Scaling Relationship Between the Wavelength of Longitudinal Ridges and the Thickness of Long Runout Landslides on the Moon

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Abstract The formation mechanism of longitudinal ridges in long runout landslides has been proposed to require ice and/or clay minerals, as low friction materials would allow the spreading of the deposit, causing the development of longitudinal ridges by tensile deformation of the slide. The necessity of ice in the formation of longitudinal ridges has been challenged by the finding that the wavelength of longitudinal ridges is 2–3 times the thickness of the deposit in both ice-free laboratory experiments on rapid granular flows and in a martian and terrestrial long runout landslide, suggesting a scale- and environment-independent mechanism. We conduct morphometric analysis of the longitudinal ridges in two landslides on the Moon, considered ice-free throughout its geological history: the Tsiolkovskiy crater landslide, and the Light Mantle avalanche in Taurus-Littrow Valley. We show that Tsiolkovskiy crater landslide exhibits a scaling relationship between the wavelength of its longitudinal ridges and the thickness of its deposit that is consistent with previous studies, supporting the idea that ice is not a necessary condition for the development of longitudinal ridges. As the Tsiolkovskiy crater landslide is laterally confined, it demonstrates that neither the development of longitudinal ridges nor the occurrence of the scaling relationship between the wavelength of the ridges and the thickness of the deposit depend on the lateral spreading of the deposit. Finally, we use the Light Mantle to test the use of the scaling relationship as a tool to estimate the thickness of the deposit when classical geomorphological methods are not applicable.

Plain Language Summary The origin of a pattern of ridges that extend in the direction of motion (called longitudinal ridges) seen in hypermobile landslides is debated. One hypothesis suggests that the pattern derives from landslides spreading over low friction surfaces, such as ice or clay minerals. However, other studies disagree on the necessity of ice and suggest an environment-independent mechanism, showing that the distance between ridge crests scales with the thickness of the deposit in both ice-free laboratory simulations, and martian and terrestrial slides. In this study, we measure the distance between the ridge crests and calculated the thickness of the Tsiolkovskiy crater landslide on the Moon, in a region where extensive ice cover is excluded through its history. We find a scaling relationship consistent with previous studies, which supports the hypothesis that ice is not necessary to form longitudinal ridges. As the Tsiolkovskiy crater landslide is laterally confined, we conclude that the lateral spreading is also not necessary to form longitudinal ridges but it does affect the thickness of landslides and the distance between the ridges. We use the Apollo 17 Light Mantle avalanche to test the application of the scaling relationship to infer landslide thickness by measuring the distance between ridges.

1. Introduction

On the Moon, mass wasting processes are mainly reported on the steep slopes of impact craters (Kokelaar et al., 2017). These events involve dry granular material, from regolith (sub mm) to boulder sized, and occur in vacuum in the absence of liquid water. These features can reach runout lengths of about 3 km. Recently these specific landslides have been studied in detail, as high-resolution images acquired by the Chandrayaan-1 Terrain Mapping Camera (TMC, 5 m spatial resolution [Kumar & Chowdhury, 2005]) and the Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC, ∼50 cm spatial resolution; Robinson...
et al., 2010) has become available (Boyce et al., 2020; Kokelaar et al., 2017; Kumar et al., 2013; Schmitt et al., 2017).

However, since the early orbital observations of the Moon from the Lunar Orbiter missions and during the Apollo program, two unusually long lunar landslides have been also observed: the Light Mantle deposit unit in the Taurus-Littrow Valley, on the near side (El-Baz, 1972) and the Tsiolkovskiy crater landslide, on the far side (El-Baz, 1972; Guest & Murray, 1969) (Figure 1). The Light Mantle deposit is easily identified by its high albedo, in contrast with the low albedo material forming the valley floor. Howard (1973) and Lucchitta (1977) attributed the presence of the Light Mantle unit to the Tycho impact event, which ejected material that traveled across the Moon and impacted the South Massif, thus triggering the avalanche that now rests in Taurus-Littrow valley. However, Schmitt et al. (2017) and van der Bogert et al. (2019) suggest that the seismic shaking generated by the Lee-Lincoln fault, which runs through Taurus-Littrow valley and may be still active (Watters et al., 2010, 2019), could have triggered the landslide. Recent orbital images reveal that the Light Mantle is composed of two distinct units, a lower- and a higher-optical-reflectance unit. This distinction is also shown by agglutinates and maturity indexes values, thus suggesting the existence of a younger Light Mantle (higher albedo) and an older Light Mantle (lower albedo) (Schmitt et al., 2017; Figure 1e). Interpreted as part of ejecta deposit units (Guest & Murray, 1969; Morse et al., 2018), the Tsiolkovskiy deposit is also commonly interpreted to be a landslide, based on its morphology and on the geometry of the impact that generated the Tsiolkovskiy crater (Boyle et al., 2020). The question on whether the Tsiolkovskiy landform is a landslide or part of ejecta deposits is open to debate and the literature does not offer a final consensus toward either interpretation (we favor the interpretation of the Tsiolkovskiy deposit as a landslide and we invite the reader to read Supporting Information S1, where we provide the argumentation in support of such interpretation). The Light Mantle avalanche and the Tsiolkovskiy crater landslides are the only two long runout landslides known on the Moon. Ancient landslides almost certainly exist on the Moon, however the regolith mixing process has likely obscured such features. Long runout landslides are distinguished for their hypermobility (conventionally expressed by the \( H/L \) ratio \(< 0.6 \) [e.g., Heim, 1932; Legros, 2002], where \( H \) is the height drop and \( L \) describes the horizontal travel length of the slide deposits, both parameters measured from the highest point of the source area to the furthest point of the deposit), but the physics behind such behavior is still poorly understood. The existence of these features on the Moon is intriguing, as the origin of the reduction of friction required to explain the hypermobility remains unknown on a dry, airless body. For the Light Mantle avalanche, Schmitt et al. (2017) suggest that the release of solar wind implanted volatiles may have fluidized the landslide in a way comparable to long runout pyroclastic flows.

Although the Tsiolkovskiy and the Light Mantle landslides have different morphological aspects, which are due to differences in their formation processes, including different preparatory and triggering factors, and modality of transport, both landslide deposits are marked by a longitudinal linear pattern that results from the existence of longitudinal ridges and troughs. On the surface of the Light Mantle avalanches, such morphological structures are subtle and extend from the base of the slope to about half the length of the deposit (e.g., El-Baz, 1972; Schmitt et al., 2017; Wolfe et al., 1981). On the other hand, the surface of the Tsiolkovskiy crater landslide shows prominent longitudinal ridges and furrows that stretch for almost the entire extent of the deposit (e.g., Boyle et al., 2020; El-Baz, 1972; Guest & Murray, 1969). These distinctive longitudinal structures are common in large-scale mass movements across the Solar System (e.g., Earth [Dufresne & Davies, 2009; Magnarini et al., 2021; Shreve, 1966]; the Moon [Boyle et al., 2020; Howard, 1973; Schmitt et al., 2017]; Mars [Lucchitta, 1979; Magnarini et al., 2019]; Ceres [Schmidt et al., 2017]; Iapetus [Singer et al., 2012]). However, the origin and the relationship with the emplacement of long runout landslides have been a matter of discussion (Figure 2), in particular whether they are linked to environmental conditions, such as the presence of friction reducing basal ice or clay minerals (De Blasio et al., 2011; Dufresne & Davies, 2009), or linked to mechanical instabilities within the rapid moving flow (Borzsonyi et al., 2009; Magnarini et al., 2019), or linked to the propagation of acoustic waves within the landslide (Magnarini et al., 2021).

Ice-free laboratory experiments on rapid granular flows (Borzsonyi et al., 2009; Forterre & Pouliquen, 2001) and studies of the martian Coprates Labes landslide (Magnarini et al., 2019) and the terrestrial El Magnifico landslide (Magnarini et al., 2021) have showed that the wavelength of the ridges is consistently 2 to 3 times...
Figure 1.
the thickness of the landslide deposit. In light of the debate about the formation mechanism of longitudinal ridges and the possible influence of an icy basal surface, the presence of longitudinal ridges in lunar landslides offers an ideal site to further investigate the recurrence of the scaling relationship between the wavelength of the ridges and the thickness of the landslide deposit on a planetary body that is considered to be ice-free throughout its geological time. Building on the study of (Magnarini et al., 2019, 2021), here we use high resolution imagery and topographic datasets to conduct morphometric analysis of the Tsiokovskiy crater landslide and the Light Mantle landslides.

Figure 2. Mechanisms proposed for the formation of longitudinal ridges in long runout landslides. Dufresne and Davies (2009) and De Blasio (2011) suggest that that longitudinal ridges are the result of the tensile deformation that landslides undergo during their emplacement over low friction surfaces, of which an icy surface is the favored condition. Instead, Magnarini et al. (2019, 2021) propose environment-independent mechanisms that rely on mechanical instability within the flow and pattern-forming acoustic waves propagating within the slide, respectively. Further description of these mechanisms can be found in Supporting Information S1.
2. Study Regions

2.1. The Tsiolkovskiy Crater Landslide

The Tsiolkovskiy crater is an easily recognizable structure on the far side of the Moon (Figure 1), for it is filled with dark basaltic material in contrast with extensive distribution of anorthositic megaregolith and paucity of mare deposit that are typical of the far side (e.g., Pieters & Tompkins, 1999). A range of ages have been assigned to the Tsiolkovskiy impact, yet all studies agree that the event occurred in the Imbrium Era (3.2–3.8 Gya) (e.g., Boyce et al., 2020; Pasckert et al., 2015; Tyrie, 1988). The Tsiolkovskiy impact partially overlapped the Fermi crater (Figure 3a). Being an oblique impact, it produced an asymmetric ejecta deposit, leaving an ejecta-forbidden area on the west-northwest side, which partially happens to coincide with the Fermi crater floor (Guest & Murray, 1969). Within this area, Guest and Murray (1969) identified a unit that is morphologically different from the ejecta blanket and likely reflects the mechanism of emplacement. The hypothesis is that this ejecta flow unit developed at the foot of the crater rim slump as a density current simultaneously with formation of the rim. Morse et al. (2018) do not consider this unit separately, mapping it as part of the ejecta blanket deposits. Conversely, Wu et al. (1972), Masursky et al. (1978), and Boyce et al. (2020) interpret the unit as a giant landslide. Access to high resolution images acquired by Lunar Reconnaissance Orbiter’s LROC allowed Boyce et al. (2020) to identify at least 3 morphologically distinct units...
different units that make up the landslide deposit, which formed as a single event 3.55 ± 0.1 Ga, following the collapse of the northwest rim of Tsiolkovskiy crater.

The Tsiolkovskiy crater landslide has morphological and morphometric aspects that are strikingly similar to giant martian long runout landslides. The Tsiolkovskiy landslide extends for about 50 km ($L$) on the broadly flat floor of the Fermi crater and has a vertical drop of about 3 km ($H$) (Figure 3c). These values give an $H/L$ ratio of about 0.06, a value that shows the high mobility of the landslide. Its thickness is estimated to be several hundred meters in the proximal areas close to the crater rim that progressively reduces to about 100 m in the distal areas (e.g., Boyce et al., 2020; Guest & Murray, 1969; Wu et al., 1972). Although the development of a giant landslide outwards from a crater appears to be a unique case on the Moon, similar development has been observed on Ceres (Schmidt et al., 2017) and on Mars (Crosta et al., 2018) (Figures S1–S5 in Supporting Information S1).

The landslide deposit is marked by longitudinal ridges that stretch for almost the entire length of the deposit in the direction of the flow (Figure 3b), in a comparable fashion to those observed in martian long runout landslides (e.g., Lucchitta, 1979; Magnarini et al., 2019). The longitudinal ridges are most prominent in the north part of the landslide deposit, whereas in the other parts of the landslide deposit ridges are less obvious or apparently absent. Boyce et al. (2020) remark that the presence of longitudinal ridges on the Moon, a planetary body that has been broadly ice-free throughout its geological time, clearly suggests that the ice is not required to develop these morphologies.

### 2.2. The Light Mantle Avalanches

The Light Mantle deposit unit in the Taurus-Littrow Valley (Figure 1) was one of the primary geological targets of the Apollo 17 mission. The Taurus-Littrow Valley is interpreted as being originated from the effects of dilation stress following either the Serenitatis impact event (Head, 1974), or Imbrium or Crisium basin-forming events (Fassett et al., 2011; Spudis et al., 2011). The mountains that bound the valley form part of the uplifted basin rim of the Serenitatis basin.

Originally thought to represent a single event, the Light Mantle deposit is probably formed of two distinct units (Iqbal et al., 2019; Schmitt et al., 2017), which developed from the NE-facing slope of the South Massif (Figure 4a). Schmitt et al. (2017) showed that the two units have different ages: 70–110 Myr for the youngest deposit, and possibly twice this age for the oldest deposit. As the origin of the Light Mantle avalanche was attributed to the secondary impacts related to the Tycho impact event (Howard, 1973; Lucchitta, 1977), the presence of two units has important implications in regard to determining the triggering events, ruling out the Tycho event as the trigger mechanism of either unit of the Light Mantle (Schmitt et al., 2017; van der Bogert et al., 2019) while motion along the Lee-Lincoln scarp is a possible source for the trigger of one of the events. Although a clearly identifiable source area is lacking, the avalanches consist of material similar to the anorthositic impact-breccia-derived regolith on the slope of the South Massif (Schmitt, 1973; Wolfe et al., 1981). The Light Mantle covers an area of 20 km$^2$ (Howard, 1973; Schmitt et al., 2017). Howard (1973) estimated an average thickness of 10 m, which gives a volume of 0.2 km$^3$. More recent considerations on impact craters and mobilized material provide a minimum volume estimation of 0.06 km$^3$ (Schmitt et al., 2017). The younger avalanche traveled a total horizontal distance ($L$) of about 10 km, of which 5 km along the sub-horizontal valley floor, and has a vertical drop ($H$) of about 2.2 km from the top rim of the South Massif (Figure 4b). Given the high mobility that has characterized the emplacement of the younger Light Mantle avalanche deposit ($H/L$ ratio is 0.22), and following Apollo 17 field work activity in the Taurus-Littrow Valley and subsequent sample analysis, gas fluidization due to release of solar wind volatiles by agitation has been speculated to be the principal mechanism involved in the long runout, although acoustic fluidization could be an alternative mechanism (Schmitt et al., 2017).

The younger Light Mantle avalanche is cut by the Lee-Lincoln thrust fault (Figure 4a), which extends across the Taurus-Littrow Valley, from the North Massif to the South Massif with an approximate N-S trend (Schmitt, 1973; Scott, 1973; Watters et al., 2010). Morphologically, the Lee-Lincoln thrust fault is expressed as a lobate scarp and it formed as a result of continued thermal contraction of a cooling Moon (Watters et al., 2010). As other lunar lobate scarps, the Lee-Lincoln thrust fault appears to be a young tectonic structure (e.g., Binder & Gunga, 1985; Watters et al., 2010), with a suggested bracket age of about 70–110 Ma for
its occurrence or reactivation (Schmitt et al., 2017; van der Bogert et al., 2019). This suggested age derives from crater-size frequency distribution measurements (van der Bogert et al., 2012, 2019), minimum exposure ages of boulders at the base of the South Massif, and considerations on its spatial association with the Nansen Moat and its burial by the Light Mantle avalanche (Schmitt et al., 2017). In regard to the avalanche triggering mechanism, the apparent contemporaneity of the youngest Light Mantle avalanche unit and the activity of the Lee-Lincoln thrust fault (van der Bogert et al., 2019) points to the faulting activity as plausible alternative explanations to the secondary impacts derived from the Tycho impact event: either through displacement of the valley floor from the South Massif, causing slope destabilization following the removal of support at the base of the slope (Schmitt et al., 2017); or through seismic shaking (Watters et al., 2019).

Apart from being characterized by high albedo material that makes its identification unequivocal on the darker valley floor from image data (Figure 4c), the two units of the Light Mantle avalanche do not have raised edges that clearly define their morphological existence. As a matter of fact, Apollo 17 astronauts Harrison Schmitt and Gene Cernan, while driving toward Station 2, were not able to tell where the contact

Figure 4. The Light Mantle avalanche. (a) Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC)-derived elevation map of Taurus-Littrow Valley, where the Apollo 17 landed in 1972 (red dot); the black line marks the Light Mantle avalanche deposit; the red line traces the Lee-Lincoln scarp, which is considered representing the superficial expression of a SW-dipping, shallow thrust fault that runs through the North Massif and the Taurus-Littrow Valley, including the Light Mantle avalanche; the continuation of the scarp to the south becomes less obvious and its superficial evidence is not clear. (b) Longitudinal topographic profile of the South Massif and of the landslide deposit. (c) Close-up of the Light Mantle Avalanche and of the base of the South Massif; longitudinal ridges that characterize the landslide deposit are mapped in red. (d) Details of the LROC NAC image M1276388423: longitudinal ridges are identified with red arrow pairs.
between the valley floor and the avalanche material was, as the change in albedo appeared subtle from the ground (EVA-2, at mission elapsed times of [H:M:S] 142:04:27; 142:05:31 [Apollo Lunar Surface Journal, 2015]). However, the astronauts recognized that they were on the deposit as the material into which craters had penetrated was different and their rims and walls brighter (EVA-2, 142:04:10; 142:05:31; 142:05:42; 142:09:14 [Apollo Lunar Surface Journal, 2015]). Dispersion of the original contact between the avalanche material and the darker floor material over at least 70 Myr of regolith formation has likely resulted in this obscuration.

The youngest avalanche deposit exhibits longitudinal ridges that extend from the base of the South Massif for about half the length of the deposit (Howard, 1973) (Figures 4c and 4d), disappearing in the distal section of the deposit. A few longitudinal ridges are also visible on the older unit of the avalanche deposit (Figure 4c). As noted by Schmitt et al. (2017), the presence of such structures may represent a record of the flow dynamics of the avalanche.

3. Data and Methods

3.1. Satellite Image Data and Stereo-Derived Topography Data

To study the Tsiolkovskiy crater landslide, we used the LROC WAC global digital elevation model (100 m/px resolution) available at the NASA Planetary Data System. We produced two LROC NAC stereo-derived digital elevation models (DEMs) (4 m/px resolution) and orthoimages (1 m/px resolution) using the USGS Integrated Software for Imagers and Spectrometers (ISIS) and the BAE Systems commercial photogrammetry suite SOCET SET, and standard methods and procedures (e.g., Henriksen et al., 2017). We estimate the horizontal precision of these DEMs to be the same as the spatial resolution (i.e., 4 m), and the vertical precision (assuming 1/5 pixel misregistration) to be ~0.5 m (Henriksen et al., 2017). These products (Table 1) were used to conduct detailed morphological mapping and detailed morphometric analysis of part of the Tsiolkovskiy crater landslide deposit (Figure 5a).

To obtain the regional topography of the Taurus-Littrow Valley, we made used of LROC NAC-derived digital elevation models (5 m/px resolution; vertical precision ~0.5 m) and orthoimages (120 cm/px resolution) available at the NASA Planetary Data System (Henriksen et al., 2017). To conduct morphological mapping and morphometric analysis of the Light Mantle avalanche deposit we used digital elevation model (150 cm/px resolution) and orthoimage (50 cm/px resolution) products provided by Haase et al. (2019), and LROC NAC low sun-angle image M1276388423R (Table 1).

3.2. Morphological Characterization and Thickness Estimation

In ArcGIS, we used digital elevation models and orthoimages to map longitudinal ridges on the landslide deposits (Figures 3b and 4c). At the Tsiolkovskiy crater landslide, six transverse profiles were traced: three profiles, each about 10/12 km long, within the areas covered by the NAC-derived DEM generated for this
In order to extend our morphometric analysis to almost the entire extent of the deposit exhibiting longitudinal ridges, we decided to use both the WAC-derived DEM and the NAC-derived DEM. In order to do so, we first checked that the thickness estimated with the WAC-derived DEM is comparable with the thickness derived from the NAC-derive DEM, as we assumed the latter more accurate. We compared the thickness estimated along profile P1, P2, and P3 obtained with WAC-derived DEM and NAC-derived DEM. As the difference between the WAC-derived and the NAC-derived thickness is negligible (see Figure S7 in Supporting Information S1), we show that the morphometric analysis can be conducted using both datasets. Along each profile, the distance between adjacent ridge crests were measured. In order to estimate the thickness of the Tsolkovskiy crater landslide, we built the topography of the valley floor underneath the deposit by interpolating topographic contours of the area around the landslides (see Supporting Information S1) and applied the method, including Python scripts and error estimation, as in Magnarini et al. (2019). Similarly, two transverse profiles were traced on the Light Mantle avalanche deposit (P7 and P8 in Figure 7a) and the distance between adjacent ridge crests were measured.

Figure 5. Morphometric analysis of longitudinal ridges at the Tsolkovskiy crater landslide using Narrow Angle Camera (NAC)-derived digital elevation model. (a) Lunar Reconnaissance Orbiter (LROC) NAC-derived digital elevation models over LROC WAC base image; longitudinal ridges are mapped with blue lines; fuchsia lines are the transversal profiles (P1-A/A’, P2-B/B’, P3-C/C’) along which the morphometric analysis of the ridges was conducted and the thickness of the landslide deposit was estimated. (b) Plot showing the scaling relationship between the spacing between longitudinal ridges and the thickness of the landslide deposit found in ice-free laboratory experiments on rapid granular flows (gray area); the dark blue dots represent the results from the morphometric analysis conducted at the Tsolkovskiy crater landslide; results from the same analysis conducted for other case studies are also showed (light blue dots: Coprates Labes on Mars; yellow dots: El Magnifico landslide on Earth). (b–d) Transversal profiles at P1, P2, P3, respectively; black lines are the landslide deposit topographic profiles, orange ticks show the location of longitudinal ridges as mapped in (a), green lines show the landslide basal surface and correspond to the reconstructed Fermi crater floor surface.
4. Results

In this section, we present the results from the morphometric analysis of the longitudinal ridges that we obtained following the approach used in Magnarini et al. (2019).

4.1. Morphometric Analysis of the Tsiolkovskiy Crater Landslide

We conducted the morphometric analysis along the six transverse profiles that were traced on the two LROC NAC DEMs and orthoimages produced for this study (Figure 5) and on the WAC DEM and global mosaic (Figure 6). At each profile, we measured the distance between the ridges and obtained an average...
spacing, which was considered representative of the wavelength of the ridges (S in Table 2). Using the LROC WAC DEM and the interpolation-derived basal surface, we also calculated the average thickness of the deposit corresponding to each profile (T in Table 2, Figures 5b–5d and 6c–6e). For each profile, we calculated the ratio between the average spacing between the ridges and the average thickness of the landslide deposit (S/T ratio in Table 2).

Figure 6b shows the S/T ratio values found at the six profiles and how they compare with results from previous studies (Magnarini et al., 2019, 2021). The S/T ratio values obtained with the WAC-derived DEM fall within the range of the scaling relationship between the two parameters found in laboratory experiments on rapid granular flows, which is represented by the gray area: Profile 4 shows an S/T ratio of 2.25, Profile 5 shows an S/T ratio of 2.42, and Profile 6 shows an S/T ratio of 2.32. Instead, for the S/T ratio values obtained with the NAC-derived DEM, only Profile 3 shows an S/T ratio of 2.04 that falls within the range of the scaling relationship between the two parameters found in laboratory experiments on rapid granular flows. However, Profile 1 and Profile 2 have S/T ratio values of 1.9 and 1.89, respectively, just slightly below the minimum value of the range of the scaling relationship.

Figure 7. Morphometric analysis of the longitudinal ridges at the Light Mantle avalanche. (a) Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC)-derived digital elevation model (Haase et al., 2019) over LROC NAC base image mosaic; longitudinal ridges are mapped with blue lines; fuchsia lines are the transversal profiles (P7-A/A', P8-B/B') along which the morphometric analysis of the ridges was conducted. (b) Plot showing the scaling relationship between the spacing between longitudinal ridges and the thickness of the landslide deposit found in ice-free laboratory experiments on rapid granular flows (gray area); we used the scaling relationship to infer a minimum and a maximum value of the landslide deposit, given that we have an average spacing between the ridges; aquamarine lines and values refer to P7 and dark green lines and values refer to P8. (c and d) Transversal profiles at P7 and P8, respectively; black lines are the landslide deposit topographic profiles, orange ticks show the location of longitudinal ridges as mapped in (a).
4.2. Morphometric Analysis of the Light Mantle Avalanche Deposit

We conducted the morphometric analysis along the two transverse profiles that were traced on the LROC DEM produced by Haase et al. (2019) (Figure 7a). At each profile, we measured the distance between the ridges and obtained an average spacing, which was considered representative of the wavelength of the ridges (Figures 7c and 7d; $S$ in Table 2). As the Light Mantle does not show a deposit that unequivocally stands out on the surface of the Taurus-Littrow Valley and the presence of the Lee-Lincoln fault further complicates the geomorphology of the area, it was not possible to estimate the thickness of the landslide deposit using the interpolation method as done for the Tsiolkovskiy crater landslide. The incapability of providing an estimate of the thickness of the landslide deposit in correspondence of the transverse profiles does not allow to calculate the $S/T$ ratio for the Light Mantle avalanche. However, assuming that the expected range of the $S/T$ ratio is also valid for the Light Mantle avalanche, we use the ratio to provide an estimation of the thickness of the landslide deposit, given that we have a value of $S$ (Figure 7b; Table 2). The obtained values of thickness will be discussed and commented upon thickness estimations based on considerations on impact craters and mobilized material provided by Schmitt et al. (2017).

5. Discussion

5.1. Scaling Relationship Between the Wavelength of the Ridges and the Thickness of the Landslide Deposit

The results of the morphometric analysis conducted for the Tsiolkovskiy crater landslide show the existence of a scaling relationship between the thickness ($T$) of the Tsiolkovskiy crater landslide deposit and the wavelength ($S$) of the longitudinal ridges ($S = 2 \times T$). The value of the ratio ($\sim 2$) is in agreement with values reported in the literature: ice-free laboratory experiments on rapid granular flows demonstrated that the wavelength of the ridges is within 2–3 times the value of the thickness of the flow (Borzsonyi et al., 2009; Forterre & Pouliquen, 2001); at field scale, the same scaling relationship have been found for the Coprates Labes long runout landslide, in Valles Marineris, Mars (Magnarini et al., 2019) and the El Magnifico long runout landslide, in Chile, Earth (Magnarini et al., 2021) (Figure 6b).

The morphological similarity between the longitudinal ridges that characterize the deposit of martian long runout landslides and the longitudinal features of the deposit of terrestrial landslides emplaced on glaciers has been noted for a long time (e.g., Lucchitta, 1978, 1979). The existence of these morphologies in martian landslides has been suggested to represent evidence for the presence of ice at the time of landslide emplacement. According to Dufresne and Davies (2009) and De Blasio (2011), the presence of a basal icy surface would explain both the hypermobility of long runout landslides, by providing a low friction sliding surface,
and the formation of longitudinal ridges, by tensile deformation of the sliding mass due to spreading over a low-friction surface.

However, ice-free laboratory experiments on rapid granular flows by Forterre and Pouliquen (2001) demonstrated that ice is not a necessary condition for the development of longitudinal ridges, which instead develop from a mechanical instability within the flow that is generated by the interplay of a rough surface and the high velocity of the flow. Moreover, it was found that the wavelength of the laboratory-scale longitudinal ridges is always 2 to 3 times the thickness of the flow. For the first time at field scale, Magnarini et al. (2019) found that the same scaling relationship characterized the longitudinal ridges and the thickness of the Coprates Labes landslide, on Mars, therefore concluding that the presence of longitudinal ridges in martian long runout landslides should not be used as evidence for the presence of ice on Mars at the time of landslide emplacement.

The presence of longitudinal ridges at the Tsiolkovskiy crater landslide should be on its own an argument against the idea that a basal icy surface is required to develop such structures (Boyce et al., 2020), as it is well established that the Moon has been free from such large-scale ice throughout its geological time, particularly at equatorial regions. Indeed, the finding of the scaling relationship between the wavelength of the longitudinal ridges and the thickness of the landslide deposit at the Tsiolkovskiy crater landslide provides support to the idea that ice is not a necessary condition for the development of longitudinal ridges in long runout landslides. Moreover, this conclusion is also further reinforced by the finding of the same scaling relationship at the terrestrial El Magnifico landslide, in the north region of the Atacama Desert, Chile, where ice was also not involved (Magnarini et al., 2021).

The recurrence of the same scaling relationship between the wavelength of the longitudinal ridges and the thickness of the landslide deposit on three different planetary bodies (i.e., Mars [Magnarini et al., 2019], Earth [Magnarini et al., 2021], and the Moon [this study]) suggests that the mechanism involved in the formation of longitudinal ridges is independent of environmental conditions. Moreover, it suggests that the mechanism is not sensitive to the gravitational acceleration. It is beyond the scope of this study to discuss the type of formation mechanism of longitudinal ridges, however we suggest that it is likely linked to the high-energy/high-speed nature of long runout landslide emplacement events. Indeed, this consideration can be plausibly extended to the origin of longitudinal grooves observed in martian double layer ejecta deposit, as their morphology and behavior is closely related to the longitudinal ridges in long runout landslides (Boyce et al., 2014). Future morphometric analysis of longitudinal ridges and grooves of double layer ejecta deposit is required in order to find whether the same scaling relationship reported in long runout landslide also occurs.

Finally, we note that at the Light Mantle landslide longitudinal ridges decay rapidly with distance and then disappear in the distal half of the deposit, in contrast with the case of the Tsiolkovskiy crater landslide and the Coprates Labes landslide on Mars. This may suggest that the Light Mantle, following the increase of its thickness that occurs in the proximal half of the deposit, fails to maintain a critical thickness to support the development of longitudinal ridges. Future laboratory experiment or rapid granular flows should aim to investigate the potential existence of a critical minimum thickness, a parameter that could yield further constraints about the mechanism responsible for the formation of longitudinal ridges.

5.2. The Effect of Lateral Confinement on the Thickness of Landslide Deposit and on the Behavior of Longitudinal Ridges

Dufresne and Davies (2009) and De Blasio (2011) have suggested formation mechanisms of longitudinal ridges in long runout landslides that involve tensile deformation of the sliding mass (i.e., a process similar to boudinage formation by necking), which is favored by lateral spreading over a lubricating basal surface. However, there exist examples of laterally confined long runout landslides that nevertheless exhibit longitudinal ridges, therefore indicating that these morphologies can also form in the absence of lateral spreading. Amongst these cases is the Tsiolkovskiy crater landslide. The north part of this landslide (i.e., the part where the morphometric analysis was conducted for this study; the “North Slide” in Boyce et al., 2020) is laterally confined to the east by the internal rim slope of the Fermi crater for about 20 km; moreover, the ejecta deposit of the Tsiolkovskiy impact event, which partially fills the Fermi crater, forms a topographic high to
the south of the landslide (Figures 1f and S9 in Supporting Information S1). We also identified two martian long runout landslides characterized by remarkable longitudinal ridges that were confined at the time of their emplacement: a landslide in Tithonium Chasma is laterally confined by high relief constituted by the chasmata wall to the east and deposits (likely a combination of sedimentary and mass-wasting deposits) to the west (Figure 8a); and a landslide in Ophir Chasma that was obstructed and diverted by interior layered deposit (ILDs) mounds (Grindrod & Warner, 2014, Figure 8b).

Although the lateral confinement of long runout landslides does not preclude the development of longitudinal ridges, it does affect their behavior, as well as controlling the thickness of the landslide deposit. In unconfined long runout landslides, generally, the landslide spreads laterally and the deposit thickness gradually decreases with distance, terminating always with roughly the same thickness, tens of meters (Melosh, 1983). As the landslide spreads laterally, the ridges diverge and, as they diverge, the spacing between them increases. However, according to the scaling relationship between the wavelength of longitudinal ridges and the thickness of the landslide deposit, as the slide gets thinner, the distance between the ridges must decrease. The situation is solved by the appearance of new smaller ridges in between diverging ridges (Magnarini et al., 2019). In this way, the actual distance between ridges decreases while the thickness of the deposit decrease, in accordance with the scaling relationship. Instead, laterally confined long runout landslides show more constant thickness throughout their length, in the range of hundreds of meters. As the thickness of the deposit does not vary much, also the distance between the ridges does not change considerably, explaining why the longitudinal ridges remain fairly parallel.

We conclude that the spreading of long runout landslides does not cause the development of longitudinal ridges but it does cause the landslide deposits to become thinner and the ridges to diverge (Figure 9).

![Figure 8](image_url) Laterally confined landslides. (a) The long runout landslide in Tithonium Chasma, Mars, is laterally confined by high relief; the part of the landslide deposit confined shows parallel longitudinal ridges; the corrugated terminal part is made by compressional ridges that generate due to frontal confinement of the landslide (MRO CTX image mosaic: D04_028673_1752, P17_007707_1751, F16_042031_1744, J03_045987_1756). (b) The long runout landslide in Ophir Chasma, Mars, was confined and diverted by interior layered deposits (ILDs) at the time of emplacement and they have now retreated due to erosion; the diverted lobe bends and consequently do also longitudinal ridges, which nevertheless remain parallel due to the lateral confinement (MRO CTX-derived orthoimage: P22_009750_1765–B01_009895_1764; modified after Grindrod & Warner, 2014).
the thickness of the landslide deposit is maintained. Therefore, we conclude that is the thickness of the landslide that dictates the behavior of longitudinal ridges. This observation reinforces the conclusion that whatever the mechanism involved in the origin of longitudinal ridges, it is environmentally independent, thickness-dependent, and likely to be intrinsic to the high-velocity nature of long runout landslides.

5.3. Estimating Deposit Thickness Based on Expected Scaling With the Wavelength of Longitudinal Ridges

Given the validity of the scaling relationship between the wavelength of longitudinal ridges and the thickness of landslide deposits, the ratio between these two parameters can be applied to infer the thickness of the deposits where its calculation is not otherwise possible using typical methods in planetary geomorphology (e.g., estimation based on the elevation of the deposit rim above the valley floor; interpolation of the valley floor topography to reconstruct the surface underneath the deposit). This is the case of the Light Mantle landslide in Taurus-Littrow Valley, as its deposit does not have edges that stand out topographically over the valley floor and the presence of the Lee-Lincoln scarp cutting through the deposit complicates the geological relationship between different units.

An estimated average thickness of 10 m was initially given by Howard (1973). Based on considerations on impact craters and mobilized material, Schmitt et al. (2017) provide thickness estimation at different locations of the landslide deposit: at least 3 m in the NW portion (the furthest part, where Shorty crater is located), at least 6–10 m in the SE portion, and less than 16 m at the base of the South Massif. These estimates are based on the sizes of craters that penetrate the Light Mantle and excavated material buried by the landslide, and represent upper-limits on the thickness of the deposit.

As we have calculated the average wavelength of longitudinal ridges \( S \) along two different transverse profiles (Figure 7, P7 and P8), we derived a minimum \( T_{\text{min}} \) and a maximum \( T_{\text{max}} \) thickness of the landslide deposit at these two different locations by applying the scaling relationship between the two parameters (i.e., \( T_{\text{min}} = S/3 \) and \( T_{\text{max}} = S/2 \); Figure 7b, shaded cells in Table 2). The profile P7 is located at the base of
the South Massif and so the range of thickness we obtained at P7 (24.41–36.61 m) can be compared with the estimated thickness at the base of the South Massif provided by Schmitt et al. (2017) (<16 m). The profile P8 is located less than 1 km further along the direction of the flow and no previous estimation of the thickness at this area was given; the range of thickness we obtained at P8 (41.37–62.06 m) is almost double the value obtained at the base of the South Massif. The thickness of unconfined landslide deposits is usually expected to decrease with distance. In order to account for the increase of thickness, two possible explanations can be invoked: (a) the existence of a topographically depressed area prior to the landslide event that is now entirely filled with landslide debris and/or (b) the scouring potential of the high speed landslide impacting on the valley floor, causing removal of valley floor material, then entrained into the landslide debris. Analysis of material collected at Station 3, particularly the double core tube sampled there (73001/2) may reveal dynamics of the deposit and how much material was entrained in its emplacement.

However, using the morphometry of longitudinal ridges to infer the thickness of the deposit must include considerations about the modification of surface topography due to impact cratering and seismic shaking. These processes contribute, to different degrees, in the re-distribution of surface material and possibly causing the obliteration of the original morphology. The activity of lunar lobate scarps has been found responsible for altering the aspect of crater rim (i.e., morphological freshness), thus causing seismic resetting of crater size-frequency distribution (van der Bogert et al., 2012, 2018). The morphological freshness of craters present on the deposit of the Light Mantle landslide has been modified by the seismic shaking generated by the activity of the Lee-Lincoln scarp, which run through the Taurus-Littrow Valley and the deposit of the Light Mantle landslide (van der Bogert et al., 2019). Watters et al. (2019) suggest that the Lee-Lincoln thrust fault may be still active. Therefore Taurus-Littrow valley may represent an important site where to study recent and active geological processes on the Moon. If seismic shaking affected the aspect of the craters on the Light Mantle landslide, we should expect that it would also modify the morphology of longitudinal ridges. For instance, seismic shaking could cause re-distribution of material downslope, from the top of ridges to the bottom of troughs. This material re-distribution can cause the attenuation of the morphology and even the total removal of topographic evidence of longitudinal ridges, both situations resulting in the underestimation of the actual number of longitudinal ridges formed during the emplacement of the landslide. Consequently, the underestimation of the number of longitudinal ridges would result in the overestimation of the distance between the ridges (i.e., wavelength of the ridges), thus in the overestimation of the thickness of the deposit. Therefore, caution is necessary in the use of the scaling relationship between the wavelength of longitudinal ridges and the thickness of landslide deposit in order to derive the thickness, especially in the case of relatively small scale longitudinal ridges (such as longitudinal ridges of the Light Mantle landslide compared to the longitudinal ridges of the Tsiolkovskiy crater landslide), which are more easily and quickly obliterated.

6. Conclusions

We report on the occurrence of a scaling relationship between the wavelength of longitudinal ridges and the thickness of the Tsiolkovskiy crater landslide deposit. We found that the wavelength of the longitudinal ridges is ∼2 times the thickness of the deposit at three different locations of the deposit. This value is consistent with previous findings in experimental work on rapid granular flows and field-scale long runout landslides on Mars and on Earth. The significance of the existence of such scaling relationship across scales, planetary bodies, and lithologies is important in the light of the debate around the formation mechanism of longitudinal ridges in long runout landslides. Its recurrence clearly suggests that the presence of longitudinal ridges cannot be used to infer environmental conditions or lithology involved during the emplacement of long runout landslides. We suggest that similar morphometric analysis should be conducted for longitudinal ridges that characterize double layer ejecta of martian impact craters in order to investigate whether a scaling relationship between the wavelength of the ridges and the ejecta thickness also exists for similar morphologies formed during different geological process. This may further elucidate the relationship between longitudinal ridge morphology and high-energy/high-speed events.
Data Availability Statement

The standard data products used in the study are available from the NASA PDS: LROC WAC-derived DEM (Scholten et al., 2012) is found at Lunar Orbital Data Explorer—Data Product Page (wustl.edu); LROC NAC-derived DEM and LROC NAC-derived orthoimage (Henriksen et al., 2017) are found at Lunar Orbital Data Explorer—Data Product Page (wustl.edu). The LROC DEMs and orthoimages produced for this work are provided through the data repository Figshare (Magnarini, 2021).

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