The steepest slopes on the Moon from Lunar Orbiter Laser Altimeter (LOLA) Data: Spatial Distribution and Correlation with Geologic Features

Mikhail A. Kreslavsky, James W. Head

Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064 USA

Abstract

We calculated topographic gradients over the surface of the Moon at a 25 m baseline using data obtained by the Lunar Orbiter Laser Altimeter (LOLA) instrument onboard the Lunar Reconnaissance Orbiter (LRO) spacecraft. The relative spatial distribution of steep slopes can be reliably obtained, although some technical characteristics of the LOLA dataset preclude statistical studies of slope orientation. The derived slope-frequency distribution revealed a steep rollover for slopes close to the angle of repose. Slopes significantly steeper than the angle of repose are almost absent on the Moon due to (1) the general absence of cohesion/strength of the fractured and fragmented megaregolith of the lunar highlands, and (2) the absence of geological processes producing steep slopes in the recent geological past. The majority of slopes steeper than 32°–35° are associated with relatively young large impact craters. We demonstrate that these impact craters progressively lose their steepest slopes. We also found that features of Early Imbrian and older ages have almost no slopes steeper than 35°. We interpret this to be due to removal of all steep slopes by the latest basin-forming impact (Oriente), probably by global seismic shaking. The global spatial distribution of the steepest slopes correlates moderately well with the predicted spatial distribution of impact rate; however, a significant paucity of steep slopes in the southern farside remains unexplained.

1. Introduction

The statistical characterization of topographic slopes is a valuable tool for comparison of planetary landscapes and formulating an understanding of landscape evolution processes (e.g., Sharpton and Head, 1986; Kreslavsky and Head, 1999; Aharonson et al., 2001; Thomas et al., 2002; Rosenburg et al., 2011). The steepest slopes are of special interest because they are more sensitive to alteration and degradation processes; on the Moon with its generally old and stable surface, this sensitivity is important. On one hand, the presence of steep slopes indicates the youthfulness of the related geologic features. Therefore, the steepest slopes are an independent source of information about feature ages. On the other hand, statistical differences about the occurrence of steep slopes for geologically similar features of different stratigraphic position provide information about the nature and peculiarities of slope-modification processes in different geological epochs. In this paper we analyze the steepest slopes on the Moon and present our primary conclusions.

Slope steepness depends on the baseline at which the slopes are considered: generally, the shorter the baseline, the steeper the slopes. Slopes at long baselines, kilometers and longer, are limited by the total topographic amplitude of associated topographic features and are less useful because in a sense they just duplicate the information that can be derived from the topographic amplitudes (e.g., crater and basin depths, etc.). In this paper we focus on the shortest baselines at which we can accurately derive slopes. The necessity of accurate and statistically unbiased measurements of the steep slopes dictates the use of laser altimeter data. Topographic data derived from stereo images (e.g., Robinson et al., 2010; Scholten et al., 2012) despite their potentially high resolution, have some shortcomings for the statistical analysis of steep slopes, because the images used for photogrammetric analysis often have shadows in association with the steepest slopes of certain orientation, which makes it impossible to derive elevation differences reliably for some slopes. Here we use data from the Lunar Orbiter Laser Altimeter (LOLA) (Smith et al., 2010a, b) onboard the
Lunar Reconnaissance Orbiter (LRO), and study steep slopes at the shortest baselines allowed by this instrument, namely, 25 m. Initially, the general statistical results about slopes obtained from the LOLA data set have been reported by Rosenburg et al. (2011). Here we specifically focus on the steepest slopes.

In this paper, when we use the word “slope” in a quantitative sense, we mean the so-called “two-dimensional” slope, also known as the absolute value of the topographic gradient. For discussions of the relationships between two-dimensional slopes and one-dimensional slopes (also known as slopes along profiles) see, e.g., Aharonson and Schorghofer (2006), and Rosenburg et al. (2011). Useful equations for converting isotropic slope-frequency distributions of one-dimensional slopes to two-dimensional slopes and vice versa are listed by Kreslavsky et al. (2015).

In this paper we first describe the technical details of slope calculations and analyze the related biases. Then we consider the slope-frequency distribution and briefly discuss the paucity of slopes steeper than the angle of repose on the Moon. Then we analyze the association of the steepest slopes with specific geological features, on the Moon mostly associated with large impact craters of different stratigraphic age, and we discuss the observed trends. Finally, we consider the global distribution of the proportion of the steepest slopes and compare it with other global data sets.

2. Slope calculation and bias analysis

Normally, every time a LOLA laser shot probes the surface (every “shot”), it obtains range (and inferred elevation) measurements in 5 small (~5 m) “spots” that form a specially designed pattern on the surface: Spot 1 is in the center and Spots 2, 3, 4, and 5 around it are separated from it by ~25 m and are located in the vertexes of a square (Smith et al., 2010a,b). The coordinates of each spot and the measured elevations are available as LOLA Reduced Data Records (RDRs) from the NASA Planetary Data System (PDS). For any three non-collinear points with known coordinates and elevations, straightforward geometric calculations yield the topographic gradient vector; its absolute value is the (two-dimensional) slope. For each LOLA shot we calculated four slopes at ~25 m baseline using four triplets of spots 1-2-3, 1-3-4, 1-4-5, and 1-5-2. Slopes were calculated with respect to a reference sphere. For our purposes, the difference between slopes with respect to the geoid and to the sphere is negligible.

The internal LOLA ranging precision is ~10 cm; however, for the steep slopes and rough terrains considered in this paper, the precision is worse due to actual elevation variation within the ~5 m LOLA spot. A possible ~1 m uncertainty within each spot corresponds to ~4° uncertainty in slope. This uncertainty does not affect our ability to distinguish between steep (>32°) and typical (~10°) slopes, and very steep (>40°) and steep (>32°) slopes. The effect of this uncertainty on the result is also reduced by the large statistics.

We performed the slope calculations for the entire set of LOLA data obtained during LRO operations in its circular orbit phase from September 2009 to December 2011 (LRO orbits 1005 – 11403). When LRO was in the non-illuminated portion of the Moon or close to it, distortion of the alignment of the LOLA laser beams and the detector optical axes regularly occurred due to the thermal contraction (see Smith et al. 2010b for details). We excluded all data affected by this LOLA anomaly. The data set used consisted of ~6 × 10⁶ successful laser shots, so we calculated ~2.4 × 10⁵ slopes. Fig. 1 presents the histogram (incremental slope-frequency distribution) for this dataset.

We selected and listed all ~6 × 10⁶ slopes steeper than 32°; such slopes are steeper or comparable to the angle of repose of dry material and therefore are interesting for the analysis of slope degradation. Fig. 2 presents the spatial distribution of the steepest slopes on the Moon. Each black dot marks the location of the slopes steeper than the value listed; many points overlap. The data coverage of the surface is inhomogeneous: a typical distance between orbit tracks at low latitudes is on the order of 0.8 km; however, the distance varies widely, and there are gaps as wide as ~4 km.

The dataset contains a tiny proportion of spurious points, wrongly measured elevations not marked as bad data points in the data release. Such points usually produce spurious steep slopes. Among ~5 × 10⁵ slopes steeper than 45°, about 80% are spurious, and the rest are genuine. This number of spurious slopes is an approximate estimate based on our automated analysis of proximity of steep slopes to each other. For example, if slopes from the spot triplets 1-2-3 and 1-5-2 are steeper than 45° and have similar orientation, while slopes form two other triplets of this shot as well as all slopes from neighboring shots are gentler than 32°, it is likely that spot 2 elevation is spurious. We manually checked ~10 cases like this using images. The majority of the scattered black dots in Fig. 2a are spurious, although some of them may be genuine steep slopes associated with walls of small young craters. For slopes steeper than 40° (Fig. 2b) the proportion of spurious points in the scattered slopes is still noticeable; it becomes negligible for gentler slopes. Clusters of black dots in locations of large young impact craters (Fig. 2a) coincide with steep crater walls.
Fig. 2. Spatial distribution of slopes steeper than (a) 45°, (b) 40°, (c) 35°, (d) 32°. Simple cylindrical projection for the entire Moon centered at the center of the nearside. Each black dot marks the position of a steep slope; many dots overlap.
therefore are genuine. Among \(1.4 \times 10^5\) slopes steeper than 40° (Fig. 2b), the percentage of scattered spurious points is still significant, but here they do not dominate. For slopes steeper than 35° (\(1 \times 10^6\), Fig. 2c) the proportion of spurious points is already negligibly small. In Fig. 1b, the steep-slope tip of the distribution (38–40°) decreases more gently than the main rollover (34–37°); this is probably due to the contribution of the spurious data points.

There is a small proportion of missing (or marked as bad) data points in the LOLA data set. However, on steep terrain, this percentage is significantly higher and can reach about one half on the steepest slopes. This means that our data significantly underestimate (up to a factor of two) the absolute percentage of the steepest among all measured slopes. Moreover, the proportion of missing data points is different for different spots and depends on slope orientation. This means that the statistics of slope orientation (direction of the topographic gradient vector) is biased. When we tried to analyze the rose diagrams of steep-slope orientation, we found that they are obviously biased: the slope orientation distributions are weirdly anisotropic with characteristic directions aligned with the five-spot configuration axes. The rose diagrams calculated separately for each of the four spot triplets used were different. Thus, the described bias makes it impossible to study the statistics of slope orientation with the data used.

We analyzed this issue in more detail and found that the proportion of missing data points as a function of slope is a rather stable quantity for each of the five spots; it does not depend on latitude and only weakly drifts through the mission. This means that the relative spatial variations of the proportion of steep slopes are detected reliably. In other words, both the association of steep slopes with particular geologic features and global spatial distributions of steep slopes are obtained reliably.

3. Paucity of steep slopes

The global slope-frequency distribution (Fig. 1) has a distinctive structure. The downward roll-over at the zero-slope margin is usual for two-dimensional slopes of natural surfaces. The most frequent slopes are \(1–3°\) steep, and the slope-frequency distribution has a heavy steep-slope tail. Preliminary analysis by Kreslavsky et al. (2015) showed significant differences in the nature of slope-frequency distributions between highlands and maria and the presence of another characteristic slope of \(\sim 6°\) in highlands. Fig. 1 mixes highlands and maria together; however, it is dominated by the highlands. The frequency distribution of slopes is an interesting subject of a separate study; here we only focus on the steepest slopes (\(\geq 32°\), as shown by the shaded domain in Fig. 1). For these slopes, the frequency distribution sharply drops (Fig. 1b), reflecting the strong relative paucity of slopes steeper than typical angles of repose (e.g., Jaeger et al., 1988) of dry materials (28–35°).

A characteristic vertical scale associated with the steep slopes is comparable to the slope baseline, that is, about tens of meters in our case. At this vertical scale the lunar highlands are composed of megaregolith (e.g., Hartmann, 1973), a layer of impact-fragmented, disintegrated material. Slopes in such material are maintained by dry friction between the fragments; therefore, the occurrence of steep slopes in the megaregolith is limited by the angle of repose. This explains the paucity of slopes steeper than the angle of repose in the highlands.

Another, complementary (rather than alternative) explanation of this observation is the absence of geological processes capable of producing new steep slopes on the Moon. On the Earth, at the scale of tens of meters, nearly vertical cliffs are constantly produced by water erosion (streams, rivers, waves), a process absent on the Moon. On Mars, the majority of slopes steeper than 45° at 300 m baseline are associated with the huge walls of Valles Marineris and walls of young Cerberus Fossae (Kreslavsky and Head, 2003a,b); these steep linear walls are created by tectonics. On the Moon, morphological evidence of geologically recent tectonic deformation has been reported (e.g., Watters et al., 2012); however, the associated features are minor in their distribution and magnitude and no steep slopes at a 25 m baseline are produced. Steep cliffs on the Earth and Mars are also associated with collapse features, however, such features ultimately originate from water erosion, absent on the Moon, and volcanic, processes generally absent on the Moon in the recent geological past (Copernican period and later part of Eratosthenian periods, 1–2 Ga) (Hiesinger et al., 2011). Braden et al. (2014) have recently described features interpreted to represent basaltic volcanism occurring in the last 100 million years, but the majority of these features are too small to be reliably detected in our data. Volcanic and tectonic processes capable of producing steep slopes (Head and Wilson, 2016) generally date back to the Imbrian and earlier periods (\(\sim 3\) Ga and older) (Hiesinger et al., 2011).

The only widespread process that does effectively produce geologically young steep slopes is impact cratering. In the next subsection we see that the majority of the steepest slopes on the Moon are associated with impact craters. Slopes in fresh craters, however, rarely exceed \(\sim 45°\). This occurs because during crater formation, there is a significant concentration of seismic/acoustic energy, which mobilizes material; this, in turn, makes steep crater walls unstable.

In summary, on the Moon, we observe a virtual absence of slopes significantly steeper than the angle of repose. We explain this by a combination of two factors: (1) an absence of cohesion/strength of the fractured and fragmented megaregolith of the lunar highlands, making slopes steeper than the angle of repose unstable, and (2) the absence of active geological processes that could produce slopes steeper than the angle of repose (e.g., volcanic vents, collapse features, lava flow channels) in the competent material of the lunar maria in the recent geological past.

4. Association with geologic features

4.1. Large impact craters

As we noted in Section 2, the majority of inferred slopes steeper than 45° are actually artifacts caused by unidentified spurious points in the LOLA data set. However, some slopes steeper than 45° are present on the Moon. Almost all of them are associated with large Copernican-aged impact craters. In Fig. 2a, dense clusters of black dots indicating the locations of steep slopes clearly mark all of the largest Copernican-age craters (except Taruntius, an impact crater that will be discussed later). For progressively gentler slopes (40°, 35°, 32°, Fig. 2b–d), large craters of Eratosthenian and Late Imbrian age appear in the maps. Usually, craters of Early Imbrian age and older are not seen as distinctive clusters of steep slopes in the maps (Fig. 2).

Eratosthenian and Late Imbrian craters appear as empty circles in the maps (Fig. 2c and d), sometimes with a small cluster of dots in the center, indicating that the steep slopes are associated with crater walls and sometimes with the central peak(s). Many Copernican craters appear as filled circles, indicating that steep slopes are also associated with terraces or are caused by the presence of meters-sized blocks on the floor.

All these observations are readily explained by the progressive degradation of steep slopes in impact craters (Head, 1975). Freshly formed large craters have some steep slopes and meter(s)-sized blocks on the crater floors are apparently responsible for some steep slope data point retrievals. The blocks disappear geologically rapidly, at time scales on the order of 100 Ma (Basilovsky et al., 2013, 2015). The slopes also degrade, and talus deposits accumulate at the base of the slopes. The volume of talus material needed
to hide a steep wall is proportional to the square of wall height, while the rate of talus accumulation is approximately proportional to the height of exposed part of the wall; therefore taller walls preserve their steepness for longer times. Short steep slopes on/near crater floors disappear first, and tall outer parts of crater interior walls keep their steepness for longer periods. Meters-size blocks on the crater floors apparently responsible for some steep slope data point retrievals also disappear rather quickly, at time scales on the order of 100 Ma (Basilevsky et al., 2013, 2015). The talus accumulation rate also strongly depends on slope: steeper slopes degrade more rapidly. Thus, progressive degradation of steep slopes and the accumulation of talus appears to be a very plausible mechanism to explain the absence of steeper slopes in relatively older craters.

The sharp difference in steep slope occurrences between Late Imbrian and Early Imbrian craters is readily explained by the hypothesis that basin-forming impacts can cause global resurfacing. On the basis of the kilometer-scale topographic roughness signature, Kreslavsky and Head (2012) argued that the Orientale basin-forming impact event, separating the Early and Late Imbrian epochs, was the last large basing-forming impact, and thus was the last event producing global slope resurfacing at the kilometer spatial scale. Naturally, this global resurfacing event is also the latest event that instantly removed all preexisting steep slopes globally. Kreslavsky and Head (2012) suggested that global seismic effects produced by basin-forming impacts (Schultz and Gault, 1975) are the physical mechanism responsible for such global resurfacing. In this interpretation (Kreslavsky and Head, 2012), global seismic shaking immediately following the initial impact caused pervasive mobilization of surface material and failure of pre-existing steep slopes, which effectively erased almost all pre-existing steep slopes. In this scenario, each large basin-forming impact event erased all preexisting steep slopes; therefore all currently observed steep slopes are predicted to have been created after the latest of these large impact events, the impact that formed the Orientale basin. We found that large (~10 km) distal secondary craters associated with the Orientale impact are characterized by abundant 32°–35° steep slopes on their walls, similar to typical Late Imbrian primary craters. This is consistent with global seismic shaking, because the seismic wave travels rapidly and precedes the arrival of the secondary-forming projectiles (Schultz and Gault, 1975).

There are some exceptions to the prominent and well-understood degradation trend described above. Below we consider two of the most obvious examples.

The crater Taruntius (56 km in diameter) has been mapped as Copernican in age by Wilhelms (1987) on the basis of its associated bright rays; however it has no slopes steeper than 32° except those associated with superposed small craters. The morphology of this crater seen in the high-resolution LROC NAC images is also inconsistent with its Copernican age. The identification of Taruntius as Copernican in age is probably incorrect. The ray system may be a visual effect due to the superposition of faint rays from distal craters, and/or includes a compositional aspect of bright material that acts to subvert the simple regolith mixing-rate interpretation of the crater-ray degradation time scale (Hawke et al., 2004). However, Taruntius clearly postdates the Mare Fecunditatis volcanic plains of Late Imbrian age; it is therefore Late Imbrian or younger in age and should have steep slopes according to its age. Taruntius is also a floor-fractured crater (Schultz, 1976; Wichmann and Schultz, 1996; Jozwiak et al., 2012, 2015) and the process of intrusion and uplift could have caused tilting and local seismic shaking sufficient to modify the slopes.

The crater Tsiolkovskiy (180 km in diameter) has been mapped as Late Imbrian in age by Wilhelms (1987). This age is constrained on the younger side by the Late Imbrian age of mare infill of the crater interior, which in turn was obtained from counts of 100 m–1 km craters (Tyrie, 1988), although counting of craters larger than 500 m on the mare infill yielded an age close to the Imbrian/Eratosthenian boundary (Williams et al., 2013). Tsiolkovskiy’s walls and central peak have a number of sites with slopes steeper than 45° and clearly appear in the 40° steep slope map (Fig. 2b). According to this steep slope signature it is predicted to be on the younger side of the Eratosthenian age. Tsiolkovskiy’s rim is also known for its anomalously high rock abundance (Greenhagen et al., 2013) inferred from night-time thermal infrared emission (Bandfield et al., 2011). The observed rock abundance is typical of Copernican-aged craters only, and abundant rocks together with other morphological characteristics of Copernican-age craters indeed are seen in high-resolution LROC NAC images (Neish et al., 2013). Anomalously steep slopes explain the anomalously high rock abundance: rapid regolith downwasting on steep slopes exposes rocks. The presence of steep slopes, however, remains unexplained. A possible explanation is that both Tsiolkovskiy and its mare infill are close to the Copernican/Eratosthenian boundary in their age, while the high density of superposed craters on mare infill is due to an anomalous contamination with secondaries. The latter is consistent with an anomalously high hectometer-scale topographic roughness displayed by the Tsiolkovskiy mare infill (Kreslavsky et al., 2013).

4.2. Impact basins

The Orientale basin, the youngest impact basin on the Moon (Wilhelms, 1987; Whitten et al., 2011) is apparent on the steep slope maps (Fig. 2b–d). The basin rings (Montes Rook and Montes Cordillera) have steep slopes, including those steeper than 40° (Fig. 2b). The hypothesis of global small-scale resurfacing by basin-forming impacts (Kreslavsky and Head, 2012) predicts that all other, older basins would not have steep slopes because these slopes would be removed by the seismic effects of the latest Orientale impact. In general, this is correct: no other basin shows as pronounced a signature as Orientale. There are, however, some qualifications.

The outer ring of the Schrödinger basin does not show any enhancement in steep slopes. This basin is of Early Imbrian age, meaning that it predates Orientale, therefore the absence of steep slopes here is consistent with steep slope removal as a consequence of the Orientale-forming impact. There are, however, some steep slopes in the inner ring. These steep slopes are actually associated with tectonic graben cutting the ring and floor and therefore may postdate the Orientale impact. This interpretation is strengthened by the close association of floor-fracturing with the era of mare volcanism (Jozwiak et al., 2012, 2015), and the location of volcanic vents in association with these graben (Kramer et al., 2013). Furthermore, the abundance of boulders on the floor of the Schrödinger basin and their association with the floor graben and scarps (Kumar et al., 2016) supports a post-Orientale basin origin for these steep slopes.

A part of the Imbrium basin outer ring, Montes Apenninus, has some moderately steep (32°–40°) slopes (Fig. 2c and d), while all other exposed parts of this basin ring do not have steep slopes. It is not clear, however, what is special about Montes Apenninus that produces this anomaly. It is possible that some tectonic or other processes (for example the formation of the adjacent 83 km diameter Archimedes crater) triggered several large landslides in this particular region after the Orientale impact and before emplacement of the latest Mare Imbrium volcanic material embaying Montes Apenninus.

All Nectarian-age and older basins (those predating the Imbrian impact) (Fassett et al., 2012) do not appear as circles with abundant steep slopes in the map of slopes steeper than 35° (Fig. 2c). Only one basin, Crisium, becomes visible in the map of
slopes above 32° (Fig. 2d) due to a slightly higher density of scattered steep slopes within its proximal ejecta. It is presently not clear what particular factors are responsible for this increase in the scattered steep slope abundance.

4.3. Other features

Walls of several sinuous rilles (see Hurwitz et al. 2013, for the global distribution, characteristics and modes of origin of sinuous rilles) often have slopes steeper than 35° due to the exposure of bedrock outcrop layers in the upper parts of the rille walls. The most prominent examples are seen in Vallis Schröteri in the Aristarchus Plateau. Some linear rilles of tectonic origin (graben) also have consistently steep walls, for example, the graben in Schrödinger previously mentioned, a system of graben on the Humboldt crater floor, Rima Hyginus and Rima Ariadneae. These features postdate the Orientale basin impact; thus, the preservation of their steep slopes is consistent with global seismic shaking as a small-scale resurfacing mechanism for earlier steep slopes, while steep slopes that formed post-large impact basin by tectonic (linear rille) and thermal erosion (sinuous rilles) processes remain well preserved.

Scattered steep slopes in Fig. 2b–d are often related to small young craters. Some scattered slopes in the 32°–35° range are at the walls of old craters (Early Imbrian or possibly older); however, they are not grouped in clusters or chains. Fig. 2d gives the impression that scattered steep slopes are everywhere, but this is a visual effect caused by size of the dot used to make the figure: as seen from Fig. 1: slopes steeper than 32° are still rare: they comprise only ~0.15% of all measured slopes and due to lost data points (see Section 2), only about ~0.3% of the total surface area.

5. Global distribution

As discussed in Section 2, although the absolute proportion of steep slopes is strongly biased, the relative spatial variations are reliable. The apparent paucity of steepest slopes in the polar area seen in Fig. 2 is related to distortion due to the projection. To study the global variations of steep slope abundances we need to mitigate the inhomogeneity of surface sampling with LRO orbit tracks. To do this we first mapped the proportion of the steepest slopes in the simple cylindrical projection at 8 pixels per degree sampling. For each pixel of the map we counted the number of good slope measurements, the number of those steeper than 35°, and then divided the latter by the former. In this way we excluded any spatial inhomogeneity in the measurements. Since the absolute value of the proportion of steep slopes is biased, we normalized the map by the mean percentage of the steep slopes. The majority of pixels have zero values. To study the global variations and remove the effects of the huge concentration of steep slopes in specific individual large young craters, we smoothed the percentage map down to the lowest spherical harmonics. Fig. 3a and b shows the resulting global distribution smoothed down to harmonics of degree two and three, respectively. It is seen that there is some concentration of the steepest slopes toward the equator. There is also a relative paucity of steepest slopes in the southern farside (approximately consistent with the South Pole–Aitken basin) and a maximum in the central–eastern farside. Fig. 4 shows separately the latitudinal dependence of the percentage of the steepest slopes averaged over all longitudes.

From the analysis in Section 4.1 we know that the steepest slopes are predominantly produced by impacts and that these degrade with geological time. Therefore it is reasonable to expect that the number of steepest slopes is proportional to cratering rate,
Correlation with topography is even more puzzling. Kreslavsky et al. (2013) noted and discussed the correlation between roughness and topography. They suggested the following explanation: On the basis of geodynamical reasoning, the equator is close to topographic highs, and relative roughening of the equatorial region might be caused by more frequent impacts. This explains the generally higher roughness at low latitudes and therefore some part of the correlation with topography. After that, the similarity between other global-scale details of the distributions might be coincidental. The same logic can be applied one-to-one to the steepest slopes.

6. Conclusions

Our analysis of the steepest slopes on the Moon shows that their occurrence is controlled by a limited set of processes. The steepest slopes are formed by impacts, and in the geological past by several tectonic and volcanic processes; these slopes slowly degrade through geological time and can be instantly removed as a consequence of large scale basin-forming impacts. The latter effect probably occurs due to intensive global seismic shaking (Schultz and Gault, 1975; Kreslavsky and Head, 2012). Due to the simplicity of this set of processes, steep slopes can be effectively used in geologic studies to assess ages. Global removal of the steepest slopes by the Orientale impact, the latest basin-forming impact, is a good global stratigraphic marker. For craters postdating the Orientale impact, slopes correlate with crater age. Although it does not seem possible to accurately calibrate slopes of the crater walls in terms of absolute ages, slopes do give an independent constraint on the stratigraphic age of craters.

Our observations revealed several puzzling facts related to the steepest slopes. The steepest part of these outstanding questions is the significant relative paucity of steepest slopes in the southern facies, in the South Pole–Aitken basin region.

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