Regolith textures on Mercury: Comparison with the Moon

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\textbf{ABSTRACT}

Surfaces of atmosphereless planetary bodies, including the Moon and Mercury, are covered with regolith. Regolith-related processes define surface morphology at scales of meters and tens of meters. We systematically surveyed all available images of the surface of Mercury with image resolution better than 2.5 m per pixel, and compared the observed regolith textures with those on the Moon. In a manner similar to the Moon, a typical surface contains many impact craters of different degrees of degradation, which indicates that regolith gardening smooths all topographic features. Textures characteristic of surfaces of large young craters with thin regolith are similar on both bodies. There are several types of sharp geologically young textures on Mercury that do not have lunar analogs. Hollows are young sharp irregular depressions on Mercury; they were discovered in images of lower resolution and attributed to sublimation of unidentified, moderately volatile material. Our survey reveals small, decameter-size hollows both spatially associated with known large hollow clusters and scattered at great distances from them. The existence of small hollows provides new constraints on the nature of these enigmatic features. Two types of fresh, geologically young regolith textures on Mercury, \textit{finely textured slope patches} and \textit{chevron texture}, have no analogs on the Moon, and their formation mechanism is unclear. We propose that sintering of regolith particles due to high peak surface temperatures cause formation of a slightly indurated decimeter-thick crust at the regolith surface on Mercury. We hypothesize that such a crust can play a key role in formation of these uniquely regolith textures of Mercury.

\textbf{1. Introduction}

In a manner similar to other atmosphereless planetary bodies, the surfaces of Mercury and the Moon are covered with a layer of regolith, a fragmental, highly heterogeneous material. Formation, modification and transport of the regolith occur due to meteoritic and micrometeoritic impacts and a number of other processes (e.g., McKay et al., 1991). Indirect evidence suggests that Mercury regolith layer is thicker than on the Moon (Kreslavsky and Head, 2015; Kreslavsky et al., 2014; Zharkova et al., 2015), which likely results from a higher micrometeoritic flux (Cintala, 1992; Borin et al., 2009) and is consistent with a higher degradation rate of kilometers-size craters (Passet et al., 2017). Regolith-related processes form the meter- and decameter-scale morphology of the surface.

Imaging data enabling study of the meter- and decameter-scale morphology on Mercury are scarce. Here we report on our systematic survey of all available images suitable for analysis of surface morphology at such scales. We start with a description of the data set we used. Then we report on our findings about surface morphology. We first describe each type of morphology observed, compare them to lunar analogs, analyze any geographical and geological correlations, and then discuss their significance and possible origin. In the concluding section of the paper we consider prospects for future studies of these morphologies with instruments on board the BepiColombo mission to Mercury.

\textbf{2. Data and methods}

We surveyed images obtained by the Narrow Angle Camera (NAC) of the Mercury Dual Imaging System (MDIS) instrument (Hawkins et al., 2007; Denevi et al., 2018) onboard the MERCURY Surface, Space Environment, Geochemistry and Ranging (MESSENGER) during its orbital mission to Mercury. We selected images of the highest resolution and the finest sampling (better than 2.5 m/pix, informally called “high resolution” hereafter) acquired from February to April of 2015, during the late...
phase of the mission, when MESSENGER was on a low-periapsis orbit, and the MDIS NAC camera was used well beyond its nominal regime. Individual high resolution images are small (0.25 Mpix), have a considerable amount of smear (because of the short range to the surface), low signal-to-noise ratio (because of the short exposures needed to keep image smear reasonable), and do not overlap: the distance between each of them (~15 km) is much greater than the image size (~0.5–1 km). These images cannot be used to produce mosaics, unlike the regular (10–20 m/pix) operation mode of the NAC. Moreover, they cannot be placed in the context of lower-resolution images because of the large difference in resolution and small image size. Even in the rare cases when a high resolution image overlaps a regular NAC image, it is usually impossible to pinpoint the high resolution image location on the context image. In a way, the high resolution images are random samples of surface morphology. Although the absence of the context reduces the usefulness of the high resolution images for photogeological analysis, they still provide invaluable information about features and processes, which would be impossible to obtain from regular MDIS data.

We systematically screened all ~3000 nadir-looking high resolution (~2.5 m/pix sampling) MDIS NAC images with smear less than 10 pixels, and sunlight incidence angle less than 70° (to avoid images with a large area of shadows). These screened images are located in a region between 40° and 70° N and 210–320° E. This region is dominated by the intercrater plains (Fig. 1). We quantitatively assessed typical surface morphology in each image and searched for peculiar or unusual morphologies. One of us (AYuZh) screened the whole image set and selected images with specific morphologies, which ensured uniformity of morphologic identification criteria (see the list in supplementary materials).

To compare the typical surface morphology on Mercury to the Moon we used Lunar Reconnaissance Orbiter Camera (LROC) NAC images (Robinson et al., 2010). Those images are large, have a high signal-to-noise ratio, and are numerous. In a few cases we selected representative lunar images with morphologies of interest and artificially degraded their quality to mimic the high-resolution MDIS NAC images and to make the image comparison more objective. This was done through smearing (that is application of a linear filter with a ~1 pixel wide 5–10 pixels long kernel) and adding white noise.

### 3. Survey results

#### 3.1. Degradation of small impact craters

Primarily, surfaces of Mercury and the Moon as seen at high resolution are similar. The most abundant morphological features are small impact craters of different sizes (tens and hundreds of meters) at different stages of degradation (Fig. 2). Fresh craters are deeper and have crisp rims; the freshest are bright and have high-albedo proximal ejecta. The majority of craters are degraded: shallow and smooth, in a manner similar to the Moon (e.g., Basilevsky, 1976). Small craters on the Moon are known to degrade due to local regolith gardening and emplacement of ejecta from distal larger impacts; smaller craters degrade more rapidly (e.g., Soderblom, 1970; Fassett and Thomson, 2014). Ultimately crater degradation leads to their obliteration. Small craters (~100 m and smaller) on typical lunar surfaces are thought to be in a kind of equilibrium: emplacement of new craters is generally balanced by obliteration of older ones. The presence of the whole range of crater degradation stages in almost each high resolution MDIS image suggests that the same process of crater degradation and obliteration occurs on Mercury. Of course, this would be highly expected; however, direct observational evidence for this is still important.

Both on the Moon and Mercury, the apparent density of discernable craters varies from site to site to a great degree. These variations are caused, at least partly, by occasional sampling of clusters of secondary craters. It also may be caused by variations in image quality and illumination/observation geometry. For the Moon, the variations of equilibrium crater density away from secondary clusters have been documented quantitatively by Xiao and Werner (2015). On average, the small crater density on Mercury seems lower than on the Moon (Fig. 2). A lower equilibrium crater density would be consistent with a higher degradation rate (Fassett et al., 2017) and a thicker regolith (Kreslavsky et al., 2014), however, this should be analyzed in more detail in a quantitative manner. The small size of the high resolution images, and therefore the small number of craters in each of them, together with huge variations in crater density, make such quantitative analysis impossible with the data set in hand.

![Fig. 1. Map of a part of Mercury (Lambert azimuthal equal-area projection) showing locations of high resolution MESSENGER MDIS NAC images. Small blue circles, all images surveyed; violet boxes, images containing FTSP; orange circles, images containing “Elephant hide”; yellow pentagons, images containing chevron texture. Background is low-resolution MDIS image mosaic; grayed area shows smooth plains according to Denevi et al. (2013).](image-url)
3.2. Elephant hide texture

3.2.1. Background

It has long been known that on the Moon regolith-covered slopes, both moderately steep and gentle, have a specific subtle decameter-scale texture dubbed “elephant hide” or “leathery” texture (e.g., Plescia and Robinson, 2010; Antonenko, 2012) (Fig. 3a). Xiao et al. (2013b) provided the first overview of its occurrence. They used a term “creeps” for such textures, which is incongruous: “pure” regolith creep caused by micrometeoritic impacts operates as topographic diffusion (Soderblom, 1970); it effectively smooths down all small-scale topographic features and does not produce any patterns and textures. Hereafter we adhere to “elephant hide” as a descriptive term for these textures.

Detection of “elephant hide” and its apparent anisotropy strongly depend on illumination geometry (e.g., Howard and Larsen, 1972), which makes systematic observations of this texture difficult. Our analysis of lunar high-resolution stereo images indicates that several meters-high relief is associated with the largest spatial elements of this texture; therefore, the “elephant hide” is not a purely observational artifact. The “elephant hide” texture drapes over old heavily degraded craters; however, small fresh craters are superposed on it (Fig. 3a), which indicates that the characteristic time scale of development of such a texture is comparable to the time scale of degradation of ~100 m craters.

The “elephant hide” formation mechanism is unknown. Antonenko (2012) suggested seismic shaking as a factor producing the pattern. From everyday life experience and from laboratory studies (e.g., Jaeger et al., 1996) we indeed know that shaking of granular materials produces patterns at their free surfaces; however, more detailed consideration shows that such patterns are often produced by kinds of standing waves that can only occur in confined settings, in the presence of boundaries. Self-organizing patterns in unconfined settings can also be formed (e.g., Jaeger et al., 1996), but this was observed under external shaking with well-defined frequency. Seismic shaking has a wide frequency spectrum and lunar regolith is not confined in horizontal direction; therefore, it is still to be shown that seismic shaking could...
indeed produce any regolith patterns. The seismic hypothesis also does not explain, why the “elephant hide” is observed only on slopes, but not on horizontal surfaces.

The latter fact suggests that the “elephant hide” is related to down-slope regolith transport. Robinson et al. (2010) and Plescia and Cintala (2012) attributed “elephant hide” to downslope creep of the regolith without further explanation; Xiao et al. (2013b) treated “elephant hide” as the obvious morphological expression of regolith creep. This, however, should not be taken for granted. Topographic diffusion is often used to describe regolith transport (e.g., Soderblom, 1970; Fassett and Thomson, 2014). Simple theoretical analysis shows that topographic diffusion cannot generate any patterns, even if the diffusion is non-linear (that is, the diffusivity increases with the slope). Moreover, anomalous diffusion, which involves non-local transport (e.g., Fouchoula-Georgiou et al., 2010) also cannot generate textures under rather general assumptions. In accordance with the theoretical predictions, observations unambiguously indicate that decameter-scale craters are subdued and obliterated by regolith transport, which indicates that regolith creep indeed operates as topographic diffusion (with possible complications). Any decameter-scale pattern would be subdued and obliterated at the same time scale as the decameter-scale craters. The ubiquity of “elephant hide”, therefore, indicates that some other process generates the texture at rates sufficient to overcome the smoothing effect of topographic diffusion. Thus, the “elephant hide” formation mechanism still remains poorly understood.

3.2.2. Observations

On Mercury, “elephant hide” is typically not observed. The illumination geometry on all surveyed images is favorable for its identification; we very often encounter “elephant hide” in the lunar images taken under the same incidence angle. In general, slope distribution on Mercury is narrower than on the Moon (e.g., Erмakov et al., 2019; see Fig. 1 in that paper), therefore the paucity of “elephant hide” could be to some degree explained by the paucity of suitable slopes; however, this cannot account for the observed absence of the pattern as suitable slopes are certainly abundant in the images surveyed. Lunar “elephant hide” is still easily seen after image quality is degraded (Fig. 3a). We experimented with lunar images of artificially reduced resolution to mimic possible textures of different characteristic spacing scale. We found that “elephant hide” would still be observable in the high resolution images on Mercury, if its characteristic spatial scale is up to ~8 times shorter than on the Moon. For example, if the spacing is inversely proportional to gravity, we still would see the pattern clearly.

In rare cases we do observe a texture very similar to the lunar “elephant hide” texture. An example is shown in Fig. 3b, and locations of observed “elephant hide” are mapped in Fig. 1. In the absence of context images, it is difficult to distinguish, whether or not this pattern occurs on slopes, and is absent on horizontal surfaces (as on the Moon). We do not observe what settings or associations would be specific to “elephant hide” occurrence. They all are in the northern half of the surveyed area; however, their number is so small that this could easily be just by chance. There are some examples of “elephant hide” in regular-resolution MDIS NAC images, however, we did not analyze them systematically.

3.2.3. Discussion

Mercury is characterized by more rapid crater degradation and therefore faster topographic diffusion in comparison to the Moon (Fassett et al., 2017). As discussed above, the “elephant hide” is shaped by a balance between an unknown texture-forming process and degradation due to topographic diffusion. More rapid topographic diffusion would shift the balance toward subler textures, even if the texture-forming process operates at the same efficiency. The subler texture might become indistinguishable in the images. This is consistent with the occurrence of the observed mercurian “elephant hide” at high latitudes, where illumination conditions (lower Sun) are better for identification of subtle textures. Of course, it is possible that the unknown texture-forming process itself does not operate everywhere on Mercury.

3.3. Young features: impact craters

3.3.1. Background

As we discussed in Section 3.1 above, the majority of decameter-scale topographic features both on the Moon and Mercury are smooth and subdued due to the presence of a regolith layer and its gardening acting as topographic diffusion. Sharp slope breaks, “crisp” morphology and absence of superposed degraded craters indicate geologically young features and a thin regolith layer. On the Moon, almost all such young features are related to the most recent impact events. Young small craters have sharp rims, and, unless craters are too small, finely textured ejecta. Young (Copernican age) large craters display a rich morphology of impact melt flows and pools with thermal contraction cracks, fresh mass-wasting features on the walls, etc. (e.g., Plescia and Spudis, 2014). In older craters, these small-scale morphological features become subdued and indistinguishable (Head, 1975; Wood et al., 1977).

3.3.2. Observations

Small fresh impact craters with sharp rims occur in a large number of the Mercury images surveyed. Their morphology is very similar to their lunar counterparts.

The high resolution images sampled only one large young crater, an unnamed 34-km crater at 64.6° N 104.6° W. Morphologies observed there are also very similar to those in Copernican craters on the Moon. Fig. 4a shows an example of characteristic textures of impact melt on a low terrace near the floor of this crater; Fig. 4b shows a similar morphological on the Moon on the floor of crater Kepler. Both scenes contain knobs apparently formed by unmelted blocks, and thermal contraction cracks in impact melt partly bridged by accumulating regolith.

Fig. 4c shows two small impact melt ponds to the eastern outer wall of the same crater on Mercury. Lower resolution images show abundant larger melt ponds in the same area. Such a large amount of impact melt is not observed outside craters of the same size on the Moon (Xiao et al., 2014; Cintala and Grieve, 1998), likely because a lower impact velocity on the Moon leads to a lower melt volume in comparison to craters of the same size on Mercury. Fig. 4d shows a melt pool of similar morphology on the eastern outer slope of lunar crater Tycho, which is much larger (~85 km). We do not observe apparent differences in small-scale morphology of large craters between the Moon and Mercury.

Among the surveyed images, we observe several examples of specific textures of proximal ejecta and streamlined texture of regolith disturbed by proximal impacts. For each occurrence we identified a crater responsible for these textures, either the large crater mentioned above, or smaller craters appearing fresh in low-resolution image mosaics. We did not observe obvious difference between these textures and textures observed in proximal continuous ejecta and proximal parts of crater rays on the Moon (Xiao et al., 2014).

3.4. Young features: hollows

3.4.1. Background

On Mercury, in addition to the youngest impact craters, the high resolution images reveal other “crisp” morphologies suggesting a thin regolith layer and a young age and having no obvious lunar analogues. Hollows are good examples of such features.

Hollows are irregular flat-floored depressions of specific morphology identified in regular-resolution MDIS images (Blewett et al., 2011, 2013, 2016; Thomas et al., 2014). They often have bright interiors and halos, and are characterized by a lower (bluer) spectral slope in the visible and near-infrared. Hollows often form large clusters covering tens or even hundreds of square kilometers. In these large clusters, individual depressions merge with each other forming chaotic patterns. The largest
clusters of hollows occur in large impact craters, their central peaks and peak rings; hollows are often but not always associated with low-reflectance material (e.g., Denevi et al., 2009; Xiao et al., 2013a); smaller hollows also occur within small craters as well as sporadically without any apparent geological associations (Blewett et al., 2013, 2016).

Hollows are interpreted to have formed by sublimation of some moderately volatile material (e.g., Thomas et al., 2014; Blewett et al.,

Fig. 4. Morphologies of impact melt on Mercury and the Moon. (a) Impact melt near the floor of an unnamed impact crater at 64.6°N 104.6°W, D = 34 km (MDIS image CN1067123666M, 64.8°N, 255.4°E, pixel size 1.1 m, sunlight incidence angle: 73.6°). (b) Impact melt on the floor of the lunar crater Kepler (portion of LROC image M1188607587R, 8.1°N, 321.9°E, sunlight incidence angle 67.4°). (c) Impact melt ponds to the east of crater at 64.6°N 104.6°W (MDIS image CN1067093876M, 64.9°N, 257.6°E, pixel size 1.1 m, sunlight incidence angle: 73.3°). (d) Impact melt pond on the eastern outer wall of the lunar crater Tycho (portion of LROC image M1182515316R, 41.7°S, 351.1°E, sunlight incidence angle 57.8°). Both lunar images have artificially reduced image quality to mimic high resolution MDIS NAC image quality.

Fig. 5. Examples of small hollows on Mercury (a) MDIS NAC image CN1066557528M (56.0°N, 290.9°E, pixel size 1.3 m, sunlight incidence angle: 62.0°); (b) CN10665587367M (60.0°N, 290.8°E, pixel size 1.2 m, sunlight incidence angle: 64.9°); (c) CN1066825590M (50.3°N, 270.3°E, pixel size 1.7 m, sunlight incidence angle: 62.8°). Thin vertical lines are image artifacts.
revealed the following three facts.

3.4.2. Observations

Unfortunately, the surveyed set of the high resolution MDIS NAC images did not sample any known hollow cluster. We found decameter-size features that are morphologically identical to “classic” hollows, but smaller. The best but still representative examples are shown in Fig. 5. The morphological similarity suggests the same formation mechanism. On this basis we refer hereafter to those small features that are similar to hollows simply as hollows.

The hollow edges are sharp at high resolution, which makes the conclusion of hollow youthfulness even stronger, and makes it even more probable that hollow formation and expansion is ongoing. Hollows possessing bright halos (such as those in Fig. 5b, c) have reasonably been interpreted as currently active (e.g., Thomas et al., 2014; Blewett et al., 2013), while hollows that lack such halos (Fig. 5a) have been thought to be inactive. The sharpness of inactive hollow edges (Fig. 5a) at this high resolution indicates that the time scale of topographic softening due to diffusive regolith gardening is longer than the time scale of halo removal. This is consistent with bright halos being formed due to a thin veneer of spectrally distinctive material (e.g., Thomas et al., 2014; Blewett et al., 2013), either fine-grained or chemically specific.

We found 14 hollow-bearing images in our regular survey; their locations are shown in Fig. 6. We also noticed unambiguous hollows in three more images not included in the regular survey due to excessive cations are shown in Fig. 6. We also noticed unambiguous hollows in three more images not included in the regular survey due to excessive smears. Their locations are also marked in Fig. 6. For comparison, we also show positions of hollow clusters catalogued by Blewett et al. (2013). Analysis of the spatial distribution of the small hollows that we found revealed the following three facts.

First, a number of small hollows are apparently spatially associated with large hollow clusters. Small hollows associated with large hollow clusters may form in peripheral, thin parts of the hollow-forming layers. A number of small hollows (e.g., Fig. 5c) are scattered on the floor of Sholem Aleichem, an old 190-km crater centered at 50.9°N 90.5°W (Fig. 6). These associations support our conclusion that small hollows are essentially the same features with the same probable formation mechanism as larger “classic” hollows.

Second, we found small hollows (Fig. 5a,b) scattered within the inter-crater plains at a considerable distance from known larger hollows (Blewett et al., 2013; Thomas et al., 2014). We did not observe any systematic difference in morphology between such dispersed small hollows and those associated with larger clusters (compare Fig. 5b and c). This means that small amounts of hollow-forming material are present over large areas. Again, the available data do not enable us to distinguish, whether this material is local or delivered to the site by distal impacts. However, the latter is less likely in the case of the dispersed small hollows: the putative volatile material is unlikely to survive the ejection and re-impact at the velocity needed to reach a range of hundreds of kilometers.

Third, we observe a regional correlation between the occurrence of small and larger hollows: in Fig. 6 both newly found small hollows and known larger ones are in the southeastern part of the region surveyed, while the northern and western parts are almost free of hollows. Therefore, our observations of small hollows do not contradict the conclusion about regional variations in the occurrence of hollow-forming material (e.g., Blewett et al., 2013, 2016).

3.5. Young features: finely-textured slope patches (FTSP)

3.5.1. Observations

We identified another type of young fresh “crisp” morphology on Mercury with no direct lunar analog. We called this type of unusual textures “Finely-Textured Slope Patches” (FTSP) and found seven (7) images containing the texture. The best examples are shown in Fig. 7 and their locations are shown in Fig. 1. FTSP are patches of finely (meter-scale) textured slopes. This texture is characterized by a “wavy” slightly chaotic pattern with sharp outlines. It is dissimilar from landslides or other similar formations found on the

The morphological similarity suggests the same formation mechanism. On this basis we refer hereafter to those small features that are similar to hollows simply as hollows.
slopes of young craters of different diameters on the Moon. The relatively small size of the individual elements of FTSP’s and their sharpness, as well as the sharpness of their boundaries, distinguish FTSP from the previously described “elephant hide” texture (Section 3.2).

The locations of FTSP’s examples at the global level do not reveal clear relationships with other relief features. FTSP occur amid typical intercrater plains and old impact basins; there are no large young craters or hollows nearby and there are no resolvable albedo or colour peculiarities close to FTSP locations that would be seen in low-resolution image mosaics.

All FTSP examples found are in the southern half of the surveyed region. Slopes bearing FTSP have different orientations, however, they avoid north-facing directions. Given the small number of features found, the latter observation can be due to coincidence. FTSP often occur in groups. In this case they occupy slopes of the same orientation (Fig. 7b).

As far as we know, there are no such features on the Moon. Steep slopes of large Eratosthenian-age impact craters are free of small craters due to active mass wasting and display somewhat similar texture, but with much larger spatial scale. Those textures, however, do not form isolated sharply outlined patches and likely occur on steeper slopes.

Crispness of morphology and the absence of superposed small impact craters suggest that FTSP formed recently. The formation mechanism is not clear.

3.5.2. Discussion

FTSP have some morphological similarity to several types of small terrestrial landslides (Fig. 8). Both are characterized by very sharp arcuate convex upward outlines on the uphill side of the structure and a more diffuse lower boundary. This similarity suggests recent massive regolith sliding as a possible FTSP formation mechanism. It remains

Fig. 7. Finely textured slope patches on Mercury (a) MDIS NAC image CN1067272492M (53.6° N, 239.4° E, pixel size 1.0 m, sunlight incidence angle: 72.1°); (b) CN1067361831M (50.6° N, 232.1° E, pixel size: 1.4 m, sunlight incidence angle: 73.1°); (c) CN1067099716M (50.8° N 251.3° E28424, pixel size 1.4 m, sunlight incidence angle: 68.0°); (d) CN1067004297M (46.69248/256.6586, pixel size 2.2 m, sunlight incidence angle 64.8°); (e) CN1067123530M (52.8° N, 249.8° E, pixel size 1.2 m, sunlight incidence angle 69.2°); (f) CN1067183041M (46.6° N, 243.8° E, pixel size 2.1 m, sunlight incidence angle: 68.5°); (g) CN1067510747M (47.4° N, 220.5° E, pixel size 1.9 m, sunlight incidence angle: 75.7°).
unclear, however, why such slides occur on Mercury, but not on the Moon. Possible very recent strong seismic events might trigger such slides on Mercury, and not on the Moon. It is not clear, however, why FTSP in groups occur on slopes of the same orientation.

Formation of small terrestrial landslides (similar to that shown in Fig. 8) involves formation of a mechanically weak layer due to soil saturation with water. Of course, such saturation does not occur on Mercury. It is essential, however, that formation of such morphology by sliding requires a more cohesive layer at the surface and mechanically weaker layer some depth. The high day-time temperature on Mercury enhances and accelerates diffusive sintering of regolith particles (Starukhina, 2000), which likely leads to formation of an indurated, mechanically stronger uppermost regolith layer; its thickness would be a part of the diurnal thermal skin thickness, that is tens of centimeters. A role of such a predicted sintered layer in formation of FTSP is consistent with their absence in the northern part of surveyed area and on north-facing slopes, where the maximum diurnal temperatures are lower and sintering would be weaker.

3.6. Young features: Chevron texture

3.6.1. Observations

We identified one more type of fresh texture on Mercury with no direct lunar analogs. We refer it as chevron texture. Examples are shown in Fig. 9 and locations of images with identified chevron texture are shown in Fig. 1. The texture is formed by shallow, elongated depressions, triangular in planform. All depressions are elongated in approximately east-west direction with the triangle tips pointing toward the west, and open sides facing the east (Fig. 9). We ensured that the texture is not an image artifact. Its orientation is not parallel to the exposure smear direction. Although the texture orientation is very similar to the camera frame transfer direction, analysis of the image at pixel-level zoom and comparison with the obvious frame-transfer-related artifacts (like in Fig. 5) clearly shows that the texture is formed by true regolith topography.

Chevron texture is best expressed at gentle convex slope breaks of background topography, especially at the western rims of old subdued subkilometer- and kilometer-size craters. Sharpness and superposition over subdued relatively small craters indicates the youthfulness of this texture.

Almost all occurrences of the chevron texture are located in the north-east corner of the surveyed area (Fig. 1), where the texture is rather common: the proportion of images there that show this texture is high. In all four scattered locations outside this concentration area (Fig. 1) the texture is subtle, not well expressed, and it is thus possible that chevron textures at those locations are misclassifications. We examined images of somewhat lower resolution to the east of the surveyed area and identified a number of additional occurrences of chevron texture within the same latitude belt; they have approximately the same orientation. The texture becomes difficult to identify if image resolution is coarser than 4 m/pix. The easternmost location identified is at 7° W longitude, and there are no images suitable for chevron texture identification to the East of this.

3.6.2. Discussion

Chevron texture resembles small-scale textures produced in terrestrial environments by erosion by wind or water flow. Under present-day conditions such processes on Mercury are impossible. In principle, a transient atmosphere can persist on Mercury during some geological time, in contrast to the Moon, where any atmosphere would dissipate to

![Fig. 8. Terrestrial landslide in Churn Creek Protected Area, British Columbia, Canada. The scene is centered at 51.51° N, 122.35° W. Google Earth image.](image)

![Fig. 9. Examples of chevron textures on Mercury (a) MDIS NAC image CN1066229937M (66.2° N, 320.1° E, pixel size 2.1 m, sunlight incidence angle 66.9°); chevron textures are seen in the lower, eastern part of the image; (b) CN1066289535M (67.4° N, 316.7° E, pixel size 2.2 m, sunlight incidence angle 68.3°); chevron textures are seen in the upper, western part.](image)
space geologically rapidly. A transient atmosphere of Mercury could be formed as a consequence of impact of a large volatile-rich body. For example, if geologically young large (97 km) impact crater Hokusai was formed by a cometary impact, the projectile would have a diameter of 10–30 km (Ernst et al., 2018); such a comet would deliver an amount of volatiles equivalent to a global atmosphere with ~15–300 Pa pressure. A part of that volatile amount would condense at the night side of the planet. Such an atmosphere would be less dense than on Mars; however, due to huge temperature contrasts it is reasonable to expect extremely strong winds, and it seems plausible that winds in such an atmosphere may have some geomorphological effect.

Thus, a wind hypothesis for the chevron texture formation cannot be immediately rejected on the basis of the current absence of the atmosphere. However, we would expect winds to act everywhere on the planet or at least, in some latitudinal zones. The local occurrence of chevron texture in a very limited region (Fig. 1) is not consistent with wind erosion mechanism, and therefore we reject it.

Another idea suggested by morphological similarity of chevron texture to terrestrial erosional morphologies is that the depressions are formed by sandblasting by fine-grained ejecta from recent impacts. There is no large young impact crater in the immediate vicinity of the observed chevron texture; consistency of the texture orientation suggests a remote source. Two large young rayed craters close to the chevron texture area are Hokusai (57.8 N, 16.6 E, D ~ 97 km) ~1300 km away and Degas (37.1 N, 127.3 W, D ~ 55 km) ~2200 km away. The great circles connecting the chevron texture area and both craters (the analogs of straight lines on a spherical planet) are directed approximately east – west through the whole chevron texture area. Putative ejecta from Degas would approach from the west, which is consistent with the direction expected from the pattern, form the tips toward the open sides of the triangular depressions. However, no chevron texture is observed in the parts of the surveyed region between the chevron texture area and Degas. Ejecta from Hokusai would come from the opposite direction, less consistent with the chevron morphology. However, an actual Hokusai ray could be traced up to the chevron texture area, and the location of the texture patches at the upper parts of east-facing slopes is consistent with sandblasting from the east. This makes Hokusai a more likely candidate.

On the Moon, regolith in distal parts of the crater rays does not display any specific morphology. So-called “herringbone” pattern of secondary crater clusters on the Moon (Oberbeck and Morrison, 1973) is much larger, occurs closer to the primary craters, and is rather different morphologically. The presence of erosion-like textures on Mercury might be explained by the presence of the predicted mechanically stronger uppermost regolith layer indurated due to sintering, as discussed above.

3.7. Young features: absence of irregular mare patches

On the Moon, in addition to the impact craters, “crisp” morphologies suggesting a thin regolith layer are observed in so-called irregular mare patches (IMP) (Braden et al., 2014; Valantinas et al., 2018; Qiao et al., 2019). These features are of debated origin (Schultz et al., 2006; Braden et al., 2014; Wilson and Head, 2017) and are very rare. We did not see IMP analogs in the surveyed high resolution images on Mercury. If irregular mare patches on Mercury were present as rarely as on the Moon, the probability of finding one in the random sample of high resolution images would be extremely low. Therefore, the absence of irregular mare patches in the high resolution images does not necessarily signify their absence on Mercury. Identification of a small IMP in low-quality high resolution MDIS images would be difficult. At first glance, lunar IMP look similar to hollows: both are sharp, freshly-looking depressions. The discriminating morphological difference is that slopes outlining high-albedo low-lying internal IMP subunits have convex-upward profiles (Blewett et al., 2016), with gentle slopes at the top and a sharp slope break at the contact with the high-albedo floor, while hollows seem to be outlined by more typical scarps with concave profile, and sharp slope breaks at the top. These distinguishing morphologies are difficult to see in the high-resolution images. The presence of bright halos rather reliably identifies the features in Fig. 5b,c as small hollows. In Fig. 5a, however, the halos are absent, and it is difficult to discern whether the outlining slopes are concave or convex. We classified the features in Fig. 5a as hollows; however, we cannot be entirely sure that they are not analogs of lunar IMP on Mercury. We also see a few tiny, barely resolved depressions that might be slightly degraded IMP analogs; however, they cannot be identified with any certainty.

4. Conclusions

4.1. Summary of findings

We surveyed meters and tens-of-meters scale textures of the surface of Mercury and compared them to textures of observed on the lunar surface. As expected, we see a great similarity between the two atmosphereless bodies. We clearly see morphological signs of the presence of regolith on Mercury and subdued morphologies, especially, degraded craters, smoothed due to regolith formation and transport. The “elephant hide” texture, ubiquitous on the Moon is, however, almost absent on Mercury, at least, in the region surveyed.

We identified several types of geologically young morphological features on Mercury that do not have lunar analogs. The existence of small hollows provides important additional constraints on the nature and formation mechanisms of these enigmatic features. The chevron texture and FTSP are specifically features on Mercury unrelated to hollows. Their origin remains unclear. We hypothesize that the presence of an indurated uppermost crust in the regolith may explains the presence of such features on Mercury and their absence on the Moon. The formation of such an indurated crust occurs due to rapid diffusive sintering of regolith particles under high day-time temperatures (Starukhina, 2000).

4.2. Prospects

Our analysis of the small-scale textures on Mercury is limited by the quality and areal coverage of available high resolution MESSENGER MDIS NAC images. The most limiting factor is that the images lack geological context: the resolution gap between the high resolution images and the available lower-resolution context images is too wide, and the knowledge of camera attitude is insufficient to pinpoint the location of the high-resolution sample. The forthcoming BepiColombo mission to Mercury (Benkhoff et al., 2010) will provide such a context and thus will enable better understanding of the regolith textures.

The High-Resolution Imaging Channel (HRIC), a part of Spectrometer and Imagers for Mercury Planetary Orbiter BepiColombo - Integrated Observatory System (SIMBIO-SYS) (Flamini et al., 2010), will take 4 Mpix mosaical images of high signal-to-noise ratio with ~5 m/pix sampling at low latitudes and somewhat coarser sampling in our survey area. Global coverage will not be achieved during the nominal mission; however global sampling will occur. The internal fine texture of FTSP will not be resolved in HRIC images; however, the patches themselves are likely to be identifiable. Chevron texture is likely to be resolved in its best, most pronounced occurrences. Thus, HRIC images will not only provide context for the high resolution MDIS NAC images, but will enable a global survey of the textures. In particular, HRIC images will prove or disprove the association of the chevron textures with crater rays. HRIC images will also enable testing our hypothesis that sintered crust on top of regolith of Mercury plays a role in the formation of textures. This hypothesis predicts a correlation of texture appearance and occurrence with latitudes and longitudes (due to the difference between peak temperatures at the “hot pole” and “cold pole” longitudes), which can be documented with HRIC images.
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Appendix A. Supplementary data

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References


