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Key Points:

- Boulder movement in and near lobate landforms on steep slopes at high latitude on Mars is common
- These changes could contribute to rapid slope evolution and to formation of the lobate landforms
- This represents a new style of slope activity on Mars

Supporting Information:

- Supporting Information S1
- Table S1
- Movie S1
- Movie S2
- Movie S3
- Movie S4

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Active Boulder Movement at High Martian Latitudes

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Abstract Lobate stony landforms occur on steep slopes at high latitudes on Mars. We demonstrate active boulder movement at seven such sites. Submeter-scale boulders frequently move distances of a few meters. The movement is concentrated in the vicinity of the lobate landforms but also occurs on other slopes. This provides evidence for a newly discovered, common style of activity on Mars, which may play an important role in slope degradation. It also opens the possibility that the lobate features are currently forming in the absence of significant volumes of liquid water.

Plain Language Summary Tongue-shaped lobes of boulders occur on steep slopes at high latitudes on Mars. Boulders in those lobes, as well as on nearby slopes, commonly move short distances. Several processes could contribute to moving the boulders, but liquid water is probably not involved. This is a new type of active surface process on Mars and may be an important contributor to forming the lobes or changing steep slopes.

1. Introduction

Lobate features have been described at several locations at high latitudes on Mars (Gallagher et al., 2011; Gallagher & Balme, 2011; Hauber et al., 2011; Johnsson et al., 2012). These landforms (Figure 1) are tens of meters in scale and form larger-scale patterns and are distinct from the “lobate debris aprons” that occur in the midlatitudes (e.g., Squyres, 1978). They have been interpreted to form as a result of surface creep, possibly as solifluction lobes indicating freeze-thaw processes and liquid water in geologically recent times. Since present-day liquid is minimal and widespread melting of frozen ground unlikely at present (Hecht, 2002; Ingersoll, 1970; Kreslavsky et al., 2008; Mellon & Phillips, 2001), this interpretation implies that the lobes are not currently active.

For all fresh landforms on Mars, it is important to determine whether present-day conditions (and perhaps uniquely Martian processes) are capable of creating the features. To test whether the Martian lobate landforms are currently evolving, we examined high-resolution images with a long time separation to look for signs of change. Deformation of creeping landforms is likely to be a slow process and challenging to observe from orbit. However, some of the lobate features appear as arcuate accumulations of boulders (Figures 1b and 2), where the boulders and associated rubble may move in incremental steps and highlight any current surface activity. Additionally, any evidence for surface changes in the vicinity of the lobes would help us to interpret the formation and evolution of the local surface.

2. Methods

We selected seven northern plains craters as study sites, at latitudes 58.7–72.4° and a range of longitudes (Table S1 in the supporting information). All locations except Site 5 are in the *LHI* lowland unit of Tanaka et al. (2014); Site 5 is within crater ejecta material that superposes that unit. All sites include some boulder-rich lobes. The sites all have long-temporal-baseline coverage in High Resolution Imaging Science Experiment (HiRISE) images (McEwen et al., 2007). HiRISE Reduced Data Record (RDR) images are typically map-projected at 0.25 or 0.5 m/pixel, and we conducted blink comparisons at the full available resolution to look for boulder movement. Subsections of images were manually aligned in Photoshop and shifted as needed to register them accurately enough to blink compare. We examined each site twice, once using sections of the standard RDRs and once warping one of the sections to better align with the other

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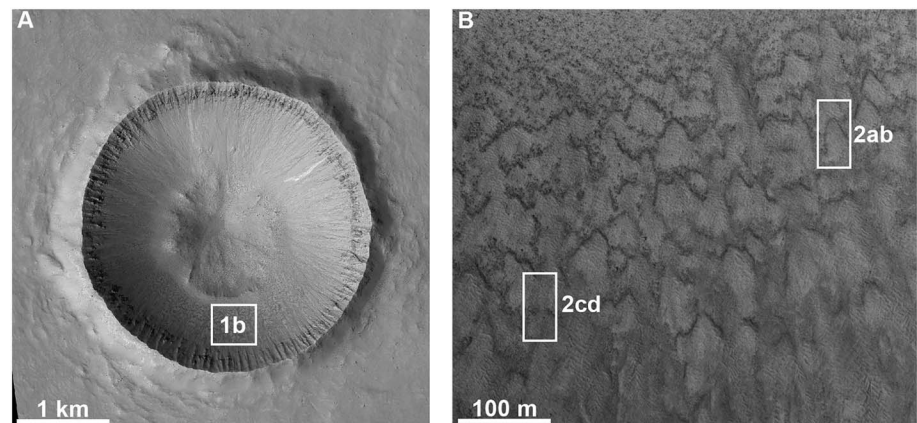


Figure 1. Overview of Site 1. (a) Lobate features are concentrated on the north-facing wall. A bright deposit is associated with a gully at upper right. (b) Enlargement showing lobate features in more detail. Box shows the location of Figures 2a and 2b. The regular texture between many of the boulder lobes could be aeolian bedforms or due to ground ice processes. (HiRISE image ESP_026564_2405).

image. The reduced geometric difference in the warped images makes it easier to detect small changes, and this approach uncovered a number of additional changes. Since this involves an additional resampling, we used the original RDRs to confirm changes found in the warped images. Comparisons were made between images with similar lighting and viewing angles (in most cases within 5°), and we then used additional observations to investigate the timing of changes. If we were not confident that a given boulder could be distinguished in an image because of the lighting conditions or presence of frost, that image was not treated as a constraint on the timing. For Site 2, we only looked for boulder movement in the immediate vicinity of the lobes, due to the large size of the crater, and did not search all of the crater slopes in the images. At the remaining six sites, the entire crater is covered by single HiRISE images and we searched all crater wall slopes, including those without lobate features.

We consider boulder movement to be confirmed (Figure 2) if we can identify a boulder in different positions in before-and-after images, including when several boulders disappear and nearby boulders appear but defining a one-to-one correspondence is difficult. Table S2 also includes notations for boulders that appeared or disappeared but where the position in the comparison image could not definitively be determined. In these cases, the boulder may have begun in or moved to a position where it could not be distinguished from adjacent boulders or rubble, or rotated from/to an orientation where it did not cast a notable shadow. Table

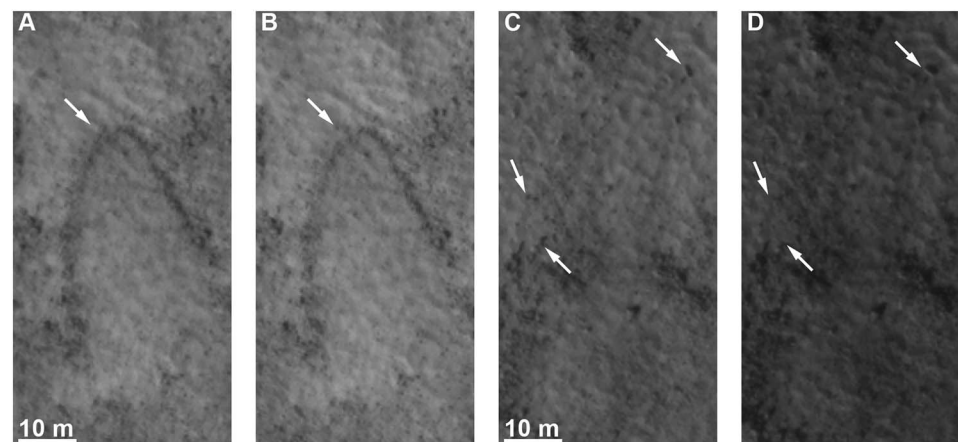


Figure 2. Examples of boulder changes. (a, b) A boulder detach from a lobate structure and advance several meters. (c, d) A boulder rotate down slope (upper right arrow) and additional shadows that disappear (lower left arrows). Possible corresponding boulders appear downslope. (HiRISE images ESP_026564_2405 [a], ESP_035346_2405 [b and c], and ESP_042889_2405 [d]. See the supporting information for blink comparisons).

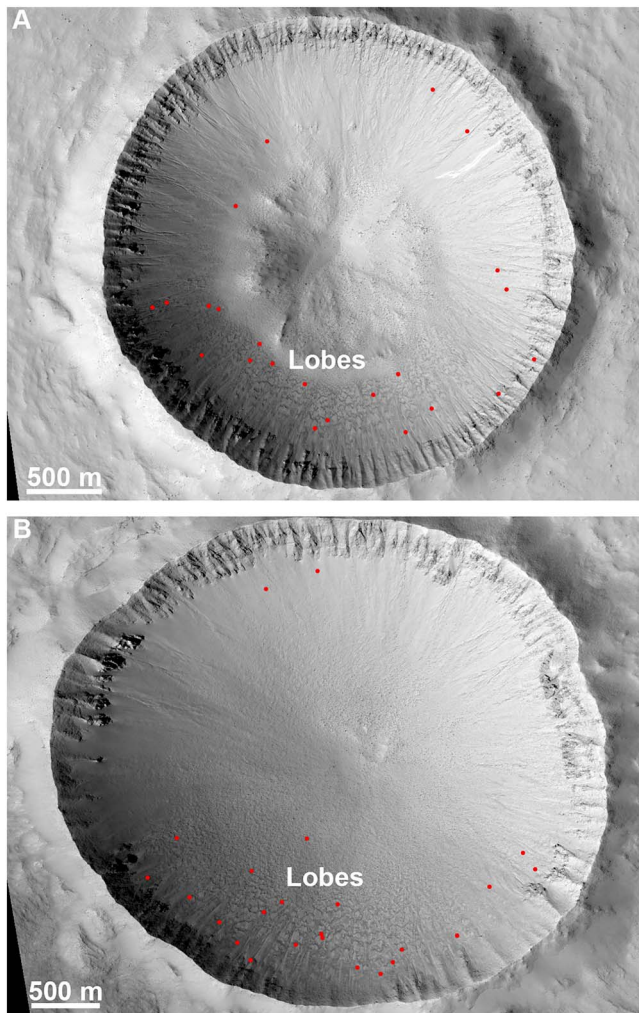


Figure 3. Locations of boulder shifts at Sites 1 and 7. Shifts are concentrated near the lobate features. (HiRISE images ESP_035346_2405 [a] and ESP_053669_2395 [b]). Note that movement only occurs on the crater walls, not on the shallowly sloping floor.

throughout the slopes, including near the base. The level of activity varies widely between sites. Sites 1 and 7 each had dozens of confirmed or probable movements. Sites 2 and 5 were nearly inactive, and the candidate changes there were only found on the second search using images warped for better alignment. Lobes at Sites 2 and 5 are relatively poorly defined. This difference in activity appears to correspond to the youth and preservation state of the craters, since the craters at Sites 1 and 7 have morphologically distinct ejecta and outcrops exposed around more than half of the rim, suggesting that they have experienced less degradation to date. Rim outcrops are nearly absent at the other sites, other than Site 6. Even there they are partially degraded or buried, making them less prominent than at Site 1 or Site 7.

While the sites with the most movements (1 and 7) have rocky outcrops near the crater rims, the boulder movements and lobate features are less frequent on the sides of the craters with prominent outcrops. The movements are concentrated in the vicinity of lobes (Figure 3); the extent to which this is due to a greater concentration of available boulders and rubble is not clear. Those two sites also have poorly developed gullies, another indicator of recent slope activity, but the distinct lobes are not on the slopes with the best-defined gullies.

The mean distance of confirmed movements is 4 m, but the distances are not normally distributed. Most of the shifts (47/58) are ≤ 4 m. In general, these short movements are very different from energetic bouncing rock-falls observed elsewhere on Mars (Figure 4) and do not leave any visible track between the starting and final

S2 also includes probable movements, which reflect a qualitative judgment of lower confidence due to the small size of the boulder, short distance of the movement, or other factors. In many cases we can see likely before-and-after positions that are consistent across multiple images, so this is a deliberately conservative interpretation.

Due to the small size of the boulders (almost all <1 m), we considered the possibility that the movements were illusory, for instance, due to a boulder casting a shadow in one image but not in another. Several lines of evidence rule this out. The lighting of most of the image comparison pairs is similar and thousands of boulders in the comparison areas appear unchanged between images. Many changes can be seen across multiple images, not only in a single comparison. All observed candidate movements have the boulder moving downhill, regardless of the lighting or slope orientation, and we did not observe any candidate movements near the centers of craters where slopes are low (Figure 3). Seams between the HiRISE CCDs in a single image can produce the appearance of movement or appearing/disappearing boulders, but that effect can be readily identified and excluded.

The observed examples are a lower bound on real activity. Both geometric and lighting differences can make real changes difficult to distinguish. Moreover, the boulders we examine range in size down to the limit of HiRISE resolution and many of the translation distances are short (meters); short-distance movements of smaller boulders would not be observable. These challenges mean that it is likely that additional changes occurred within our data but were not observed or were not considered sufficiently strong candidates. Lighting differences and seasonal frost also cause the timing of events in a number of cases to not be constrained as tightly as the available observations might allow in theory.

3. Observations

We observed dozens of short (meters) movements of boulders. Examples are shown in Figure 2 and in the supporting information animations. Because of the small size of the boulders, it is significantly easier in most cases to see the changes when viewed as animations. Movements occurred both among the lobate features and on other slopes. The shifts occur

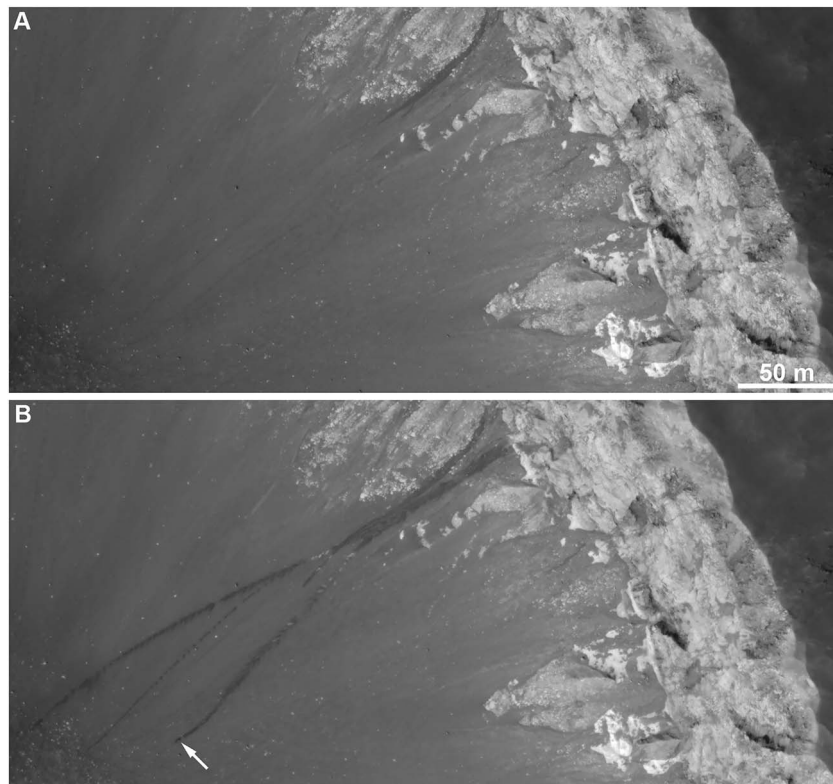


Figure 4. Rockfalls in a crater in Meridiani Planum. Tracks and bounce marks in (b) show the paths of individual fragments. Arrow indicates one fragment that is resolved by HiRISE. (HiRISE images ESP_039760_1775 [a] and ESP_040327_1775 [b]).

positions. The longest observed shift (45 m) is associated with a faint track. In a number of cases, movements end with the boulder on the upslope side of another, unmoved boulder (Animation S3). In addition to the boulder movements, some larger-scale relatively dark striations were observed but not associated with resolvable moving boulders or topographic changes. These features are not enumerated here.

We examined the slopes at the locations of moving boulders. We resampled HiRISE Digital Terrain Models of Sites 1, 2, 4, 6, and 7–10 m per post. This may reduce slopes from local highs at the scale of boulders but also minimizes small-scale noise. We reprojected them to a north polar Lambert equal area projection to minimize distortion, and then generated slope maps using ESRI ArcMap™. The slopes at the locations of the definite moving boulders ranged from 17° to 40° with most between 25° and 35° (mean 28°, standard deviation 4°).

As a comparison, we also examined slope activity in a recent crater in Meridiani Planum (2.2°S, 353.8°E). This 0.8-km-diameter crater is estimated to have formed ~200 ka and formed within the weak sulfate rocks of the “Burns formation” (Golombek et al., 2010), and thus, it should be particularly prone to mass wasting. We observed several new rockfall tracks within this crater (Figure 4 shows an example), generally forming tracks that are hundreds of meters long and lacking resolved boulders. One apparent short-distance boulder movement was also observed, but close to several other likely shifts, suggesting that it was part of a larger rockfall event. Multiple boulder tracks in the initial image had faded in later images, confirming that rockfalls are a common occurrence here. These observations suggest that at this equatorial location the style of mass wasting is different from the high-latitude sites that are the focus of this study, with more energetic rockfalls.

4. Discussion

These observations demonstrate the occurrence of a previously undetected style of active slope change on Mars. The slopes over which the boulders move are steep but can be below the angle of repose for dry

sand. We interpret these observations to indicate that the high-latitude boulders are not being mobilized simply by gravity, as in classic rockfalls (Figure 4); some additional forces are contributing to mobilizing the boulders. Moreover, the difference in style from the equatorial rockfalls suggests that the process relates to latitudinal characteristics such as the occurrence of seasonal frost or perennial ground ice, although other factors like lithology might also be systematically different.

What process is driving this activity? We first consider the possibility of terrestrial-style solifluction, which has been suggested to be the origin of the lobate features (Gallagher et al., 2011; Gallagher & Balme, 2011; Hauber et al., 2011; Johnsson et al., 2012). The term solifluction encompasses multiple processes, including gelifluction (movement of saturated soil due to thaw), plug-like flow, and creep due to periodic heave in freezing ground through the formation and melting of lenses of diurnal or annual frost and needle ice (e.g., Matsuoka, 2001). Processes involving significant amounts of seasonal liquid water are very unlikely on present-day Mars: Melting at the ice table is unlikely because the temperature of stable ground ice should not exceed ~ 210 K in the current epoch (Mellon & Phillips, 2001) and is expected to be lower at these latitudes. Additionally, the distribution of salts observed by the Phoenix lander (at similar latitude) suggested only thin films of liquid in geologically recent time (Cull, Arvidson, Catalano, et al., 2010). Due to low H₂O concentration (e.g., Appéré et al., 2011; Cull, Arvidson, Morris, et al., 2010), diurnal or annual surface frost or ice deposition is also unlikely to move boulders. Local cold-trapping could increase the frost abundance near rocks (e.g., Svitek & Murray, 1990) but even the cold-trapped abundances are small, although this might be enough to initiate minor displacements. Hence, a process closely approximating terrestrial solifluction is unlikely.

Numerous other factors could cause boulders to move on Martian slopes, including (i) small impacts, (ii) seismic activity, (iii) CO₂ frost processes, including basal sublimation and seasonal mass loading of the slopes, (iv) aggradation or sublimation of underlying ground ice causing disturbance of the surface, (v) thermal expansion and contraction of ground ice, (vi) mineral hydration and dehydration cycles, and (vii) aeolian removal of material supporting the boulders or direct vibration of the boulders by the wind. We consider the first two factors listed to be unlikely drivers of the changes reported here because the boulder movements are too widespread and frequent, over too many distinct time periods (Site 1 had movements in five distinct intervals), for these processes to be reasonable. We did not observe any evidence for new impact craters similar to those seen elsewhere on Mars (Daubar et al., 2013). Moreover, the Daubar et al. (2013) impact flux indicates that the expected number of new impact craters >3.9 -m diameter within a 10-km radius is approximately 0.001 per Mars year (and 4-m craters only have local effects), so the likelihood of multiple impacts large enough to move boulders at Site 1 is extremely small. Viking Lander 2 operated a seismometer in a northern plains setting similar to our study sites, although at lower latitude (48°N). It observed no confirmed seismic events in 0.24 Earth years of observation (Goins & Lazarewicz, 1979). The fact that wind was a major source of seismometer noise and provided multiple false signals that were similar in strength to the one good candidate seismic event (Anderson et al., 1977) suggests that seismic forces stronger than routine wind gusts are rare. If the seismic activity levels at our study sites are similar, they are unlikely to regularly move boulders. Moreover, seismicity is unlikely to produce a latitudinal dependence in the style of rock movement.

The remaining processes could all occur on an annual or continuous basis and so are more consistent with widespread, frequent changes. CO₂ frost-related processes cannot be the sole cause of movement, since at least two events occurred during summer when such frost is absent; however, many others may be due to CO₂ frost effects, and the winter frost represents a strong and regular disturbance to the slopes, which is thought to drive much larger mass movements in gullies (Dundas et al., 2017). In addition to simply loading the surface, CO₂ frost could act on boulders in two ways. First, regolith pressurization and basal sublimation are known to move sand and dust at high latitudes on Mars (e.g., Kieffer, 2007). The gas pressures in the regolith might also abet slower downslope movements in a manner similar to an elevated water pore pressure. Second, CO₂ ice may lock boulders in place while the underlying soil contracts, leading to relative movement (Orloff et al., 2013) or setting the boulder into a position of gravitational instability once the frost sublimates.

Ice table changes could disturb boulders via differential sublimation or aggradation driven by climate changes (e.g., Mellon & Jakosky, 1995). Aggradation via ice lens growth can occur via vapor deposition

and movement of unfrozen water films (Sizemore et al., 2015). This process might provide a slow, cold-climate equivalent of solifluction, where gradual lens growth and associated frost heave eventually destabilizes boulders and triggers a downslope change of position. Note that the mobility of boulders may be impaired by being frozen into the ice table (cf. Sizemore et al., 2010). Ice table depths in these locations are predicted to be 2–7 cm beneath ice-free soil (Mellon et al., 2004). Boulders of a sufficient size (greater than roughly 0.5–1 m) cannot conduct enough heat to their base to prevent being frozen to the ice cemented ground (Sizemore et al., 2009; Sizemore & Mellon, 2006). Furthermore, changes in the ice table depth and boulder temperatures, due to recent orbital changes and associated climate change, may induce sublimation and subsequently release boulders that may have otherwise become unstable due to creep or removal of adjacent ice-free soil. Indeed, sublimation and recession of the ice table are expected in the northern middle and high latitudes due to precession of perihelion (Mellon & Jakosky, 1992, 1995; Zent, 2008), where boulder movements have been observed.

Hydration/dehydration and thermal expansion/contraction cycles might induce creep and would have similar effects, although perhaps different vertical profiles. Hydrated minerals have been detected in surface materials; seasonal hydration changes of 2–4 wt.% have been reported (Jouglet et al., 2007; Milliken et al., 2007), but subsequent analysis suggested that there was no detectable variation in regolith hydration, with variations attributed to clouds or frost (Audouard et al., 2014), so this effect may be weak. Thermal expansion and contraction are almost certainly operating with a magnitude of 3–10 mm of seasonal vertical displacement of the soil surface (Mellon et al., 2008). This is shown by the occurrence of thermal contraction crack polygons, which are thought to sort and transport boulders at these latitudes (Mellon et al., 2008, 2009). Fisher (2005) described a combined process of thermal cycling and ice aggradation that might enhance surface deformation. However, the polygons are often not well developed in the immediate vicinity of the boulder lobes (regular textures [Figures 1 and 2] could be due to aeolian processes), which could indicate that the relative rate of lobe formation outpaces polygon formation. In some cases, polygon troughs are clearly present, indicating that this is a relevant slope deformation process.

Aeolian processes could remove support from beneath boulders and initiate their movement by gravity, and some of the features around the boulders may be bedforms (Figure 1b). We have not observed bedform movement at these sites, although sand movement is common on Mars (Bridges et al., 2013) and minor changes may have been undetected. The wind is known to scour material from around boulders in some places on Mars (Malin & Edgett, 2001). Additionally, vibration from the wind might help cause creep; as noted above, the effect of wind on Viking Lander 2 was similar to weak seismic signals. However, while aeolian processes may be active they are unlikely to be dominant, as they should operate at all latitudes.

We emphasize that these are all processes that should be occurring on present-day Mars and the question is regarding their relative importance and quantifying their effects on the surface. Detailed modeling will likely be needed to distinguish between the dominating boulder movement mechanisms.

The data presented here are not sufficient to definitively show whether current processes are causing the formation of the boulder lobes or merely modifying preexisting features. There are, however, reasons to suspect that the boulder lobes are actively forming. Many of the boulder-rich lobate features appear qualitatively fresh and distinctive. The frequency of boulder movement is significant and would be expected to disrupt and degrade the lobes, if they are not being actively formed and maintained, even if the process moving boulders is not the same as the one forming the lobes. Polygonal patterned ground is thought to be actively forming at these latitudes (Mellon et al., 2009), which typically drives cryoturbation of the surface, which would act to disrupt lobes; this also suggests that distinct lobes must have been actively forming recently enough to counter these disruptive effects. In addition, we observed several examples of boulders coming to rest on the upslope side of other boulders or debris, demonstrating that these movements can have a concentrating effect consistent with lobate landform development. In a similar manner, large blocks on Earth are known to result in flattened regolith bulges on the upslope and cavities on the downslope side (e.g., Putkonen et al., 2012). Some boulders do move on slopes lacking defined lobate features, which could indicate that boulder movement is independent of the development of the lobes. Alternatively, boulder movements might be associated with lobe formation, but with defined lobes also requiring some additional conditions or a certain absolute rate. The concentration of boulder movements near lobes (Figure 3) favors this possibility but is not definitive, as those slopes may contain more boulders. It should be noted that lobate

landforms without boulders also exist at high latitudes (Gallagher et al., 2011; Gallagher & Balme, 2011; Hauber et al., 2011; Johnsson et al., 2012); the presence of boulders is not a requirement for lobate landforms, but under some of the processes above, boulder movement and creep of ice or regolith might be driven by the same or related effects.

In aggregate, our observations demonstrate substantial boulder movement in the vicinity of the boulder lobes, which is consistent with (but does not prove) the hypothesis that they are currently forming. The possibility of widespread freeze/thaw cycles influencing these landforms during a past climate cannot be ruled out but may not be required. If the lobate features form via current processes, those processes could vary in intensity over time. A definitive test would likely require in situ study or a much longer time baseline of orbital observations. Regardless of whether the lobes are currently forming, the observed changes demonstrate currently active processes capable of frequently moving boulders. The driving processes may play an important role in the removal of steep slopes at high latitudes (cf. Kreslavsky & Head, 2000).

5. Conclusions

We demonstrate that boulder movement on steep, high-latitude Martian slopes is frequent, indicating modern geomorphic evolution of such slopes in the current climate and a previously unknown style of slope activity. This may be a factor in the rapid degradation of high-latitude craters and contrasts with rockfalls observed in an equatorial crater. This boulder movement and its driving processes could be an important component of the formation of lobate landforms with sorted boulders and rubble. These results add another element to emerging evidence for the importance of current processes in shaping Mars's geomorphology and open the possibility of liquid-free formation of a cold-climate landform resembling terrestrial freeze-thaw features.

Acknowledgments

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