanging daytime and nighttime temperature response relative to the flow field (either staying comparatively low or high throughout the diurnal cycle). This thermophysical response is likely due to the presence of very specific amounts of horizontal mixing and vertical layering of dust, sand, and lava outcrops on the surface. Of these eleven flows, only one falls into A with a consistently higher brightness temperature throughout the diurnal cycle, however within the THEMIS instrument error. This category was not further examined because of limited statistics. Category D flows have consistently lower brightness temperatures throughout the day. These flows display a daytime temperature response of a complex surface containing a high areal percentage of larger block sizes (lava outcrops) compared to the flow field to limit the maximum daytime temperature, but with enough finer particles (either dust or sand) to lower the surface temperature at night. This suggests that there

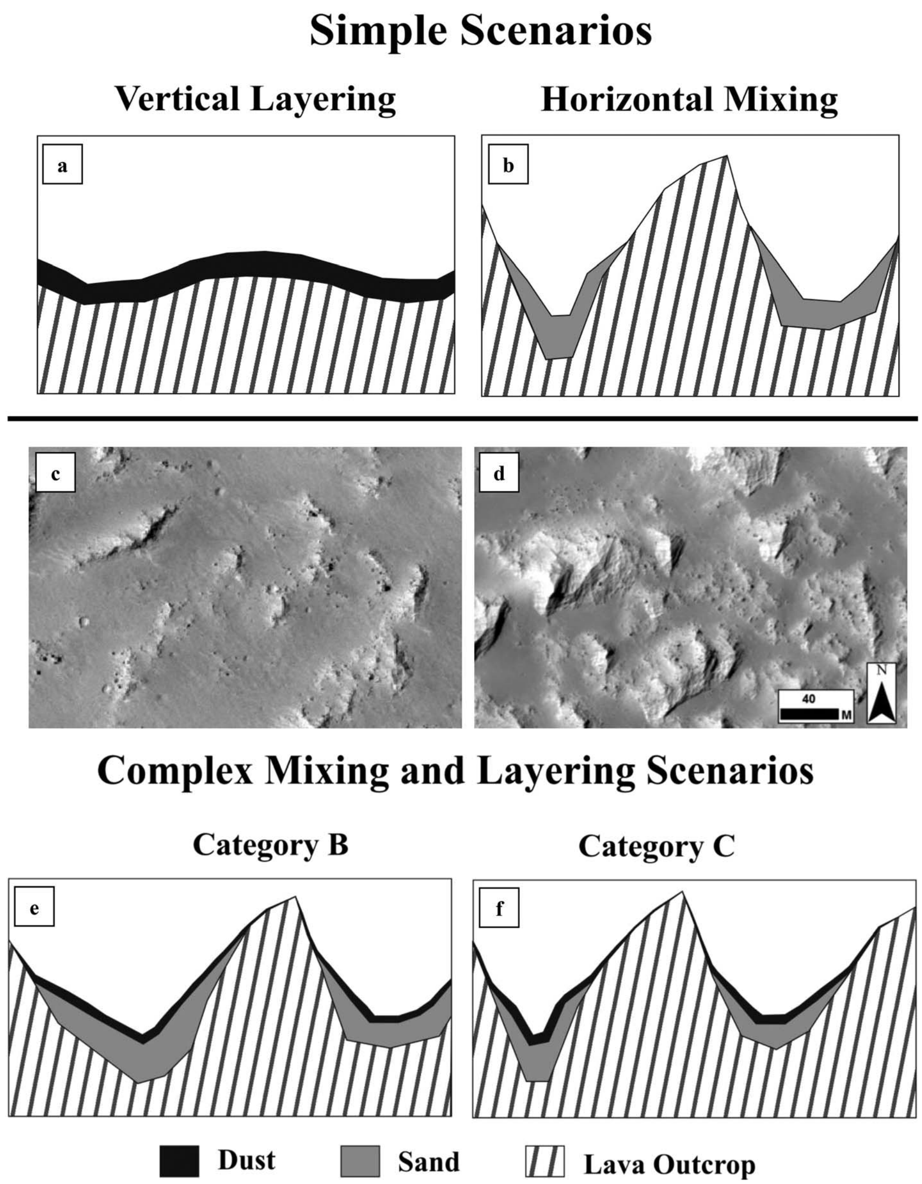

Figure 5. Possible idealized configurations (a, b, e, and f) of surficial deposits covering lava outcrops in the Daedalia Planum study site. Simple configurations are shown of (a) a vertically layered system with dust uniformly covering the lava flow and (b) a horizontally mixed system with sand deposited in low-lying regions and the lava flow surface free of dust. HiRISE images displayed at the same scale showing rough flow surfaces that correspond to our (c) category B (ESP_046450_1535) and (d) category C (ESP_041940_1570) thermophysical responses. More complex scenarios showing both horizontal mixing and vertical layering with sand deposited in low-lying regions for our (e) category B rough flows with a greater areal coverage of sand and/dust and (f) category C rough flows with the greatest abundance of exposed lava outcrops.

is a comparatively higher percentage of lava outcrops than sand and dust, but less than those surfaces with a category C response.

4.5. Latitude Distribution

The distribution of flow categories also hints at a possible latitude dependence (Figure 6). Category A and B flows predominantly appear in the southern half of the study area, whereas category C and D flows occur in the northern half. The TES-derived DCI only changes slightly between 0.95 and 0.97 within the study area and the general elevation changes from ~4,400 m in the northeast to ~2,750 m in the southwest. Even though there is a significant elevation change over the study area, the maximum elevation change within a given

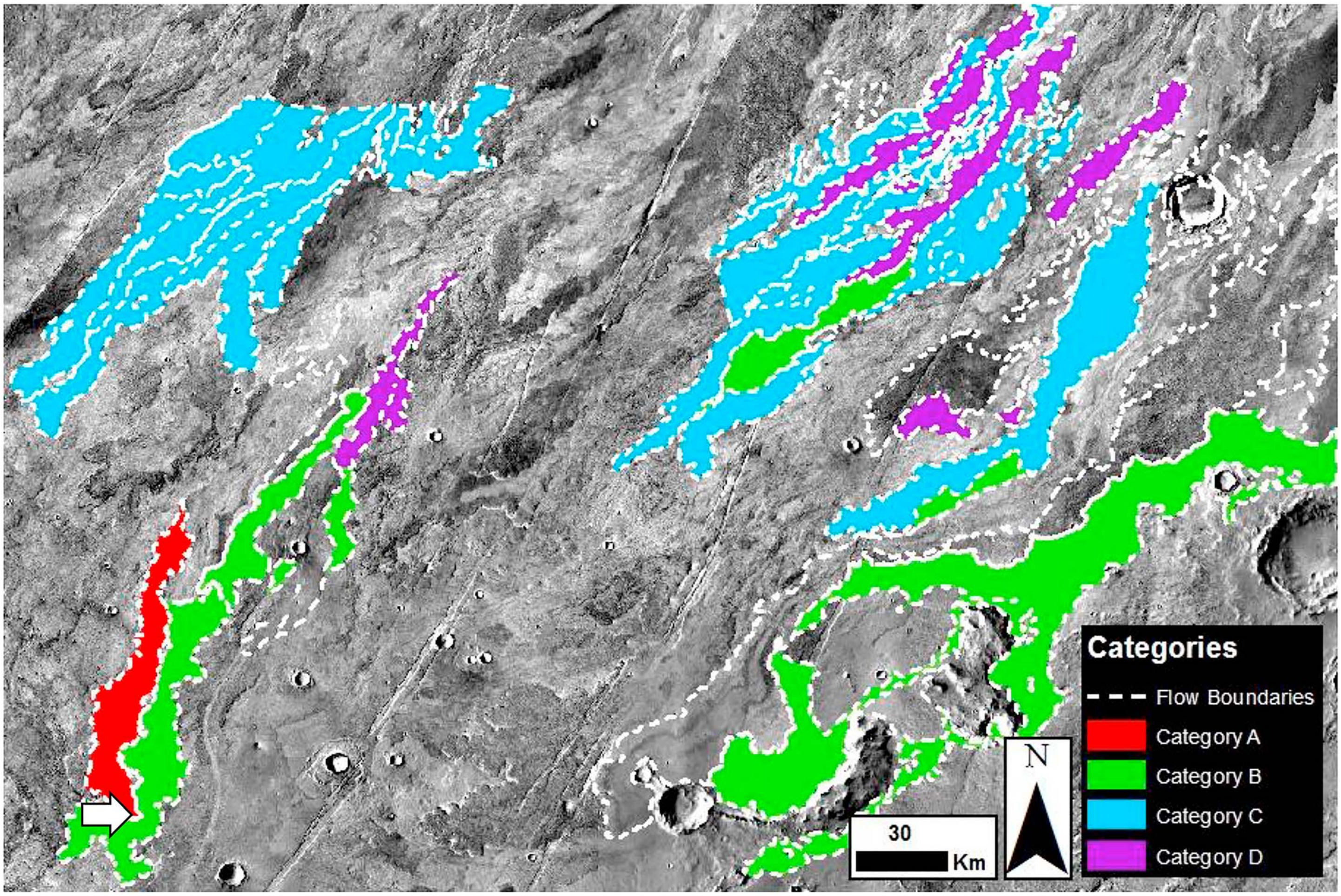

Figure 6. THEMIS nighttime brightness temperature mosaic (from Edwards et al., 2011) of the Daedalia Planum study area showing the categorized flows (bounding coordinates: longitude 120.4–127.5°W and latitude 22.0–26.8°S). The Crown et al. (2015) flow boundaries are shown with white dashed lines and the flow colors correspond to the thermophysical response categories (Table 2). The white arrow marks the location of Figure 4.

THEMIS stamp is only 850 m over a distance of ~310,000 m producing local slopes below 0.5°. Thus, elevation differences between flows are not statistically significant to affect the categorization of the flows or cause this possible latitude dependence. Recalling the previous discussion of the relationship between TI and brightness temperature responses, the latitude distribution may suggest that flows further north have a higher concentration of exposed lava outcrops. This is further supported by the presence of the single category A flow in the more southern region and category D flows in the northern portion. This distribution may suggest the presence of slightly different eolian surface processes occurring from north to south, perhaps affected by the larger Arsia Mons topography.

Table 3
Statistical Summary of the Correlation Between Surface Morphology and Thermophysical Response

Category	IR day temperature	IR night temperature	Total number of flows	Total flow percent	Number and percent of smooth flows		Number and ercent of rough flows	
A	High	High	1	2.3%	0	0.00%	1	3.1%
B	High	Low	7	16.3%	4	36.4%	3	9.4%
C	Low	High	25	58.1%	6	54.5%	19	59.4%
D	Low	Low	10	23.3%	1	9.1%	9	28.1%

Smooth flows predominantly display a category B or C response with inverse day and night delta brightness temperatures (±ΔT; see section 3.5 for explanation) in relation to the flow field as a whole, whereas rough flows principally have category C or D responses.

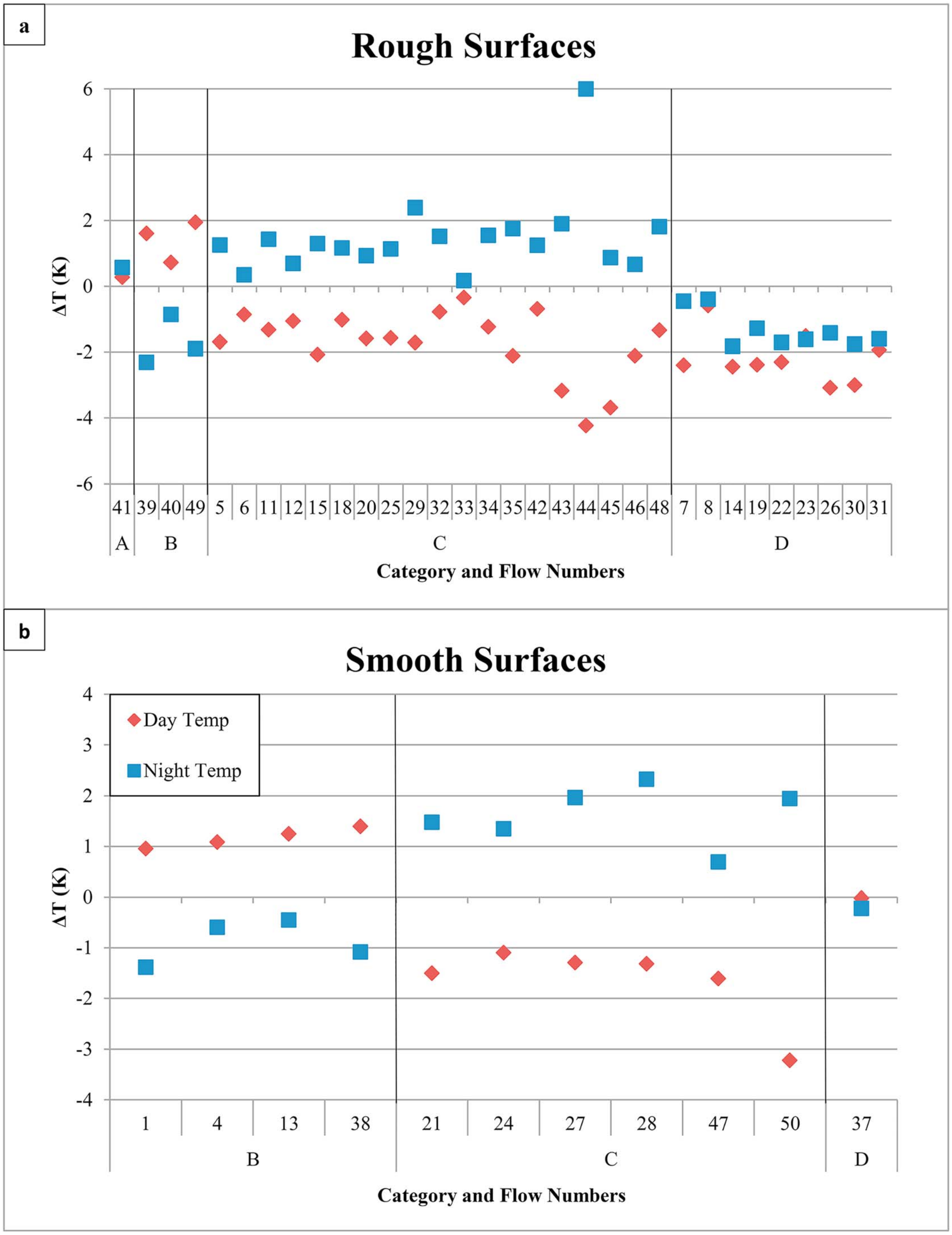

Figure 7. Delta brightness temperature (ΔT) values shown for each flow, grouped by flow category and surface morphology. These delta values were computed by calculating the difference between the average value for the THEMIS stamp and average value for each flow in order to compare values between stamps with different observation parameters (see section 3.5 for explanation; Christensen et al., 2004, n.d.). Data were further separated between (a) rough and (b) smooth surface morphologies. THEMIS data are publicly available at the ASU Mars Image Explorer (https://viewer.mars.asu.edu).

4.6. Correlation Between Thermal Response and Surface Morphology

The correlation between the four thermophysical categories and the rough/smooth surface morphology demonstrates that flow surface structure likely influences the distribution of dust, sand, and lava outcrops (Table 3; Figures 7a–7b). A slight majority (58%) of all flows, both rough and smooth, have a category C thermal signature. This suggests that enough lava outcrops are exposed and/or minimally mantled to produce a limited diurnal temperature response. Lava flows outcrops with limited sand/dust mantling would display lower daytime and higher nighttime brightness temperatures, whereas flows covered with a thick layer of dust would display a classic high daytime and low nighttime temperature diurnal cycle. Smooth elongated flows are dominantly either category B or C (combined over 90%) with a greater percentage of the smooth flows being category B compared to that of rough flows. This suggests that these flows are more likely to have greater amounts of dust and/or sand (Table 3). A percentage of the smooth flows do demonstrate a thermophysical response more indicative of a higher lava outcrop concentration (category C). However, the interpretation of their surfaces in the high resolution data is more problematic with far less surface diversity than the rough flows. It may be the case where the mixing of dust and underlying rock is simply below the scale of even HiRISE data (Figures 2f–2g).

Over 87% of rough surface flows are either category C or D, with lower daytime brightness temperatures (Table 2). Of these flows, over 59% are category C (low daytime and high nighttime brightness temperatures) with slightly higher thermal inertia values (Figure 7a). Based on CTX and HiRISE analysis of these surfaces, category C rough lava flows are the most likely to resemble a'a flows and contain a significant amount of exposed lava outcrops (Figure 5f). The visible data also show eolian forms such as ripples in the low-lying areas (Figure 2f). One possible explanation for why rough flows display thermal signatures indicative of higher concentration of lava outcrops centers on the wind interaction with the different surface morphologies. As seen in HiRISE data (Figure 2f), the lava outcrops on rough flows are visibly higher and have ventifact-appearing facets. These outcrops, therefore, may be eroding preferentially, creating localized areas preferentially swept clean of dust. The smooth flows lack large surface topography that would promote this process, thus allowing dust to accumulate.

Thus, the results of this visible and thermophysical study provide clues about the nonuniform subpixel surface characteristics of the Daedalia Planum flow field southwest of Aria Mons by identifying flows with a greater amount of exposed lava outcrops (category C) or finer-grained sand sized particles (category B) comparatively. The thermophysical variation between these flows is linked foremost to the overprinting of different areal proportions of dust, sand, and lava outcrops, which appear to be related to (if not driven by) the flow morphology (rough versus smooth). The confirmation of a greater amount of exposed lava on certain flows, detectable from orbital visible and IR data, is important for future studies aimed at unraveling this subpixel mixing and more importantly, focused on compositional and volcanological analyses.

5. Conclusions

The surface thermophysical properties and flow morphology reveal that individual flows in Daedalia Planum respond differently to diurnal heating, suggesting that the area is not completely (or uniformly) mantled by dust as previously assumed. Interestingly, this diversity in postemplacement eolian activity is not simply a function of age (Berman & Crown, 2019; Crown et al., 2015). Decorrelation and the limited spectral analysis of the thermal IR data suggest that there is no significant compositional difference that would cause these thermophysical variations, nor does assuming that this is a dusty region on Mars. In order to further examine and quantify this variability, the diurnal temperature and TI responses of individual flows were evaluated in relation to the mean of the study area. The goal was to determine the cause of the unusual thermophysical variability seen in this region. The conclusion, described below, is that it is a complex relationship between the flow surface morphology and the vertical layering and/or horizontal mixing of dust, sand, and lava outcrops. Certain flows and areas within flows appear to have significantly higher amounts of lava outcrops, which will be targeted for further investigation.

Most flows demonstrate an expected inverse diurnal temperature response resulting in two distinct diurnal curves (Table 3). Flows with a higher daytime and lower nighttime temperature (category B) have lower TI values indicating that these surfaces have the largest range of temperature variability over a day and have faster rates of heating and cooling. These flows either have a higher concentration of sand on the surface with a minor presence of lava outcrops and dust or a significantly thicker dust coverage compared to neighboring flows. With the inverse diurnal temperature response, category C flows with higher TI values have the most limited range of diurnal temperature variation and the slowest rate of heating and cooling. These flows contain a visibly greater areal distribution of lava outcrops with sand in low-lying regions and some level of nonhomogeneous dust coverage. Ripples are also seen in the low-lying regions of these rough flows in HiRISE images. Analysis of surface morphology in both visible and thermal infrared data demonstrates that rough flows with a category C response contain the highest concentration of identifiable lava outcrops.

The subpixel surface horizontal mixing and vertical layering of thermophysical units is detected in higher spatial resolution orbital thermal IR data and may be seen in other regions on Mars with similar eolian mantling. This work successfully quantified the small-scale thermophysical properties of individual lava flows in Daedalia Planum, developed an approach to understand the thermophysical units responsible, and identified the surfaces with the greatest amount of exposed lava outcrops. This was completed in an area previously overlooked for any thermal IR analysis because of the TES-derived albedo and a dust cover index values. Importantly, a likely significant areal percentage of lava outcrops are present on the surface of some of these flows suggesting the presence of particular eolian surface process that interacts with the surface topography of the rough flows, keeping them relatively dust free. Work is ongoing to quantify the areal percentages of the thermophysical units and complete a more detailed spectral analysis of the flow areas with more outcrops present. Those results could constrain any down-flow spectral changes or differences between flows, which would lead to a better understanding of the compositional and rheological properties of individual flow emplacement in this complex and interesting flow field on Mars.

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References

Bandfield, J. L. (2009). Effects of surface roughness and graybody emissivity on Martian thermal infrared spectra. *Icarus*, *202*(2), 414–428. https://doi.org/10.1016/j.icarus.2009.03.031

Bandfield, J. L., Rogers, D., Smith, M. D., & Christensen, P. R. (2004). Atmospheric correction and surface spectral unit mapping using Thermal Emission Imaging System data. *Journal of Geophysical Research*, *109*, E10008. https://doi.org/10.1029/2004JE002289

Berman, D. C. & Crown, D. A. (2019). Chronology of volcanism in Southern Tharsis, Mars: Constraints from lava flows in Daedalia Planum. Lunar and Planetary Science Conference L, Lunar and Planetary Institute, Houston, abs. #1418.

Bleacher, J. E., Greeley, R., Williams, D. A., Cave, S. R., & Neukum, G. (2007). Trends in effusive style at the Tharsis Montes, Mars, and implications for the development of the Tharsis province. *Journal of Geophysical Research*, *112*, E09005. https://doi.org/10.1029/2006JE002873

Christensen, P. R., Bandfield, J. L., Hamilton, V. E., Ruff, S. W., Kieffer, H. H., Titus, T. N., et al. (2001). The Mars Global Surveyor Thermal Emission Spectrometer experiment: Investigation description and surface science results. *Journal of Geophysical Research*, *106*(E10), 23,823–23,871. https://doi.org/10.1029/2000JE001370

Christensen, P. R., Gorelick, N. S., Mehall, G. L., & Murray, K. C. (2004, n.d.). THEMIS public data releases, Planetary Data System node, Arizona State University, <http://themis-data.asu.edu>.

Christensen, P. R., Jakosky, B. M., Kieffer, H. H., Malin, M. C., Mcsween, H. Y. Jr., Nealson, K., et al. (2004). The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey mission. *Space Science Reviews*, *110*(1/2), 85–130. https://doi.org/10.1023/B:SPAC.0000021008.16305.94

Crown, D. A., Berman, D. C., & Ramsey, M. S. (2015). Lava flow fields of Southern Tharsis, Mars: Flow types, interactions, and ages. Lunar and Planetary Science Conference XLVI, Lunar and Planetary Institute, Houston, abs. #1349.

Crown, D. A., & Ramsey, M. S. (2017). Morphologic and thermophysical characteristics of lava flows southwest of Arsia Mons, Mars. *Journal of Volcanology and Geothermal Research*, *342*, 13–28. https://doi.org/10.1016/j.jvolgeores.2016.07.008

Crown, D. A., Ramsey, M. S., & Berman, D. C. (2010). Mapping Arsia Mons lava flow fields: Insights into flow emplacement processes and flow field development. Lunar and Planetary Science Conference XLI, Lunar and Planetary Institute, Houston, abs. #2225.

Crumpler, L. S., Head, J. W., & Aubele, J. C. (1996). *Calderas on Mars: Characteristics, structure and associated flank deformation*, *Geological Society, London, Special Publications* (Vol. 110, pp. 307–348). https://doi.org/10.1144/GSL.SP.1996.110.01.24

Edgett, K. S., & Lancaster, N. (1993). Volcaniclastic aeolian dunes: Terrestrial examples and application to Martian sands. *Journal of Arid Environments*, *25*(3), 271–297. https://doi.org/10.1006/jare.1993.1061

Edgett, K. S., & Malin, M. C. (2000). New views of Mars eolian activity, materials, and surface properties: Three vignettes from the Mars Global Surveyer Mars Orbiter Camera. *Journal of Geophysical Research*, *105*(E1), 1623–1650. https://doi.org/10.1029/1999JE001152

Edwards, C. S., Nowicki, K. J., Christensen, P. R., Hill, J., Gorelick, N., & Murray, K. (2011). Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. *Journal of Geophysical Research*, *116*, E10008. https://doi.org/10.1029/2010JE003755

Fergason, R. L., Christensen, P. R., & Kieffer, H. H. (2006). High resolution thermal inertia derived from the Thermal Emission Imaging System (THEMIS): Thermal model and applications. *Journal of Geophysical Research*, *111*, E12004. https://doi.org/10.1029/2006JE002735

Garry, W. B., Williams, D. A., & Bleacher, J. E. (2014). Geologic mapping of Arsia and Pavonis Montes, Mars. *Lunar and Planetary Science Conference XLV, Lunar and Planetary Institute, Houston,* abs #2133.

Garry, W. B., Williams, D. A., Dapremont, A. M., & Shean, D. E. (2018). The 1:1,000,000 geologic map of Arsia Mons, Mars. *Planetary Geologic Mappers Meeting 2018, abs.#7028*.

Giacomini, L., Carli, C., Sgavetti, M., & Massironi, M. (2012). Spectral analysis and geological mapping of the Daedalia Planum lava field (Mars) using OMEGA data. *Icarus*, *220*(2), 679–693. https://doi.org/10.1016/j.icarus.2012.06.010

Giacomini, L., Massironi, M., Martellato, E., Pasquare, G., Frigeri, A., & Cremonese, G. (2009). Inflated flows on Daedalia Planum (Mars)? Clues from a comparative analysis with the Payen volcanic complex (Argentina). *Planetary and Space Science*, *57*(5-6), 556–570. https://doi.org/10.1016/j.pss.2008.12.001

Hamilton, V. E., Osterloo, M. M., & McGrane, B. S. (2007). THEMIS decorrelation stretched infrared mosaics for compositional evaluation of candidate 2009 Mars Science Laboratory landing sites: Evidence for significant spectral diversity, Lunar and Planetary Science Conference XXXVIII, Lunar and Planetary Institute, Houston, abs. #1725.

Hardgrove, C., Moersch, J., & Whisner, S. (2009). Thermal imaging of alluvial fans: A new technique for remote classification of sedimentary features. *Earth and Planetary Science Letters*, *285*(1-2), 124–130. https://doi.org/10.1016/j.epsl.2009.06.004

Head, J. W., Siebert, N., Pratt, S., Smith, D., Zuber, M., Solomon, S., et al., & the MOLA Science Team (1998b). Characterization of major volcanic edifices on Mars using Mars Orbiter Laser Altimeter (MOLA) data. *Lunar and Planetary Science Conference XXIX*, abs # 1322.

Head, J. W., Siebert, N., Pratt, S., Smith, D., Zuber, M., Solomon, S., et al., & the MOLA Science Team (1998a). Volcanic calderas on Mars: Initial views using Mars Orbiter Laser Altimeter (MOLA) data. *Lunar and Planetary Science Conference XXIX, Lunar and Planetary Institute, Houston,* abs. # 1488.

Jakosky, B. M. (1986). On the thermal properties of Martian fines. *Icarus*, *66*(1), 117–124. https://doi.org/10.1016/0019-1035(86)90011-4

Johnson, J. R., Christensen, P. R., & Lucey, P. G. (2002). Dust coatings on basaltic rocks and implications for thermal infrared spectroscopy of Mars. *Journal of Geophysical Research*, *107*(E6), 5035. https://doi.org/10.1029/2000JE001405

Kieffer, H. H. (2013). Thermal model for analysis of Mars infrared mapping. *Journal of Geophysical Research: Planets*, *118*, 451–470. https://doi.org/10.1029/2012JE004164

Kieffer, H. H., Neugebauer, G., Munch, G., Chase, S. C. Jr., & Miner, E. (1972). Infrared thermal mapping experiment: The Viking Mars orbiter. *Icarus*, *16*(1), 47–56. https://doi.org/10.1016/0019-1035(72)90136-4

Lang, N. P., Tornabene, L. L., McSween, H. Y. Jr., & Christensen, P. R. (2009). Tharsis-sourced relatively dust-free lavas and their possible relationship to Martian meteorites. *Journal of Volcanology and Geothermal Research*, *185*(1-2), 103–115. https://doi.org/10.1016/j.jvolgeores.2008.12.014

Lopez, T., Antoine, R., Baratoux, D., Rabinowicz, M., Kurita, K., & d'Uston, L. (2012). Thermal anomalies on pit craters and sinuous rilles of Arsia Mons: Possible signatures of atmospheric gas circulation in the volcano. *Journal of Geophysical Research*, *117*, E09007. https://doi.org/10.1029/2012JE004050

Malin, M. C., Bell, J. F. III, Cantor, B. A., Caplinger, M. A., Calvin, W. M., Clancy, R. T., et al. (2007). Context Camera investigation on board the Mars Reconnaissance Orbiter. *Journal of Geophysical Research*, *112*, E05S04. https://doi.org/10.1029/2006JE002808

McEwen, A. S., Eliason, E. M., Bergstrom, J. W., Bridges, N. T., Hansen, C. J., Delamere, W. A., et al. (2007). Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *Journal of Geophysical Research*, *112*, E05S02. https://doi.org/10.1029/2005JE002605

Mellon, M. T., McKay, C. P., & Grant, J. A. (2014). Thermal conductivity of coarse and fine grained soil mixtures: Measurements and Mars applications. 8th Intern. Conf. on Mars, abs. #1107.

Mouginis-Mars, P. J. (2002). Prodigious ash deposits near the summit of Arsia Mons volcano, Mars. *Geophysical Research Letters*, *29*(16), 1768. https://doi.org/10.1029/2002GL015296

Neugebauer, G., Munch, G., Kieffer, H., Chase, S. C. Jr., & Miner, E. (1971). Mariner 1969 infrared radiometer results: Temperatures and thermal properties of the Martian surface. *Astronomical Journal*, *76*(4), 719–728. https://doi.org/10.1086/111189

Pratt, D. A., & Ellyett, C. D. (1979). The thermal inertia approach to mapping of soil moisture and geology. *Remote Sensing of Environment*, *8*(2), 151–168. https://doi.org/10.1016/0034-4257(79)90014-2

Presley, M. A., & Christensen, P. R. (1997). Thermal conductivity measurements of particulate materials: 2. *Results. Journal of Geophysical Research*, *102*(E3), 6551–6566. https://doi.org/10.1029/96JE03303

Putzig, N. E., & Mellon, M. T. (2007). Apparent thermal inertia and the surface heterogeneity of Mars. *Icarus*, *191*(1), 68–94. https://doi.org/10.1016/j.icarus.2007.05.013

Ramsey, M. S., & Crown, D. A. (2010). Thermophysical and spectral variability of Arsia Mons lava flows. Lunar and Planetary Science Conference XLI, Lunar and Planetary Institute, Houston, abs. #1111.

Ramsey, M. S., Harris, A. J. L., & Crown, D. A. (2015). Constraining the rheologic properties of channelized basaltic flows on Earth and Mars. *American Geophysical Union Fall Meeting*, *abs. #P31H-04*.

Ruff, S. W., & Christensen, P. R. (2002). Bright and dark regions on Mars: Particle size and mineralogical characteristics based on Thermal Emission Spectrometer data. *Journal of Geophysical Research*, *107*(E12), 5119. https://doi.org/10.1029/2001JE001580

Scott, D. H., & Zimbelman, J. R. (1995) Geologic Map of Arsia Mons Volcano, Mars (scale 1:1,000,000), *United States Geological Survey, Geology Series Map 1-2480*.

Sheskin, D. J. (2011). *Handbook of parametric and nonparametric statistical procedures*, (fifth ed.). New York: NY, Chapman and Hall/CRC.

Simurda, C. S., Ramsey, M. S., & Crown, D. A. (2016). Surface characteristics of the Daedalia Planum lava flow field derived from thermophysical and geological mapping. *Lunar and Planetary Science Conference XLVII, Lunar and Planetary Institute, Houston, abs. #2594*.

Warner, N. H., & Gregg, T. K. P. (2003). Evolved lavas on Mars? Observations from southwest Arsia Mons and Sabancaya volcano, Peru. *Journal of Geophysical Research*, *108*(E10), 5112. https://doi.org/10.1029/2002JE001969