Areally extensive surface bedrock exposures on Mars: Many are clastic rocks, not lavas

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Key points:

1. Many bedrock plains are likely composed of mechanically weak rocks
2. Potential origins include lithified detrital sediments, pyroclastics, or impact-generated materials
3. High thermal inertia may indicate relatively friable rocks, due to ease of comminution product removal and exposure of lithified surface

Abstract

Areally extensive exposures of intact olivine/pyroxene-enriched rock, as well as feldspar-enriched rock, are found in isolated locations throughout the Martian highlands. The petrogenetic origin(s) of these rock units are not well understood, but some previous studies favored an effusive volcanic origin partly on the basis of distinctive composition and relatively high thermal inertia. Here we show that the regolith development, crater retention, and morphological characteristics for many of these "bedrock plains" are not consistent with competent lavas, and reinterpret the high thermal inertia orbital signatures to represent friable materials that are more easily kept free of comminution products through aeolian activity. Candidate origins include pyroclastic rocks, impact-generated materials, or detrital sedimentary rocks. Olivine/pyroxene enrichments in bedrock plains relative to surrounding materials could have potentially formed through deflation and preferential removal of plagioclase.

1. Introduction

The Martian cratered highlands host numerous surface exposures of intact rock, identified by morphologies that indicate lithified materials (scarp-forming, wind-eroded surfaces) and by their high thermal inertia values relative to average surfaces on Mars (e.g. Edwards et al., 2009). Thermal inertia (TI) is defined as $(k\rho c)^{1/2}$, where k is the bulk thermal conductivity, ρ is the bulk density, and c is the specific heat of the material (Kieffer et al., 1977). On Mars, TI is strongly controlled by particle size, porosity and compaction. Typical Martian surfaces, which are dominated by dust- to sand-sized particles, exhibit TI values between 28 and 355 $J \cdot m^{-2} K^{-1} s^{-0.5}$ (Putzig et al., 2005); bedrock, compacted and/or coarse particulate surfaces exhibit higher TI values.

TI values are typically modeled from nighttime surface temperature measurements, for example from the Mars Global Surveyor Thermal Emission Spectrometer (TES) (~5 km/pixel, Christensen et al., 2001) or Mars Odyssey Thermal Emission Imaging System (THEMIS) (100 m/pixel, Christensen et al., 2004a). Using THEMIS, bedrock can be spatially resolved. Given the uncertainties in partial sediment cover, as well as in atmospheric dust opacity at the time of data acquisition, most studies have not used a strict THEMIS TI threshold to define bedrock. Rather, bedrock is usually identified using a combination of TES TI > 350 $J \cdot m^{-2} K^{-1} s^{-0.5}$, a relatively higher THEMIS nighttime radiance, and morphological expressions of lithified material (e.g. eroded surfaces, scarps) (e.g. Rogers and Nazarian, 2013). We do note that with one exception, the exposures discussed in this work have at least a portion of the bedrock exposure with THEMIS TI values > 493 $J \cdot m^{-2} K^{-1} s^{-0.5}$, from the THEMIS global TI mosaic (Christensen et al., 2013). Bedrock exposures have been identified in various geologic contexts, including flat plains, crater/canyon walls, and canyon floors (Edwards et al., 2009). Our focus here is on the dozens of areally extensive, flat exposures, hereafter referred to as "bedrock plains" (**Figure 1**). We review key details about these surfaces below.

Bedrock plains are most commonly found in topographic lows of intercrater surfaces of heavily cratered terrain or as graben- or crater floor-filling materials, and can exceed ~10^4 sq km in area (Rogers et al., 2009; Edwards et al., 2009; Rogers and Fergason, 2011; Rogers and Nazarian, 2013). Portions of the bedrock plains are overlain by relatively lower-TI materials, and are surrounded by lower-TI surfaces previously interpreted as megaregolith, crater ejecta, and/or pyroclastic materials (Rogers et al., 2009; Bandfield et al., 2013) (e.g. **Figure 1b-c**). At the decameter scale, the intercrater and crater-filling bedrock plains are fractured, lack evidence for fine-scale layering, and range from flat/smooth to rugged, with apparent topographic relief. The formation ages of many of the intercrater bedrock plains are likely between Middle and Late Noachian and late Noachian/Early Hesperian, based on stratigraphic relationships for some units (e.g. **Figure 2**) as well as good spatial correspondence with the "Late Noachian highlands" unit mapped by Tanaka et al. (2014). But some units are too small (order of <1,000 km^2) to demonstrate Noachian formation ages and/or have no dateable cross-cutting units, and thus could be younger than Early Hesperian.

Though intercrater plains and crater floors are the most common contexts for bedrock plains, other bedrock plains include the sulfate-bearing "etched unit" of Terra Meridiani (Hynek et al., 2002; Arvidson et al., 2005), the floor materials of Nili Patera caldera (Christensen et al., 2005), the intermontane regions of Libya Montes (Christensen et al., 2004b), and a fractured, banded plateau in the Nili Fossae region (Hamilton and Christensen, 2005). The Nili Fossae bedrock plain is of particular interest because it is near two of the proposed landing sites for the Mars 2020 rover: Jezero crater (Goudge et al., 2015) and Northeast Syrtis (Bramble et al., 2017).

With the exception of Terra Meridiani, bedrock plains are typically enriched in olivine and/or pyroxene compared to surrounding low-TI surfaces, determined through analyses of infrared spectra (Rogers et al., 2009; Rogers and Fergason, 2011; Loizeau et al., 2012; Ody et al., 2012; Edwards et al., 2014). Spectral evidence of secondary minerals in olivine/pyroxene-enriched bedrock plains is thus far undiscovered, with the exception of the Nili Fossae olivine-bearing unit, which is altered in places (Ehlmann et al., 2008). Some bedrock plains contain feldspathic rocks (Wray et al., 2013; Carter et al., 2013; Rogers and Nekvasil, 2015), with variable alteration (Wray et al., 2013). Last, it should be noted that the observable characteristics of bedrock plains differ significantly from the Hellas basin rim intercrater plains sedimentary units described by Salese et al. (2016), which show subhorizontal bedding, alteration minerals, no olivine enrichment, and relatively low TI values.

The formational mechanism(s) of bedrock plains are not well understood. Previous studies of the intercrater surfaces and crater/graben-filling high-TI units favored an effusive volcanic origin for these materials, primarily based on: the distinctive compositions compared to surroundings (Rogers et al., 2009; Ody et al., 2012; Rogers and Nazarian, 2013;

Edwards et al., 2014), the mare-like appearance at THEMIS resolution (smooth plains with wrinkle ridges), and relatively high TI values (>1200 $J \cdot m^{-2} K^{-1} s^{-0.5}$) in a few locations (Rogers et al., 2009; Rogers and Nazarian, 2013; Edwards et al., 2014). Detrital sedimentary origins were less favored due to the lack of olivine-bearing source regions for the olivine sediments (e.g. Rogers and Nazarian, 2013); although some spectrally-undistinctive crater filling bedrock materials were interpreted as sedimentary (McDowell and Hamilton, 2007). Olivine-enriched bedrock plains in Nili Fossae, Libya Montes and Nili Patera have been interpreted as effusive volcanics (Christensen et al., 2004b; Hamilton and Christensen, 2005; Tornabene et al., 2008) or alternatively for Nili Fossae and Libya Montes, impact melts (Mustard et al., 2007).

In this work, we re-examine intercrater and crater/graben-filling bedrock plains with a focus on high-resolution morphologies and crater retention, as well as by comparing the thermophysical characteristics of these distinctive units with known volcanic plains in Hesperia Planum and Syrtis Major. Our observations suggest that many bedrock plains are relatively friable materials, consistent with clastic rocks, rather than lavas.

2. Observations

2.1 Bedrock plains lack thick regolith cover, unlike Hesperian volcanic plains

Hesperian volcanic plains are extensive, flat-lying units thought to have formed during high effusion rate, fissure-fed eruptions (Greeley and Spudis, 1981). Crater/graben wall exposures and ejecta from small diameter craters found in Hesperian volcanic plains exhibit high TI values and/or visibly blocky materials, suggesting mechanically strong materials at depth, consistent with lavas (Bandfield et al., 2013; Warner et al., 2017). Hesperia Planum and Syrtis Major serve as useful volcanic plains reference surfaces because they are at equatorial latitudes (thus less affected by Amazonian periglacial reworking), are not dust mantled, and in some areas directly contact older, bedrock plains exposures.

Hesperia Planum and Syrtis Major typically exhibit TES TI values (170-310 $J \cdot m^{-2} K^{-1} s^{-0.5}$) consistent with fine to coarse sand or a mixture of dust and coarser materials; plains bedrock exposures within these two regions are rare (**Figure 1**). In Hesperia Planum, typical morphologies observed in high resolution imagery are bedforms or smooth, featureless surfaces, suggesting a surficial layer dominated by unconsolidated sediment. These observations indicate that the Hesperian lavas are covered with a regolith, similar in grain size and unit thickness (~1 to 10 m) to Hesperian volcanic units in Gusev crater and Elysium Planitia (Golombek et al., 2006a; 2017; Warner et al., 2017).

In the absence of surface processes that remove (e.g. eolian or fluvial resurfacing) or prevent regolith from forming (e.g. burial), a thick regolith is expected for Noachian/Hesperian-age bedrock exposed to repeated impact events (Hartmann et al., 2001). However, a thick regolith is not present on the bedrock plains, as indicated by the relatively higher TI values and morphological indicators of exposed rock (**Section 1**). Why is this? Increased strength or duration of erosional processes (e.g. wind, fluvial) on bedrock plains could potentially explain the minimal regolith cover. However, preferential erosional strength/duration cannot explain all of the bedrock occurrences because there are locations where regolith-covered Hesperian lavas directly contact or are in close spatial and topographic proximity to bedrock plains. For example, at the southern margin of Syrtis Major Planum, bedrock plains are directly subjacent to the Hesperian lavas. A striking difference in TI and sediment cover is observed across this boundary (**Figure 2a-b**), indicating a direct relationship between regolith cover and its underlying source unit. It is unlikely that long-term landscape modification by eolian processes would preserve such a well-defined contact if the two units were similarly resistant to erosion and exposed to the same surface processes. Even if denudation of the landscape occurred prior to emplacement of the Hesperian lavas, a meters-thick regolith should have developed on the denuded surface after that event(s). This, however, is not observed. A sharp difference in TI is also found at the eastern margin of Hesperia Planum, where low-TI, regolith-covered Hesperian lavas contact bedrock plains (**Figure 1c**). This example is discussed further in **Section 3.2**.

We hypothesize that the difference in regolith cover across the bedrock plains-Hesperian volcanics contact is related to differences in material properties, where the bedrock plains represent mechanically weak materials relative to Hesperian lavas. Comminution products from mechanically weak materials would be expected to include few blocks and a larger proportion of fine-to-medium sand-sized particles (e.g. Malin and Edgett, 2000; Golombek et al., 2006b, 2010) that are easily moved by wind (Greeley et al., 1980). In contrast, regolith developed from mechanically strong materials would include a larger proportion of blocks and coarser particulate material, as observed at other lava plains localities where surface processes are limited to impact gardening and eolian modification

(Golombek et al. 2006; Warner et al. 2017). Over time, this would lead to buildup of a regolith dominated by unconsolidated materials that were not mobilized by wind (e.g. coarse sand and larger, as well as subsequently trapped dust) on competent surfaces (e.g. Golombek et al., 2006a, 2017), whereas mechanically weak materials (perhaps consisting of weakly consolidated, dominantly fine-to-medium sand-sized clasts) would experience constant deflation, exposing a lithified surface.

This hypothesis of material properties controlling regolith thickness is founded in similar observations of known clastic rocks elsewhere on Mars. For example, Noachian sulfate-bearing sandstones in Meridiani Planum exhibit an Amazonian exposure age, which was attributed to relatively rapid resurfacing from eolian scour of highly erodible rocks (Golombek et al., 2006b, 2014). The Amazonian exposure age and comparatively high erosion rates of finely layered units in Valles Marineris and Arabia Terra have also been attributed to their friable nature (Malin and Edgett, 2000; Grindrod and Warner, 2014). Last, the Columbia Hills of Gusev crater are dominated by clastic rocks, and exhibit less regolith cover than the adjacent (and younger) Hesperian plains (Grant et al., 2006). The Gusev example is described in more detail below, building on the findings of Grant et al. (2006) but with a focus on the orbital TI signatures.

In Gusev crater, Mars Exploration Rover observations show that regions of the Columbia Hills exhibit less regolith cover compared to the superjacent Hesperian plains (Grant et al., 2006). This is consistent with TI measurements from orbit, where the Columbia Hills exhibit relatively high THEMIS TI (~350-500 $J\cdot m^{-2}K^{-1}s^{-0.5}$), compared to the Hesperian basaltic unit (~180–210 $J\cdot m^{-2}K^{-1}s^{-0.5}$) (**Figure 2c**). In contrast, *in-situ* TI measurements from individual blocks of each of these units show that the Hesperian basalts exhibit TI values of ~1200 $J\cdot m^{-2}K^{-1}s^{-0.5}$, which is higher than TI values from rocks of the Columbia Hills (~600 $J\cdot m^{-2}K^{-1}s^{-0.5}$) (Fergason et al., 2006). The areally dominant Columbia Hills rock type causing the high TI signature from orbit is likely the “Algonquin”/”Comanche” class, interpreted as variably altered olivine-bearing basaltic tephra (Ruff et al., 2014). To the southwest of the Columbia Hills, materials with similar texture and TI to the Algonquin/Comanche rocks outcrop through windows in the Hesperian basaltic unit (**Figure 2c**), and may be lateral extensions of the Algonquin class (Ruff et al., 2014). The Algonquin class rocks would likely be mechanically weak compared to Gusev plains lavas (e.g. Thomson et al., 2013). The gradient in TI between the Hesperian basaltic unit and the stratigraphically lower unit is sharp; the extent of the regolith cover closely corresponds with the margins of the Hesperian units (**Figure 2c**), suggesting control by the material properties of both units.

2.2 Morphological observations and crater retention

Bedrock plains commonly exhibit parallel to sub-parallel striations that resemble yardangs or wind-eroded morphologies, suggestive of friable materials (**Figure 3a-b**). On Earth, yardangs are typically observed in friable units and are rarely observed in crystalline rocks such as basalts, but examples do exist (Inbar and Risso, 2001). Nonetheless, other morphological indicators of friability, such as outcrops with smooth or scalloped textures, are present in some bedrock plains (**Figure 3c-d**).

Lavas are competent, high shear strength materials that retain small craters through increased resistance to comminution, erosion, and diffusive slope processes. In contrast, friable materials do not retain small craters as well, and are subject to faster erosion rates than armored, rocky basaltic surfaces by 1 to 3 orders of magnitude (Golombek and Bridges, 2000; Golombek et al., 2006a,b; 2014; Sweeney et al., 2016). We investigated cumulative crater frequency as a function of crater diameter (>200 m) for nine bedrock units, and compared these densities with those from nearby lower-TI surfaces of roughly equal area (**Text S1**). Low-TI surfaces were chosen from the same or younger global chronostratigraphic unit (defined by Tanaka et al., 2014) as the bedrock surface. Low-TI surfaces from Early, Middle or Late Noachian highlands chronostratigraphic units (eNh, mNh, lNh) were presumed to consist of regolith derived from ancient basaltic crust, and were chosen as close in elevation as possible to the bedrock units (<300 m) to reduce possible influence of differences in slope modifying processes and wind activity over the two surfaces (**Table S1**).

The bedrock plains show between 18 and 78% lower crater density than adjacent low-TI surfaces (**Table S2, Figure 3e**), and in addition, small craters commonly appear less well-preserved on the bedrock (**Figure 3a-b**, **Figure S10**). Furthermore, except for regions 2 and 3, the crater frequency curves for the bedrock units exhibit shallower slopes than the curves for the low-TI units, particularly for diameter bins below ~500-700 m (varies by region). This is consistent with stronger resurfacing on the bedrock units and easier removal of craters at or below ~500-700 m diameter (note that we ignore possible crater scaling effects with target properties, van der Bogert, 2017; **Text S1**). We caution that differences in crater populations across these two surface types could also arise from spatial differences in wind strength; this could be tested with mesoscale atmospheric modeling. However, in general, these observations suggest that bedrock plains do not preserve small craters as well as adjacent low-TI surfaces.

3. Discussion

3.1 Does exposed rock always indicate friable rock?

Impact comminution should result in at least a meter of regolith for Late Amazonian surfaces, increasing to tens to hundreds of meters thickness for Hesperian and Noachian surfaces (Hartmann et al., 2001). Though nearly regolith-free ancient surfaces could arise from weak mechanical strength and friability, combined with erosion (e.g. Malin and Edgett, 2000; Golombek et al., 2014) (**Section 2**), exposures of Noachian/Hesperian *competent* bedrock could occur through other scenarios. For example, Noachian surfaces that were rapidly buried would have been protected from impact comminution as long as the burial cover was present; later exhumation would result in exposed rock (Hartmann et al., 2001). Exhumation would have had to occur in the late Amazonian, otherwise a ~meters-thick regolith would have subsequently developed (Hartmann et al., 2001). One potential example of where effusive volcanic bedrock may have been protected through burial is at the eastern margin of Hesperia Planum (**Figure 1c**), where there is minimal difference in small crater preservation between the bedrock plains and the Hesperian lavas (**Table S2**).

In some cases, fluvial erosion and later wind activity could have helped to expose competent bedrock. Olivine-enriched bedrock in Ares Vallis (Rogers et al., 2005), which exhibits high retention of small diameter craters (**Figure S11**), may be an example of this scenario. Though this bedrock could have been exposed as early as the first outflow event (likely Hesperian), and thus subjected to impacts for significant duration, episodic flooding events in Ares Vallis may have continued through the Early Amazonian (Warner et al., 2009). These later events could have removed any regolith that had formed up until that point. Then, strong katabatic winds, funneled by the canyon, may have continued to keep those olivine-bearing surfaces free of comminution products; continuance of low sediment cover in the mid-to-late Amazonian would have been aided by a reduced cratering rate (and thus reduced sediment production rate) relative to the Noachian/Hesperian.

In summary, exposed rock does not necessarily indicate friable rock. But other morphological indicators, such as crater retention and morphology, can be used to assess friability (e.g. Malin and Edgett, 2000). Our observations suggest that bedrock plains may commonly consist of friable rock. If correct, this has implications for using TI to interpret rock mechanical strength from orbit. For example, previous studies have interpreted the relatively high TI values (500 to >1200 $J{\cdot}m^{-2}K^{-1}s^{-0.5}$) of intercrater and crater floor materials to represent materials of high mechanical strength (e.g. Rogers et al., 2009; Bandfield et al., 2013; Edwards et al., 2014); however, relatively high-TI surfaces could maintain their high values through high erodibility, and thus could instead indicate low mechanical strength relative to Hesperian lavas. Furthermore, these TI values are within the range of those measured from friable volcaniclastic or sedimentary rocks in the Columbia Hills (~620 $J{\cdot}m^{-2}K^{-1}s^{-0.5}$, up to ~1100 $J{\cdot}m^{-2}K^{-1}s^{-0.5}$; Fergason et al., 2006), Meridiani Planum (likely 400-1100 $J{\cdot}m^{-2}K^{-1}s^{-0.5}$ inferred from Rock Abrasion Tool grind energies, Golombek et al., 2008), and Gale crater (370–540, up to ~700 $J{\cdot}m^{-2}K^{-1}s^{-0.5}$ for mudstones/sandstones, Hamilton et al., 2014; Vasavada et al., 2017).

3.2 Potential origin(s) of bedrock plains and causes of olivine enrichment

The evidence for friability suggests that effusive volcanic origins are unlikely for many bedrock plains units, in contrast with interpretations from previous studies (Rogers et al., 2009; Rogers and Fergason. 2011; Bandfield et al., 2013; Rogers and Nazarian, 2013; Edwards et al., 2014). Given the compositional and morphological variability observed among these dozens of units there is no reason to assume that they all have a single origin. However, origin models must satisfactorily explain the typically distinctive compositions (e.g. olivine enrichments compared to surrounding low-TI surfaces), and the concentration in topographic lows. Candidate petrogenetic processes that deposited these clastic units include explosive volcanism, impact-related processes, and detrital sedimentation.

Localized, explosive volcanism could have produced some of the olivine-bearing and/or feldspathic bedrock plains units. Though evidence for draping relationships are absent for the intercrater and crater-filling bedrock plains (Rogers and Nazarian, 2013), vents located within the topographically lower parts of these basins could have produced locally-deposited tephras.

Impact-related deposition might explain some of these deposits. Large, basin-scale impacts (e.g. Isidis, Argyre, Hellas), could have produced olivine-bearing clastic rocks in the form of suevites, and also potentially as condensates from silicate vapor created during the impact (Toon et al., 2010). These silicate condensate materials could range from porous/unconsolidated to strongly welded, depending on the thickness of the deposits and temperature at time of deposition (Toon et al., 2010; Palumbo and Head, 2017). Indeed, previous authors have suggested that the Nili Fossae and Isidis olivine-bearing bedrock plains units may represent the silicate condensate (Palumbo and Head, 2017) or impact melt (Mustard et al., 2007) from the Isidis basin impact. For bedrock plains units elsewhere in the highlands, the formation ages would need to be better constrained in order to support or rule out the role of basin scale impacts.

Sediment transport and deposition has been discussed as a likely basin-filling mechanism, particularly for the flat-floored, degraded craters that are so common in the highlands (e.g., Craddock et al., 1997; Forsberg-Taylor et al., 2004; McDowell and Hamilton, 2007; Irwin et al., 2013). If sedimentary, the lack of spectral evidence for cementing minerals would suggest that they are volumetrically minor and/or spectrally bland in the infrared wavelength ranges used for spectral analysis (e.g. iron oxides). An explanation for the olivine enrichments through a detrital sedimentary process, however, requires more extensive discussion. Mineral enrichments can be produced through hydrodynamic sorting during sediment transport (e.g. Fedo et al., 2016), but it is unclear whether such sorting could occur so uniformly over the 10^2-10^3 km scales associated with olivine-bearing plains bedrock. More likely, olivine enrichment occurred after deposition, through deflation. As the bedrock plains are comminuted and eroded, denser and/or coarser olivine-bearing clasts or particles could have remained behind as lag deposits, possibly forming the patches of sediment that can be observed in depressions/hollows in high resolution imagery (e.g. **Figure 3**), and dominating the infrared spectral signatures measured from orbit. Though we introduce deflation here to describe a possible means of olivine enrichment from olivine-poor sedimentary rocks, this process could have produced olivine enrichment from any of the clastic rock types described above.

3.3 Implications for Mars 2020 landing sites

An extensive olivine-bearing unit is observed around the perimeter of the Isidis impact basin that includes the Nili Fossae region. Proposed origins for this unit include lavas (Hamilton and Christensen, 2005; Tornabene et al., 2008), impact melts (Mustard et al., 2007), or silicate condensate from vaporized crust following the Isidis basin impact (Palumbo and Head, 2017). This unit exhibits TI values between ~400-700 $J \cdot m^{-2}K^{-1}s^{-0.5}$, consistent with clastic rock or pervasively-fractured crystalline rock (Edwards and Ehlmann, 2015). Like other examples presented in this work, this Noachian-aged unit exhibits higher TI than the Hesperian-aged Syrtis Major lavas that overlie the unit (**Figure 2d**). Though portions of the olivine-bearing unit exhibit evidence for aqueous alteration (Ehlmann and Mustard, 2012) that may have weakened the olivine-bearing bedrock, significant portions appear unaltered and exhibit similar THEMIS TI values to the altered regions (Edwards and Ehlmann, 2015). Unaltered regions are found within 300 km distance and within a few hundred meters elevation from the Syrtis lavas, suggesting that preferential wind activity cannot explain the differences in TI and regolith cover between unaltered olivine bedrock and Syrtis lavas. We thus suggest that the Nili Fossae olivine-bearing unit is friable compared to Syrtis lavas, and argue that this favors pyroclastic, detrital sedimentary, or impact-related origins (e.g. Palumbo and Head, 2017).

Olivine-bearing light-toned bedrock plains are present beneath a younger, crater-retaining unit in Jezero crater. There, the geologic context would support a sedimentary origin, as suggested by Goudge et al., (2015). Finally, olivine-bearing plains bedrock is observed to the southwest of the Columbia Hills, and could represent tephras (**Section 2.1**; Ruff et al., 2014) but also could have other origins such as those described in **Section 3.2**. No matter which landing site is selected, detailed petrographic analysis of olivine-bearing bedrock plains with the Mars 2020 payload, and in terrestrial laboratories upon sample return, will likely provide insight into the formational mechanism(s) of these distinctive and widespread units.

5. Conclusions

The lack of regolith cover compared to known volcanic surfaces, as well as poor retention of small craters, suggest that many bedrock plains are not composed of mechanically strong materials, such as lavas. Rather, many of these olivine-bearing and feldspathic units likely represent clastic rocks. The high TI values of bedrock plains relative to average Martian surfaces likely reflects weak material properties. Friable materials would break down into fine particulate materials that are more easily moved by wind. In contrast, lavas comminute into blocky, coarse materials that are not easily eroded, resulting in buildup of thick regolith. Thus from orbit, TI differences between adjacent geologic units could, in some cases, appear inverted relative to their underlying differences in mechanical strength and TI. Candidate origins include pyroclastic, impact related materials and/or sedimentary rocks. We suggest that the observed olivine enrichments may have developed over time, through deflation, preferential removal of plagioclase in the finer-particulate fraction, and accumulation of olivine-bearing sediments in patchy lag deposits.

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Figure Captions

Figure 1. **(a).** Map of TES-derived TI within study region indicates that bedrock plains are rare in the Hesperian volcanic plains of Hesperia Planum and Syrtis Major Planum and common in the intercrater plains and crater floors of the highlands (white arrows indicate examples). Other locations discussed in the text are labeled. **(b-c)** Example bedrock plains in eastern Noachis Terra (regions 2 and 3, **Table S1**) and Terra Cimmeria (region 5, **Table S1**).

Figure 2. Differences in regolith cover are apparent between Hesperian volcanic plains and subjacent, older bedrock in Syrtis Major (**a-b**), Gusev crater (**c**), and northeast Syrtis (**d**). (**a**) THEMIS TI shows distinct thermophysical stratigraphy with bedrock plains underlying lower-TI lavas. **(b)** Portion of HiRISE image ESP_036579_1795. Dark-toned Syrtis lavas overlie a light-toned, basaltic fractured unit that is similar in appearance to other bedrock plains. Though the light-toned unit is included in the "Hesperian volcanics" (eHv) unit of Tanaka et al. (2014), it is stratigraphically older, and may represent Noachian bedrock. The dark-toned unit ridges protrude through swaths of sediment in topographic lows; bedforms are absent, possibly indicating a dominance of coarse-particulate materials that are not easily moved by wind. The light-toned higher-TI unit contains sparsely distributed bedforms. **(c)** In Gusev crater, Hesperian lavas exhibit low TI values from orbit, whereas subjacent, dominantly clastic materials in the Columbia Hills exhibit higher TI values. *As suggested by Ruff et al. (2014). (**d**) Northeast of Syrtis Major, Hesperian lavas overlie variably altered olivine bearing rocks (Ehlmann and Mustard, 2012). The younger lavas exhibit lower TI values and thicker regolith.

Figure 3. Morphological and crater density distribution examples suggesting some of the bedrock plains consist of friable materials**.** (**a-b**) CTX (~6 m/pixel) image mosaics of bedrock surfaces near (**a**) 215.10°E, 37.99°S and (**b**) 142.50°E, 19.80°S showing oriented, linear ridges that we interpret as yardangs. Note degraded, scalloped rims of small craters on bedrock. Color indicates relative TI (red=high; blue=low). (**c**) Portion of HiRISE image PSP_009339_1585 (25 cm/pixel), located in Peta crater near 350.88°E, 21.00°S. Bedrock unit exhibits smooth or scalloped textures in some locations. (**d**) Portion of HiRISE image ESP_047522_1555 (50 cm/pixel), located near 125.72°E, 24.38°S. Bedrock unit exhibits scalloped textures in some locations (arrows). (**e**) Crater density for bedrock and low-TI surfaces in region 9; locations shown on THEMIS day IR (**f**) and night IR (**g**) radiance. The supplementary material contains additional crater density maps and morphological examples.