Gullies and landslides on the Moon: Evidence for dry-granular flows

P. Senthil Kumar,1 V. Keerthi,2 A. Senthil Kumar,2 John Mustard,3 B. Gopala Krishna,4 Amitabh,4 Lillian R. Ostrach,5 David. A. Kring,6 A. S. Kiran Kumar,4 and J. N. Goswami7

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[1] High-resolution images from Chandrayaan-1 Terrain Mapping Camera and Lunar Reconnaissance Orbiter Camera reveal landslides and gully formation on the interior wall of a 7 km-diameter simple crater emplaced in Schrödinger basin on the farside of the Moon. These features occur on the steep upper crater wall, where the slope is ~35°. The gullies show a typical alcove-channel-fan morphology. Some gullies incise bedrock, where impact-related faults are present. Slope failure along the concentric faults also led to formation of landslides. Dark slope streaks are abundant at the bright gully regions, especially near the fan and channel deposits. Spectral characteristics inferred from data obtained by Hyperspectral Imager and Moon Mineralogy Mapper on board Chandrayaan-1 show that the gullies and landslides are characterized by high optical immaturity and devoid of prominent spectral absorption features related to water or hydroxyl molecules, suggesting youthful dry-granular flows. Mass movements on the crater wall led to the formation of arcuate ridges and ponding of fine-grained sediments on the crater floor. Runout flows from small impact craters on the slopes indicate that impact-induced seismic shaking was responsible for the downslope mass movements. Crater size-frequency distributions suggest a minimum age of 18–2 Ma for the gullies and 2 Ma for the landslides, while age of the host crater ejecta was inferred to be about 175 Ma. The gullies and landslides also occur on the interior wall of other impact craters elsewhere on the Moon and probably formed by similar processes.


1. Introduction

[2] Degradation of impact craters on planetary surfaces provides significant insights to the changes in planetary surfaces taking place with time and clues about attendant geologic and atmospheric processes. For example, the recent discovery of gullies on the interior walls of impact craters on Mars has been attributed to liquid water drainage in the recent past [e.g., Malin and Edgett, 2000]. In contrast, Treiman [2003] suggests a model without water that relies entirely on avalanches of dry-granular material. To better evaluate those processes, studies of gullies and landslides on the Moon, where liquid water is not stable, might be enlightening. Bart [2007], for example, described gullies similar to the putative water-carved martian gullies on the interior walls of impact craters in the low-latitude region (3°N–23°N) of the lunar nearside. These gullies have alcove-channel-fan morphology similar to the martian gullies. Because the Moon lacks an atmosphere and liquid water is unstable on its surface, Bart [2007] suggested dry-granular flows as the mechanism of gully formation. This report was based on the analysis of Lunar Orbiter data, which provided faint pictures of gullies, whose lengths were not more than a few hundred meters. Although such findings were not common, several aspects of the gullies remain unresolved. What initiated gully formation on the Moon? Are gullies produced by a simple flow of regolith or do they involve bedrock? Do they occur as a single or series of episodic events? What are their morphologic characteristics? What are their spectral properties? How do crater wall
materials and structural elements contribute to gully formation? Is it an entirely dry process or could it, in some way, have been influenced by regolith volatiles?

[5] We address these questions in the present study by studying gullies and landslides that we found on the interior wall of a 7 km-diameter simple crater emplaced in Schrödinger basin on the farside of the Moon, near the polar region (Figure 1). We use high-resolution images acquired by the Chandrayaan-1 Terrain Mapping Camera (TMC) and the Lunar Reconnaissance Orbiter Camera Narrow Angle Camera (LROC NAC), which resolved fine morphologic properties of the gullies and landslides at a spatial resolution of 1–5 m. In addition, spectral data from the Hyperspectral Imager (HySI) and Moon Mineralogy Mapper (M3) on board Chandrayaan-1 were analyzed to address whether the gullies and landslides are associated with enhanced water or hydroxyl molecules, optical maturity variation, and mineralogy. Furthermore, we determine the age of the gullies and landslides and the host crater using the crater-counting dating method. Based on the geological and spectral observations, we propose a plausible mechanism of formation of gullies and landslides on the Moon. In addition, we show a few occurrences of gullies and landslides on the interior walls of impact craters in the low-latitude regions of both the lunar nearside and farside to demonstrate that the features in the 7 km-diameter crater in Schrödinger basin do occur elsewhere on the Moon and suggest that they may have formed by similar processes.

2. Study Area

[4] Schrödinger basin is centered at 75°S and 135°E and located ~450 km from the South Pole on the farside of the Moon [Pike and Spudis, 1987; Shoemaker et al., 1994; Spudis et al., 1994]. It is a circular peak-ring basin with a rim-to-rim diameter of 320 km and an inner ring diameter of 150 km (Figure 1). The basin floor is nearly 8 km below the highest point on the basin rim [e.g., Mest, 2011]. The inner peak ring rises about 2 km above the basin floor. Schrödinger basin is considered to be an important target area for lunar exploration as it is located in the South Pole-Aitken basin [O’ Sullivan et al., 2011], which is one of the oldest and largest impact basins on the Moon, and it exposes materials of diverse origin such as impact melt and pyroclastic to effusive volcanism that are associated with tectonic features. The basin may also provide exposures of upper mantle origin, either in the ejecta of the South Pole-Aitken basin or in its own uplifted peak ring.

[5] Yamamoto et al. [2012] and Kramer et al. [2013] identified anorthosite and olivine-bearing lithologies in the peak ring. Smooth mare material is seen in the interior floor of the peak ring and is overlain by smooth plains material and dark mantle material that was definitely derived from a volcanic vent. The basin floor is cut by a network of grabens that are bound by normal faults; these faults cut across the peak-ring material, rough and smooth plains materials, but predate the dark mantle volcanic material. Clearly, the graben controlled the location of the volcanic vent. The basin wall material constitutes a rock mass that represents the pre-impact target substratum and is older than the plains materials seen in the basin floor. At places, the basin wall represents pre-impact faults. Irregularly shaped secondary impact craters are abundant on the basin floor; some of them were derived from the Orientale impact basin, which postdates Schrödinger basin. Some craters have central mound morphology indicating the impacts of low-velocity clustered ejecta projectiles producing these craters [e.g., Kumar et al., 2011]. The basin is considered to be one of the youngest impact basins of the Moon; crater-counting statistics place this basin at around 3.8 Ga [Shoemaker et al., 1994].

[6] During geological mapping of this basin, we found a bowl-shaped fresh crater (named as “crater 1” hereafter) with abundant interior wall modification (Figure 2). The crater was emplaced in the uplifted peak ring, which is considered to be the oldest unit in the basin. There are two other craters with diameters of 5.5 km (crater 2) and 10.5 km (crater 3), respectively, emplaced about 80 km and 200 km SSW of this crater which show similar fresh crater wall modification (Figures S1 and S2 in the Supporting Information). Crater 1 appears to have formed by a primary impact and may be correlated to the Copernican- or Eratosthenian-age grouping of craters.

3. Observations

[7] TMC image suggests crater 1 to be a fresh crater, ~7200 m in diameter and ~1700 m deep, centered at 72°12’S, 133°12’E (Figure 2). The crater was emplaced on an irregular surface of the peak ring. As a result, the rim in between the eastern and southern side is at about 300 m higher elevation than the rim between the western and northern side. The diameter of the crater varies from 6800 m to 7500 m.

Figure 1. The Chandrayaan-1 terrain mapping camera image showing 320 km-diameter Schrödinger basin. The box shows the study area with a 7.2 km-diameter impact crater (crater 1) near its center; the crater was emplaced in the peak-ring material and displays gullies and landslides on its interior walls. The other two craters (craters 2 and 3) also show similar features on the interior wall.
The crater rim between the western and northern side fits perfectly to a 6860 m diameter circle, while the rest of the rim receded as much as 600 m away from the circle, indicating greater wall collapse in those regions and the effect of pre-impact topography on the crater shape and the slopes (Figure 2a). Interestingly, the slope of the interior wall between eastern and southern sides is gentler (~30°) than that on the western and northern wall, where the slope varies from 34° to 36° (Figure 2d). The interior wall between the eastern and southern rim shows significant degradation leading to formation of bedrock spurs, gullies, landslides, and slope streaks.

When the shadow on the floor and the crater wall is enhanced by an image processing dynamic range enhancement technique, which reveals greater details in the images where pixels have nearly similar values, we observe a prominent arcuate ridge from the western to northern boundary of the crater (Figure 2b). A pond (~800 m × ~2000 m) that is composed of smooth deposits overlies the floor and embays the ridge materials (Figure 2b), indicating that the pond material postdates the ridge material. A 200 m-diameter impact crater was emplaced on the pond material. The ridge crest is ~125 m above the pond surface. The arcuate ridge is absent from the eastern to southern boundary of the floor, where the corresponding crater wall suffered greater wall collapse followed by the formation of gullies and landslides. The debris from the wall collapse has given rise to the arcuate ridge. The pond is oriented toward the landslide site near the southern wall, indicating the source of ponded material. The crater rim is also characterized by the presence of concentric faults at several places (Figure 2c), which strike parallel to the rim and dip toward the crater floor. The hanging wall of the fault is characterized by displacement in the downdip direction, followed by slumping on the interior wall. The concentric faults significantly contribute to the landslide formation on the interior wall. Similarly, the rim of craters 2 and 3 contain concentric faults leading to gullies and landslides (Figures S1 and S2).

Figure 2. (a) The Chandrayaan-1 terrain mapping camera image showing the ~7.2 km-diameter fresh crater (centered at 72°12′S, 133°12′E, see Figure 1 for the study area) emplaced in the peak-ring material of Schrödinger basin. The topographic profiles along A-A′ and B-B′ are shown in Figure 2d. A 6860 m-diameter circle fits perfectly to the crater rim from the western to the northern sides of the crater, while the crater rim recedes in other parts due to enhanced crater wall erosion. (b) The shadow-enhanced TMC image reveals the presence of arcuate ridge and the pond material on the crater floor. Note the pond is oriented toward the prominent landslide surface. (c) The TMC image showing the presence of concentric faults along the northwestern crater rim. (d) The topographic profiles along A-A′ and B-B′. The interior wall that contains the landslides (B-B′) is gentler and shallower than the interior wall with the gullies (A-A′). The ridge material is characterized by a higher topographic relief than the surrounding crater floor. The pond material has a flat surface that embays the ridge and other floor materials.
3.1. Gullies

[9] The interior wall between the eastern and southern rim shows a spectacular development of gullies, landslides, and slope streaks (Figures 3 and 4). The gullies are abundant between the eastern and southeastern walls, while the landslides dominate the southern and southeastern walls. The gullies have a typical alcove-channel-fan morphology; the alcove is a concave, elongated, triangular depression located at the head of the gully and is a zone of erosion of crater wall materials. Channels emanate from the downslope apex of the alcove. They are straight, curved, and sinuous, depending upon the slope and the presence of bedrock spurs. The channels also lengthen toward the alcoves due to progressive headward erosion. The eroded materials in the alcoves were transported along the channels and deposited at the fans or debris aprons. Fans are characterized by triangular, oval, and eye shapes. The fan deposits also contain large fragments or boulders and fine sediments derived from the alcoves or channel walls (Figures 3b and 3c). Erosion exposes the bedrock on the walls and floors of the alcoves and channels. At places, talus cones are also present (Figure 3b).

[10] Figure 3b shows a set of straight and narrow alcoves and channels that are closely arranged in a parallel manner, incising into the bedrock, indicating the presence of closely spaced weakness zones such as faults and fractures in the bedrock. During the impact process, a wide variety of fractures (radial, concentric, and conical) and faults (radial and llistric) are produced, which are exposed on the rim and interior wall after the crater formation [Kumar, 2005; Kumar and Kring, 2008]. As seen in terrestrial impact sites, the fractures/faults are composed of fault breccia that can easily be dismantled and removed by mass movement [e.g., Kumar et al., 2010]. Sediments in the fans were also derived either from a single or multiple alcoves. Talus cones were formed as a single debris apron without the channel and alcove, indicating their derivation from the loosely packed sediments that coat the crater wall. The deposits in the channels and fans are usually brighter than the underlying or surrounding sediments, which were formed by either an earlier gully-forming activity, talus sediments, impact breccia, or fall back deposits, as seen in the terrestrial impact sites [e.g., Kumar et al., 2010]. Figure 3c shows an interesting gully morphology in which a shorter fan was formed from a longer channel and alcove; the alcove shows multiple sets of erosion leading to three or more orders of channels. In contrast, the adjoining gully has a longer fan with abundant fragments, formed from shorter channels and narrow alcoves. This morphologic variation indicates the changes in the dynamics of fan formation, as the fragment-loaded fan mobilized longer distance compared to the other fan. Interestingly, these gullies also depict variation in the brightness of their surfaces, which may indicate different timings of gully formation or changes in the bedrock composition or both. Figures 3d and 3e illustrate fan deposits, which are loaded with large angular rock fragments as big as 30–50 m, derived from the bedrock exposures in either the channel or alcove region. Interestingly, none of these large rock fragments (or boulders) left their tracks on the fans or channels, suggesting the burial of the tracks by the sediments formed subsequently from the alcove regions.

[11] Figure 4 shows a distinct example of complex gullies that have bright alcoves and channels with poorly developed fans because of larger dispersion of fan sediments. A broad triangular alcove as wide as ~500 m contains at least four orders of much smaller compound alcoves; the fourth-order alcove gives rise to a broad channel and a compound fan (one of the fans is labeled in Figure 4a). The superposition relationship between the compound alcoves suggests an episodic gully activity. In Figure 4b, a bright alcove (labeled as a3) truncates a dark alcove (labeled as a2). The alcoves that have smooth and darker surface (labeled as a1) appear to have formed before the other two sets of bright alcoves (a2 and a3). An increase in the brightness from older to younger alcoves would indicate the successive generation of newer surfaces or reactivation of older surfaces, leading to an increase in the optical immaturity. Individual gullies without compound morphology also occur near or on downslope of the compound gullies (Figures 4d and 4e). They have small alcoves but have much longer channels and fans, approximately twice the length of the alcoves.

[12] The crater wall down the slope of the compound gullies contains widely spread bright and dark mantle deposits (Figures 4a and 4c). The bright mantle deposits (BMD) are likely to have derived from the bright youthful gullies, while the dark mantle deposits (DMD) underlie them. The DMD also contain coarse fragments that are likely to be derived either from the old darker gullies or colluvial sediments mixed with impact or fallback breccia. Flow of a smaller amount of DMD over the BMD as subtle channels gave rise to finger-like, 1–5 m-wide dark slope streaks that extend several tens of meters in the down slope direction (Figure 4c). Alternatively, removal of BMD because of flow of colluvial sediments on the crater wall may expose the underlying DMD, producing the slope streak structures. The small impact craters (labeled as IC 1 and IC 2 in Figure 4c) were fully emplaced in the BMD and provide its minimum thickness to be ~3 m, assuming a diameter to depth ratio of 5. On the other hand, the 7 m-diameter crater (IC 3) that exposes the DMD on its floor suggests the thickness of BMD to be slightly above 1 m. The slope streaks cause mixing of BMD and DMD materials. The streaks represent small-scale dry-granular flows that formed during or after the gully-forming event. Absence of boulders in the distal end of these streaks rules out the possibility of being the boulder tracks.

[13] We measured morphometric parameters (length, width, depth, and slope) of 15 prominent gullies (Figure 5) using the LROC NAC images and a 30 m-per pixel digital terrain model (DTM), which was generated from the Lunar Orbiter Laser Altimeter (LOLA) data (http://ode.rsl.wustl.edu/moon/indexDatasets.aspx). The gullies have a wide range of sizes. Length of alcoves varies from 15 m to 560 m, width from 10 m to 360 m, and apparent depth ranges from 10 m to 50 m. These values are typical for the lengthened alcoves, as the length is greater than the width (Figure 5a). Width of the alcoves increases with increasing length, in the observed scale range. The channels are narrower (Figure 5a), width varies from 5 m to 125 m, length from 40 m to 225 m, and depth ranges from 5 m to 30 m, which are slightly less than the depth of the alcoves. The fans are more prominent than the alcoves, in terms of length;
Figure 3. The LROC NAC image M118979214L showing the detailed illustrations of the gullies [image credit: NASA/Goddard Space Flight Center (GSFC)/Arizona State University]. (a) The LROC NAC context image showing the locations of Figures 3b–3e and Figures 4a–4e. (b) A set of gullies originating from the upper wall have typical alcove-channel-fan morphology; the materials eroded at the alcove regions are transported along the channels and deposited in the fan. Fan deposits also contain large fragments of rocks either removed from the alcoves or the channel walls. (c) A distinct example of gullies, one with bright alcove and channel materials with a poorly developed fan because of larger dispersion of fan sediments; the upper gully shows a spectacular broad alcove with four orders of channels and fan deposits, while the lower one is less complicated. Some of the head alcoves are bright, indicating the youthful activity. The lower bright gully has narrow, sinuous, irregularly shaped alcoves. The angular fragments in the fan may indicate a nonviolent, short-lived, transport mechanism. (d and e) Lobate fans formed at the base of bedrock-incised straight channels that may have exploited the intensely fractured bedrock; note the fan deposits containing large rock fragments, probably derived from the straight channel walls; the fragments do not show the trails as they may have been transported much before the surrounding sediments. The maximum size of the boulder is about 35 m.
their length varies from 50 m to 750 m, width from 15 m to 200 m, and their thickness (elevation difference between the center and boundary of the fan) ranges from 5 m to 40 m. Interestingly, the alcove width increases linearly with the increase of its length in the observed scale range (Figure 5a). On the other hand, width of fans increases linearly up to a length scale of 250 m, beyond which their width remains more or less the same, irrespective of further increase of its length (Figure 5a). When the alcove length is compared with the corresponding fan length (Figure 5b), the fan is longer than the corresponding alcove except for a few cases. It indicates greater sediment mobility in the fans in the downslope direction. The DTM also provides a new information about the slope of the gullies (Figure 5d). The slope of alcoves varies from 24° to 52°, channels from 31° to 53°, and fans from 23° to 52°. Although the slope values are in a comparable range, some fans are either gentler or steeper than the corresponding alcoves (Figure 5c). Accumulation of sediments in the fans decreases their slopes, while dispersion or collapse of fans may have led to steepening of their surfaces. Boulders are also abundant in the fan deposits. There are about 75 boulders above a diameter of 4 m (Figure 5c) with a maximum diameter of 55 m. The ratio of short axis to the long axis is less than 1, indicating that the boulders are poorly sorted rectangular fragments. The sizes of boulders do not exceed the width of channels, which

Figure 4. The LROC NAC image M118979214L showing the detailed illustrations of gullies [image credit: NASA/GSFC/Arizona State University]. (a) Large slope streaks forming from the bright gullies. The bright mantle deposits that coat the crater wall are colluvial sediments partly derived from the gully region. The bright gullies do not have prominent fan deposits suggesting a greater mobility of the fan deposits toward the crater floor. (b) Episodic gully activity. The first and second order alcoves (a1 and a2) predate the third-order bright alcoves (a3). The brightness increases from lower to higher order alcoves. The bright gullies represent the youthful sedimentary activity. (c) Examples of dark slope streaks. The slope streaks predate the bright mantle deposits; the individual dark streaks have finger-like distal ends. (d and e) Examples of gullies with narrow alcoves and channels.
would imply that the provenance of the boulders might be either the walls of channels or alcoves.

3.2. Landslides and Pond Deposits

Landslides are present on the southern and southeastern interior walls (Figures 2 and 6). Landslides are landforms produced by mass wasting processes without forming a typical alcove-channel-fan morphology. They are formed by slumping of crater wall materials along preexisting concentric faults, which are parallel to the interior wall (Figures 2c and 6). Figure 6b illustrates a fault-controlled landslide producing the morphology similar to the experimentally produced dry-granular flows [e.g., Shinbrot et al., 2004]. These structures are produced preferentially on the upper crater wall. The landslide also contains isolated channels without typical alcoves, in the middle to lower crater walls. The fan deposits have lobate margins with abundant coarse-grained fragments (Figure 6b). A 700 m-wide NNW-SSE oriented debris mound occurs along the western periphery of the crater floor and is oriented toward the landslide surface, which is associated with the concentric fault, where enhanced crater wall slumping occurred. Arguably, the landslides can also form during the modification stage of the crater formation and undergo subsequent degradation in the form of young slides. Terrestrial impact sites show clear evidence of wall slumping along the concentric faults [Kumar, 2005; Kumar and Kring, 2008].

Feature extraction using a shadow removal algorithm and image enhancement in the shadow region of LROC NAC image shows the morphology of the pond deposits in the crater floor (Figure 7). The pond has a smooth and flat surface with sediments derived from the landslides covering its upper part. The pond surface is overlain by coarse-to-fine debris derived from the landslide producing a hummocky surface along the southern periphery of the pond. In other areas, the pond material shows embayment relationship with the surrounding ridge and floor materials (Figure 7b) and is oriented in the north-south direction toward the landslide wall. The embayment relationship suggests that the pond material formed after the ridge and floor materials. If we consider the ridge materials as the products of young landslide activity, the pond formation could be younger than the landslide activity or at least formed during the late-stage landslide activity. At a few places, a number of ~ E-W oriented sinuous cracks cut across the pond materials (Figure 7a and 7c). The cracks are approximately perpendicular to the flow direction of the sediments that were derived from the landslide surface. The flattening of the pond surface is intriguing. Impact-melt ponds usually tend to have a flat surface, show embayment relationships with the surrounding materials and develop cooling cracks. Although the pond materials show these morphologic characteristics, there are no melt

Figure 5. Morphometric properties of the gullies and landslides. (a) The relationship between the length and width of alcoves (filled diamond), channels (plus) and fans (open circle). While the alcoves and channels show an increase of width with increasing lengths, some of the fans do not show increase of width approximately beyond 300 m length. (b) Length of the fans depends on the length of the alcoves, the longer fans are associated with longer alcoves. (c) Length and width of the boulders measured on the eastern crater interior wall. Most of the boulders are elongated in nature. (d) The slopes of the alcoves and fans are related to each other. The steeper fans are associated with the steeper alcoves, except for a few exceptions.
channels connected to the pond and no melt channels in other places as well. If we consider the pond materials as the impact-melt deposits, the landslide debris should now cover them. Ponds of fine-grained sediments in asteroid surfaces have been observed by several workers, who have interpreted them to have formed by seismic shaking due to micro-meteoroid impacts [e.g., Robinson et al., 2001]. We suggest that the pond materials are finer sediments derived from the landslide activity and the flattened surface is due to the seismic shaking of the host crater. However, presence of an impact-melt deposit beneath the pond materials cannot be ruled out. If the pond materials were the impact-melt deposits, the arcuate ridge materials would have formed by the crater collapse following the impact event and the impact melt ponded around them.

3.3. Small Impacts on the Crater Wall

[16] Careful observation of the LROC NAC data indicates that the interior wall of crater 1 contains many small impact craters (Figure 8). Many of them are associated with landslides in the downslope direction of the host crater interior wall (Figure 8). Some of the craters emplaced in the rim of the host crater have lost a portion of their rims by collapse and contributed to the landslide materials (e.g., Figures 8a, 8h, and 8i). Some craters were emplaced on the crater wall and show bright runout deposits emanating from the exterior wall in the downslope direction of the host crater interior wall (e.g., Figure 8g). A few impact craters do not show any landslide activity in the host crater wall. These either predate or postdate the talus deposits on the crater wall.
It is interesting to note that, although many small impact craters produced landslide activity, none of the large-scale gullies and landslides in Figures 3, 4, and 6 show presence of impact craters in their alcove regions. We also noticed a few impact craters superimposed on the concentric faults near the crater rim (Figure 6c) that caused minor slumping in the downdip direction at the place of impact, but the craters do not produce displacement or slumping in other parts of the fault.

Another possible mechanism triggering the mass wasting process can be rolling and bouncing of boulders on the interior wall. We noticed a few boulder tracks of 700 m length on the crater wall (Figure 9a). Bouncing of boulders has also produced a chain of depressions along the track (Figure 9b). However, none of the boulder tracks produced gullies and landslides on the crater wall. Bouncing of boulders, in some cases, has been attributed to the seismic activity. For example, on Mars, several boulder tracks have been observed on steep slopes in and around faults and are considered to be recent Marsquake activity [e.g., Roberts et al., 2012]. The boulder tracks observed in this study are fresh and are not covered by any other wall materials. Therefore, the rolling and bouncing of the boulders can be a recent activity and might be related to seismic shaking from recent impact events.

4. Spectral Signatures

4.1. Hyper Spectral Imager Data

We analyzed the Hyper Spectral Imager data (HySI) to characterize the spectral properties of the gullies and landslides in the interior wall of the crater and compared them with the ejecta blanket of the host crater (Figure 10a), as the spectra provide insights to composition, extent of space weathering, and the presence of immature debris on the surface. The HySI data contain 64 contiguous spectral bands in the visible and near-infrared wavelength range (420–960 nm) with a spectral resolution of 15 nm and a spatial resolution of 160 m [Kumar et al., 2009]. Figure 10a shows the locations of the spectral samples of gully 1, gully 2, and the landslide that were collected along the traverses passing through the geomorphic features, illustrated in Figures 3, 4, and 6, respectively. Single-pixel HySI spectral samples (acquired on 9 February 2009) were extracted from the areas that cover the alcove head and fan areas of the gullies and landslides, as these are small features. However,
an average value from a small window of 3 × 3 pixels at six locations from the ejecta blanket was considered for the crater exterior (Figure 10a), considering the possible heterogeneity of the ejecta deposit. The spectral radiances were first converted into albedo (assuming Lambertian surface) using effective solar irradiance at each band and sun illumination angle, following the apparent reflectance model suggested by Chavez [1996], and were subsequently normalized to the albedo values of the Apollo 16 soil samples measured in the laboratory [Pieters, 1999]. The albedo profiles are shown in Figures 10b to 10f. The spectral matching methods such as spectral feature fitting, spectral correlation similarity, spectral angle mapper, and spectral similarity were employed [Van der Meer, 2006].

The interior and exterior walls are characterized by contrasting spectral properties. The interior wall samples (gullies and landslides) show a broad dip in the 700–950 nm range (Figures 10b–10d), probably related to a broad absorption feature around 950 nm. In contrast, the ejecta samples show flat spectra in that window (Figure 10e). While the ejecta blanket is considered to be the mixture of fragments that were excavated from the crater, the interior wall contains bedrock exposures, possible impact breccias, talus, and other sediments formed from the gullies and landslides. The spectra of gullies and landslides have many similarities but show subtle differences. In the gullies (Figures 10b and 10c), the alcoves are characterized by lower albedo than the fans, although both of them have considerable spectral similarity. Similarly, in the landslide (Figure 10d), the head regions are characterized by lower albedo than the fan regions. However, the landslides have slightly higher albedo than the gullies. In addition, the optical maturity (OMAT) index provides significant insights to composition and presence of immature debris at the above sites [e.g., Hawke et al., 2004]. We calculated the OMAT values using the HySI reflectance spectra, following Lucey et al. [2000]. In an earlier study, we found that the OMAT

Figure 8. LROC NAC image mosaics M118979214LR and M126057860LR showing the relationship between the small-sized impact craters and the interior wall mass wasting features. (a, b, d, f, g, h, and i) The impact craters on the crater interior wall show significant mass wasting activities. Note the well-developed landslide features emanating from the crater rims. The arrow indicates the direction of the slope and the material transport. (c) An example of impact crater that postdates the colluvial sediments. (e) Colluvial sediments cover the impact crater, suggesting that the sediments flowed down the slope after the impact event. Location and diameter of the impact craters are as follows: (a) 134°11′14″E, 72°8′1″S; 77 m; (b) 134°11′14″E, 72°8′1″S; 63 m; (c) 134°2′3″E, 72°4′52″S; 32 m; (d) 134°4′21″E, 72°13′47″S; 83 m; (e) 134°4′37″E, 72°4′34″S; 60 m; (f) 134°1′16″E, 72°10′42″S; 15 m; (g) 134°4′4″E, 72°6′44″S; 9 m; (h) 133°25′59″E, 72°6′23″S; 50 m; (i) 133°28′28″E, 72°4′42″S; 17 m.
removed the solar irradiance spectrum at the lunar surface. Schrödinger is located at high latitudes, which means that illumination conditions are less than ideal for measuring reflected radiance that is central for imaging spectroscopy measurements. At these latitudes, the low sun angle results in a low overall signal. This causes increased noise levels in reflectance spectra and can result in challenges for the identification of mineralogically diagnostic absorption features. The best locations from which data can be extracted and still exhibit identifiable spectral features are in the sun-facing sides of crater walls and slopes.

(22) To facilitate rapid analysis of the diversity of the spectral properties of the surface, we calculate spectral parameters that summarize key absorption features including the 1 μm integrated band depth (sum of band depths between 0.79 and 1.3 μm), 2 μm integrated band depth (sum of band depths between 1.66 and 2.5 μm), and the ratio between the UV and the visible (0.42/0.75 μm) and the strength of the 2.8 μm hydration absorption. The region of Schrödinger Basin shows a low degree of spectral diversity overall. Kramer et al. [2011] analyzed the general spectral characteristics of the Schrödinger basin and showed that all of the basin floor, rim, and peak-ring materials exhibit unmistakable hydroxyl absorption features [Pieters et al., 2009; Clark, 2009; Sunshine et al., 2009] testifying to the prevalence of OH in the polar regions. They also showed that there was limited spectral diversity in the region. We extracted spectra from crater 1 that show the morphologic features suggestive of gullies. All these spectra are unremarkable and are broadly consistent with the typical spectral properties of the floor of Schrödinger basin and the surrounding basin rim and highlands material exterior to the basin. All these spectra show the 2.8 μm hydration absorption, but in the craters that show gullies, there is no change in the character of the 2.8 μm hydration band. The other work [Kramer et al., 2012, 2013] has located anorthosite, an olivine-bearing lithology, and at least one mixed anorthite and pyroxene lithology in the walls of crater 1.

5. Age of the Gullies, Landslides, and the Host Crater

(23) As indicated by the HySI data, the interior wall of crater 1 is optically more immature compared to the surface of ejecta deposit of the crater, implying that the gullies and landslides are youthful geomorphic features. The lunar surface takes several hundreds of million years to become optically mature, similar to the ejecta surface of the host crater. Hence, the gullies and landslides should be relatively much younger than the host crater. However, it is necessary to constrain the absolute age of the gullies, landslides, and floor materials. Counts of primary impact craters are used to estimate the age of geologic units on the Moon and other planetary surfaces [e.g., Neukum et al., 2001]. This method depends on the assumption that craters form randomly at a known average rate as a function of size. While the primary impacts are thought to meet these conditions, the high-velocity ejecta from large primary impact craters create small secondary craters that are strongly clustered in space and time. Since small or young geologic units may lack enough large craters for reliable statistics, small craters have been used for age estimates [see Ivanov, 2006].
Recent work by Hiesinger et al. [2012] showed that crater counts on the ejecta blankets of Copernican-aged craters can be used to derive absolute model ages that are consistent with the lunar chronology. We chose three areas on the ejecta blanket of crater 1 from the LROC NAC image mosaics (where incidence angle ranged from 71° to 76°) to determine the age of the northern and eastern proximal ejecta and the southwestern distal ejecta (Figure 12). In addition, we selected three areas in the crater interior to determine the age of the surfaces of landslides, gullies, and the debris fan deposit in the crater floor (Figure 12).

In the eastern proximal ejecta, we counted 2067 craters in the diameter range of 5–181 m in an area of 17.1 km²; the crater counting in the surface area provides an absolute model age of 175 Ma for $N(1)$ of $1.46 \times 10^{-4}$ (Figure 13a). In the northern proximal ejecta, we counted 3628 craters in the diameter range of 4–674 m, in an area of 22.1 km²; for this area, $N(1)$ is $1.48 \times 10^{-4}$, which yields an absolute model age of 176 Ma (Figure 13b), similar to the eastern proximal ejecta. The southwestern distal ejecta contains 1750 craters in the diameter range of 4–180 m, in an area of 9.1 km²; $N(1)$ is $3.09 \times 10^{-4}$, thus yielding an absolute model age of 368 Ma (Figure 13b), which is older than the age of other two proximal ejecta areas. A closer examination of the Chandrayaan-1 TMC image suggests that the impact craters in the southern part of the counting area contain a considerable amount of impact craters formed before crater 1, thus indicating a contamination from the preexisting craters. Therefore, we suggest that the proximal ejecta provides a reasonable model age of 175 Ma, as the age of crater 1.

In contrast, the crater interior preserves fewer impact craters than the ejecta blanket, largely because of active wall modification over time. The eastern wall rich in gullies...
contains 100 craters in the diameter range of 5–81 m in an area of 11.8 km². The cumulative crater size-frequency curve of the gully wall (Figure 13c) indicates a possibility of partial resurfacing (for example, multiple gully erosion/deposition events) leading to the removal of craters in the low-diameter range of the distribution [see Michael and Neukum, 2010]. Thus, two slopes at different crater diameter range are observed. A fit of the lunar production function [Neukum et al., 2001] to the crater diameter range of 40–100 m yields $N(1) = 1.54 \times 10^{-7}$, which provides an absolute model age of 18.4 Ma. On the other hand, the fit to the 10–20 m size craters yield a model age of 1.9 Ma for $N(1) = 1.56 \times 10^{-6}$, supporting the hypothesis that a younger debris flow event partially covered an older crater wall containing larger size impact craters. On the other hand, the landslide surface does not show the crater population indicative of partial resurfacing events. The landslide surface (southern to western wall) contains about 293 craters in the diameter range of 3–42 m in an area of 11.1 km², providing a model age of 1.5 Ma for $N(1) = 1.29 \times 10^{-6}$. The landslide surface represents the latest debris flow event that occurred at about the same time as the younger resurfacing event occurred on the gully wall. The floor debris fan deposit at the base of landslide wall provides a mixed age in between the landslide and gully walls (Figure 13d). We counted about 92 craters in the size range of 4–89 m, in an area of 1.0 km², providing an age of 14.5 Ma for $N(1) = 1.22 \times 10^{-5}$, thus preserving the sedimentary record possibly since 15 Ma or before. Therefore, based on these absolute model ages, we conclude that the crater wall and floor materials preserve the landslide and gully activities in the time span of 18–2 Ma as the period of active debris flow processes. However, an occurrence of older debris flow events before 18–2 Ma cannot be ruled out, as the erosion/deposition of the younger events may have removed the remnants of older events.

### 6. Gullies and Landslides from the Low-latitude Regions

[Gullies and landslides are observed within impact craters elsewhere on the Moon. We present three examples from the low-latitude regions, two from the nearside and the other from the farside of the Moon. Figures 14a, 14b, and 14c show the gullies and landslides that occur on the interior of 17 km-diameter Dawes crater (17°13’N, 26°21’E, located between Mare Serenitatis and Mare Tranquillitatis), which formed in mare basalt. These gullies and landslides resemble those in crater 1 of Schrödinger basin, and the gullies exhibit alcove-channel-fan morphology. The alcoves and channels are well developed in the layered bedrock about 100–300 m from the rim crest toward the floor, incising into the bedrock. The fans occur at the channel ends overlying other crater wall sediments and bedrock. On the southeastern wall of Dawes, the gullies and landslides occur about 150–450 m from the crater rim toward the floor (Figure 14c), where the gullies have wide

![Figure 11](image1.png) **Figure 11.** HySI spectral profiles of the ridge, pond, and floor materials. The locations of the spectral samples are shown in Figure 10a. Note the significant spectral similarity between these spectra and the spectra from the gullies and landslides as shown in Figures 10b–10d.

![Figure 12](image2.png) **Figure 12.** LROC NAC image mosaics (M126057860LR and M141391827LR) showing the areas where crater counting was carried out. Three areas at the host crater ejecta blanket and three areas at the crater interior were used for crater counting. Number of craters counted in each area is shown in parentheses. [image credit: NASA/GSFC/Arizona State University].
alcoves and channels with less well-defined fans, which do not exhibit lobate margins as seen in Figures 14a and 14b. A prominent concentric fault scarp is also exposed along the rim, where landslide activity led to the flow of debris down the slope, some of which flowed through the preexisting gullies (Figure 14c). Overall, in Dawes crater, the gullies have a wide range of sizes. The lengths of the prominent alcoves vary from 75 m to 250 m, and width from 40 m to 100 m. The channels are narrower, width varies from 20 m to 60 m, and length from 100 m to 200 m. The fans are larger than the alcoves and channels in terms of length and width; their length varies from 225 m to 350 m and width from 70 m to 130 m.

Another example of a gully from an unnamed 15 km-diameter impact crater (12°35’S, 46°03’E) is shown in Figure 14d that is located about 250 km northwest of Kepler crater in Oceanus Procellarum. The distal rays of Kepler is superimposed on this crater, postdating the unnamed crater. The crater wall is rich in landslide features with a few sporadic occurrences of gullies. The upper wall of the crater exposes several observable layers that are probably mare basalts. In this crater, the gully occurs about 150 m from the crater rim toward the floor, showing the typical alcove-channel-fan morphology. The lengths of the alcove, channel, and fan are 350 m, 150 m, and 400 m, respectively, while the widths of these features are 170 m, 60 m, and 180 m. Similarly, in the lunar highlands, an 11 km-diameter unnamed crater (15°44’N, 177°17’E) that formed in the eastern wall of Virtanen crater (40 km diameter) shows development of gullies in the upper to middle interior wall. Interestingly, these gullies are characterized by short alcoves and channels but have elongated fans (Figure S3), and the presence of gullies confirms that gullies occur on the farside at low latitudes.

Similar to crater 1 of Schrödinger basin, the interior walls of the low-latitude craters contain many small impact craters. Some of them show development of landslides from their rims in the downslope direction of the host crater interior (Figures S4 and S5). Some of the craters have lost a portion of their rims by collapse and contributed to the landslide materials. However, although a few small impact craters triggered small landslides on the crater wall, none of the large-scale gullies and landslides are associated with large-impact craters that are capable of producing these gullies and landslides. Interestingly, the low-latitude craters
also show pervasive development of concentric faults in the crater rim with a spacing range from a few meters to a few hundreds of meters (Figure 15). As shown in craters 1, 2, and 3 of Schrödinger basin, the concentric faults in these low-latitude craters have played an important role in producing the landslides. Some of their landslide materials flowed through the gullies, indicating the channel flow of the landslide sediments in some cases. Formation of the gullies in these craters requires the presence of noncohesive materials in the bedrock, which could be the fault gouge, possibly present in the impact-related radial faults in the crater walls.

7. Discussion: Origin of the Gullies and Landslides

The gullies and landslides reported in this study provide significant new insights to the processes of degradation of lunar impact craters. As suggested by the morphologic observations, model ages derived from crater-counting chronology, and reflectance spectra, the gullies and landslides are youthful geomorphic features that were formed long after the host crater. The age difference between the crater ejecta and the gullies is about an order of magnitude. Therefore, the gullies and landslides are not the products of crater wall collapse that occurs during the final stage of the crater formation. What produced these lunar gullies and landslides? On Mars and Earth, similar features can form under a wide range of surface and subsurface conditions: wind, rainfall, groundwater sapping, and buried ice melting can cause crater wall degradation; water in some form or other is involved in their formation mechanism. In contrast, the surface of the Moon is dry, although recent findings suggest traces of water (not more than a few hundred parts per million) in the upper few millimeters of the lunar regolith in the sunlit areas [e.g., Pieters et al., 2009]. As the study area is close to the lunar South Pole, the crater wall with gullies and landslides may contain water in the similar abundance level. Our analysis of M^2 dataset confirms the presence of OH molecules, but the values do not vary across the crater rim, from exterior to the interior of the crater. Therefore, the role of water in the gully
formation is insignificant. The presence of buried ice beneath the gully features is also ruled out, as the crater wall is in the sunlit area. LROC images of crater 1 taken at different times confirm that most of the crater wall is illuminated by sunlight, and the permanent shadow can exist only in a small area of the northern interior wall and the crater floor immediately south of it. Therefore, water ice cannot be linked to gully formation.

Our observations of small landslides around small impact craters on the interior wall indicate that small-scale mass wasting can occur on the interior wall due to these impacts. Contrasting crater-counting statistics between the interior and exterior walls suggest that most of the small craters on the interior wall were removed by crater wall erosion at or before ~18–2 Ma. Evidently, small impacts on the interior wall can trigger small-scale wall erosion around the impact sites only, but they cannot produce large-scale gullies and landslides that are shown in Figures 3 and 4, where none of those gullies and landslides is associated with impact craters or their relics in them. Therefore, large-scale gullies cannot be linked to small impacts on the interior wall.

Although the gullies and landslides are not the products of small impacts, the ground vibrations from nearby large impacts can trigger large-scale mass wasting on the steep slope of the crater interior. Airless asteroid bodies show evidence of landslides on the crater walls, occurrence of ponds of sediments on the crater floor, and erasure of small impact craters due to impact-induced seismic shaking [see Robinson et al., 2002; Richardson et al., 2004]. Similar processes can be considered as plausible for the lunar gully formation, although the Moon is much larger than the asteroid bodies. Because the age of the gullies is about 18–2 Ma, which is much younger than the host crater (~175 Ma), the impact events that can potentially generate ground accelerations capable of forming the gullies and landslides should be on the order of that age. Crater 1 is surrounded by a few hundred fresh craters in the size of <10 to >2000 m in the area covering a 10 km radius from the crater rim. The large craters among them are not as fresh as the gully-bearing interior wall of the crater. Many of the smaller craters appear to be younger, but they may not represent sufficiently
energetic impacts to produce the ground vibrations needed at the gully locations.

[35] Schrödinger basin contains a few young impact craters (with bright rays) with a diameter of 0.75 km, 0.80 km 0.90 km, 1.25 km, and 2.5 km with an aerial distance of 40 km, 45 km, 175 km, 190 km and 140 km, respectively, from crater 1. These craters may be as fresh as the gullies and landslides and could have formed contemporaneously with the gullies and landslides. These impact events can produce lunar quakes with magnitudes of 4.8, 4.9, 5.0, 5.3 and 6.0, at the impact sites, respectively. The equivalent seismic magnitudes were calculated using the online lunar impact crater calculator by Keith A. Holsapple, assuming rocky impactors into a hard rock target (because the regolith in the young Schrödinger is thin), an impact velocity of 15 km/s at an angle of 45°, and the impact energy–seismic magnitude relationship developed for the Chixculub impact [see Kring, 1993]. These impact-generated lunar quakes may be capable of generating peak ground accelerations at the rim of crater 1 that are adequate to trigger mass wasting processes on the crater wall to form gullies and landslides. Episodic formation of gullies as illustrated in Figures 3 and 4 would indicate the response of crater wall to the successive impacts that occurred at various parts of Schrödinger basin.

[34] It is uncertain why only a few craters (craters 1, 2, and 3) have developed fresh gullies and landslides on the interior walls if these features were arguably formed in response to the seismic shaking that should have affected other nearby craters of the same age or older. One possible explanation could be the presence of concentric faults exclusively present in the rim of these craters. These faults can significantly lower the strength of the crater wall materials, enabling rapid slumping in response to the seismic shaking. Similarly, the radial fractures and faults in the bedrock of the crater interior should have responded in a similar fashion, allowing easier crater wall erosion leading to the gullies that penetrate into the bedrock. The seismic shaking has first erased the regolith layer present on the interior wall, followed by the removal of highly fractured bedrock. In addition, the nature of the rock in the crater walls may determine if sharply defined gullies or broader crater wall slumping occurs. We note that crater 1 was produced in the uplifted peak ring of Schrödinger basin and appears to be composed of crystalline lithologies [Kraner et al., 2012] that may be fractured, whereas other craters of similar size in Schrödinger occur within the impact lithologies of Schrödinger basin. Further quantitative modeling is needed to understand the nature of peak ground accelerations that formed in response to impacts on Schrödinger basin and the nature of mass wasting that they may produce.

[35] The gullies and landslides in the low-latitude craters have many common morphological characteristics of those of the high-latitude craters. Hence, we suggest that the gullies and landslides in the low-latitude impact craters may have formed by similar processes that affected the impact craters in the Schrödinger basin. However, morphometric and spectral properties of the low-latitude gullies and landslides and the sources of seismic shaking are yet to be ascertained. Furthermore, mapping of the global distribution of gullies and landslides on the Moon would demonstrate the spatial and temporal distribution of gullies and landslides and the causes of their formation.

8. Conclusions

[36] A 7 km-diameter fresh crater on the uplifted peak ring of Schrödinger basin has interior walls that have been modified by multiple gullies and landslides. The gullies have an integrated alcove, channel, and fan morphology that begins in the upper crater wall. The gullies are 15 to 560 m long, and the channels are 10 to 360 m wide. The channels, that are 10 to 50 m deep cut through exposed bedrock and carry poorly sorted debris toward the crater floor. Landslides dominate the style of mass wasting in one quadrant of the crater and appear to have occurred along the concentric faults generated by the crater-forming process. The landslides produced a smooth-surfaced pond of debris on the crater floor. In both cases, the debris is optically immature and, thus, very young. Crater counting suggests that the gullies and landslides were formed episodically, one event at ~18 Ma and the latest one at ~2 Ma; the debris fan in the crater floor contains the impact crater record that formed possibly during this period. Crater counting of two regions in the ejecta blanket produces a model age for the host crater of ~175 Ma. Although the lunar gullies appear similar to the gullies on Mars, they occur on steeper slopes than Mars and have poorly developed channels. The gullies and landslides reported here are the products of dry-granular flows generated by seismic effects of one or more younger impacts that occurred within various regions of the Schrödinger basin. The faults present in these fresh impact craters enabled the formation of landslides and gullies in response to seismic shaking. The gullies and landslides also occur on the interior walls of other impact craters elsewhere on the Moon and have similar relationships observed in the Schrödinger basin. The lunar gullies and landslides are therefore interesting sites for future rover and human exploration.

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