The Tsiolkovskiy crater landslide, the moon: An LROC view

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ABSTRACT

Evidence suggests that the lobate flow feature that extends ~72 km outward from the western rim of Tsiolkovskiy crater is a long runout landslide. This landslide exhibits three (possibly four) morphologically different parts, likely caused by local conditions. All of these, plus the ejecta of Tsiolkovskiy crater, and its mare fill are approximately of the same crater model age, i.e., ~3.55 ± 0.1 Ga. The enormous size of this landslide is unique on the Moon and is a result of a combination of several geometric factors (e.g., its location relative to Fermi crater), and that Tsiolkovskiy crater was an oblique impact that produced an ejecta forbidden zone on its western side (Schultz, 1976). The landslide formed in this ejecta free zone as the rim of Tsiolkovskiy collapsed and its debris flowed across the relatively smooth, flat floor of Fermi crater. In this location, it could be easily identified as a landslide and not ejecta. Its mobility and coefficient of friction are similar to landslides in Valles Marineris on Mars, but less than wet or even dry terrestrial natural flows. This suggests that the Mars landslides may have been emplaced dry. The high density of small craters on the landslide is likely an illusion caused by the effects of age related differences in regolith thickness on crater morphology, and the presence of the abundant young, circular secondary craters produce by debris ejected from distant fresh craters.

1. Introduction

The Tsiolkovskiy landslide (Fig. 1) is a huge (~72 km long, with a volume of ~3745 km³) runout landslide on the Moon, located on the western rim of the 185 km diameter Tsiolkovskiy crater (20.1°S, 128.6°E). It formed when a portion of the western rim of the crater collapsed, causing material from that rim to slide on to and across the floor of the adjacent Fermi crater (El Baz and Worden, 1972; El Baz, 1973; Howard, 1973; Boyce et al., 2016). Previously, this lobate feature has also been proposed to be an unusual type of fluidized ejecta facies unique on the Moon (Guest and Murray, 1969; Guest, 1971; Howard, 1973; Schultz, 1976; Wilhelms, 1987; Morse et al., 2018), but morphologic evidence predominantly indicates that this feature is an enormous, long runout landslide (see Section 4.2).

Recently acquired data from the Lunar Reconnaissance Orbiter (LRO) (Robinson et al., 2010) and other lunar missions (e.g., Kaguya) have provided a wealth of new information about this landslide, offering an opportunity for its in-depth study not possible before now. This landslide is the only large, long runout landslide on the Moon, and while other long runout landslides are found on other solar system bodies, the Tsiolkovskiy landslide is also the largest example formed on a dry, rocky, airless body. This makes the Tsiolkovskiy landslide an excellent end-member for the study of the mechanics and conditions that control the emplacement of such rapid natural mass flows and their runout distance.

Here we use the new data from recent lunar missions to characterize the physical nature of the slide, as well as present evidence of the origin of this feature and its relationship with other parts of the crater. We present reasons for why it is the only large long runout landslide on the Moon, how its mobility relates to those of other long runout landslides, and the reasons that it appears to have a high density of small craters superposed on its surface.

2. Background

Tsiolkovskiy crater was first photographed by Luna 3 in 1959, and later at higher resolution by Lunar Orbiter and Apollo missions (Fig. 2). These missions provided images of sufficient quality to discover that a huge lobate flow feature, the Tsiolkovskiy landslide, originated from the western side of this crater.

It is evident that the Tsiolkovskiy landslide has morphological similarities to the March 27, 1964 Sherman Glacier long runout rockslide on...
Earth (Shreve, 1966, 1968), as well as certain landslides within Valles Marineris on Mars (McEwen, 1989; Harrison and Grimm, 2003), including sets of parallel grooves formed in the direction of flow (Fig. 3). Lunar Orbiter and Apollo images showed that the landslide flowed across the Pre-Nectarian age plains in the floor of Fermi crater, a ~230 km diameter Pre-Nectarian age impact crater overlapped by Tsiolkovskiy crater (Wilhelms and El-Baz, 1977; Wilhelms, 1987). Geologic mapping indicates that Tsiolkovskiy crater is most likely an Upper Imbrium age crater located in Pre-Nectarian age heavily cratered highlands in the interior of the Tsiolkovskiy-Stark basin (Wilhelms and El Baz, 1977, Wilhelms, 1987). This basin is on the southeastern edges of a relatively elevated region of the lunar farside highlands. Based on crater counts, Boyce et al. (2016) first estimated the age of both Tsiolkovskiy crater and its landslide at ~3.6 Ga and the surround Pre-Nectarian age highlands terrain at ~4.05 Ga.

Wu et al. (1972) derived a moderate scale (1:250,000) 100 m contour topographic map of the “landslide” from high-resolution Apollo 15 stereo images, from which El Baz (1973) observed that the landslide terminated in a low, rampart ridge similar to those on many terrestrial landslides. Howard (1973) also used this topographic map to compare the Tsiolkovskiy landslide with the long run-out distance of landslides on Earth and the Moon, finding that lunar avalanches such as the Tsiolkovskiy landslide are as mobile and efficient as their terrestrial counterparts. He proposed that this may have been because of lubrication by impact generated fluids, although he did not specify the fluid or its origin. El Baz and Worden (1972) and El Baz (1973) noted that the Tsiolkovskiy landslide exhibited a higher number of small, fresh craters (some appeared rimless) than the nearby older, cratered plains in Fermi crater. It was proposed that these craters could be the result of drainage of fine-grain material into void spaces initially sealed over by large blocks in the landslide, or were gas vents, or that the absence of a thick regolith on the comparatively young landslide caused the small craters to appear morphologically fresh. In addition, Boyce et al. (2016) examined high-resolution LROC images and, consistent with the idea of El Baz and Worden (1972), found that the density of small crater appears greater than the older, adjacent terrain. Boyce et al. (2016) also favored the idea of El Baz and Worden (1972) that the anomalous density is probably due to a lower rate of morphologic maturing.

Guest and Murray (1969); Schultz (1976); and Morse et al. (2018) observed that the ejecta blanket of Tsiolkovskiy is asymmetrical and attributed this ejecta asymmetry to the effects of an oblique impact that produced Tsiolkovskiy crater (Fig. 4). This oblique impact resulted in a missing section in the ejecta blanket, i.e., an ejecta forbidden zone, on the northwest side of the crater. The edges of this ejecta forbidden zone are centered at ~315° azimuth and extend outward along lines that diverge by an angle of ~75° on either side of that line (Guest and Murray, 1969; Wilhelms, 1987; Morse et al., 2018). As a result of this ejecta asymmetry, most of the landslide as well as the plains in the floor of the northwestern portion of Fermi crater are in the ejecta forbidden zone resulting in the absence of any type of ejecta facies, including chains and clusters of secondary craters, outward of the landslide or on the plains of Fermi crater in the ejecta forbidden zone as would be expected if the landslide was impact ejecta. The southern part of the floor of Fermi crater is outside the forbidden zone and contains deposits of continuous ejecta from Tsiolkovskiy crater (Fig. 4). The southern part of the Tsiolkovskiy landslide appears to have overridden these ejecta deposits near the crater rim (Boyce et al., 2016).

Greenhagen et al. (2016) determined the crater size frequency distribution on the northwest rim of Tsiolkovskiy crater, and measured a model age of 3.8 ± 0.1 Ga. Boyce et al. (2016) also counted craters on the ejecta located on northwest rim of Tsiolkovskiy crater just inside the ejecta forbidden zone boundary, and found evidence of a resurfacing event that erased craters <~350 m diameter at ~3.6 ± 0.1 Ga, but the model age for the crater population with diameters >~1 km was estimated as ~4.05 ± 0.1 Ga, likely the model age of the pre-impact terrain. Boyce et al. (2016) found evidence of resurfacing (3.6 ± 0.1 Ga) on the Fermi plains that this is most likely to be an older terrain ~4.05 ± 0.1 Ga in age. Boyce et al. (2016) also counted craters on the continuous ejecta southwest of the rim of Tsiolkovskiy crater and found a model crater age of ~3.6 ± 0.1 Ga for the entire diameter range counted. They concluded that Tsiolkovskiy landslide formed soon after formation of the Tsiolkovskiy crater at ~3.6 Ga on ~4.05 ± 0.1 Ga highlands terrain.

From Diviner Lunar Radiometer thermal measurements Greenhagen et al. (2016) found anomalously high surface rock abundance and low regolith thickness on Tsiolkovskiy crater ejecta to the southeast of the crater. These two properties are consistent with a massive well-preserved impact melt deposit in this area. Morse et al. (2018) also mapped relatively large patches of impact melt with the largest on the southern side of the crater in its continuous ejecta deposits. None of this material is found in the forbidden zone. We propose that the distribution of rock abundance is produced as a result of the oblique impact.

3. Tsiolkovskiy landslide

The main parts of the Tsiolkovskiy landslide extend outward from the western rim of Tsiolkovskiy crater for ~72 km (and a part may even extend to ~90 km). The landslide fans to a width of ~250 km at its outer edge, but can be traced back toward Tsiolkovskiy crater where it intersects the western rim on both ends of a ~90 km long, low, narrow section of the rim (Fig. 5). This low section of the rim averages ~18 km wide, stands an average of ~2.4 km above the plains in Fermi crater and ~1.6 km below the adjacent rim crests (at ~4.0 km above the floor of Fermi crater) on either side. This geometry is consistent with this low section of the rim being the scar left after collapse of the rim of Tsiolkovskiy crater that produce the landslide (also see Boyce et al., 2016).

A knob or pinnacle is located (at the 3.5 km point) near the middle of

Fig. 1. Location of the Tsiolkovskiy crater and landslide. (a) Mosaic of the eastern hemisphere. White box shows location of Fig. 1b. (b) Location of landslide on the western rim of Tsiolkovskiy crater. (Both images are LROC WAC mosaics). North is at the top of both images.
this low section of the rim. It stands ~1500 m about the average height of the rest of this section of the rim (Fig. 5). Because of the presence of this knob, the collapse of the rim would likely have been most dramatic on either side of it, resulting in greater volumes of landslide debris furnished to the landslide from those areas. This also means that while some rim collapse would have occurred in the area of the pinnacle, the amount of landslide debris produced from this area would likely have been considerable less than from the areas on either side of it. As a result, the parts of the landslide outward from the pinnacle (i.e., middle and west slides) would be expected to contain comparatively less debris than the parts of the Tsiolkovskiy landslide on either side of it (i.e., north and south slides).

Although the Tsiolkovskiy landslide likely formed as a single event, we have identified at least three, and tentatively four (i.e., north, middle, west south, and possibly a west slide), morphologically different parts (Fig. 6). These parts probably owe their differences to local conditions at the time of formation of the landslide (Boyce et al., 2016). For example, north, middle and the north part of west slides are superposed on the relatively flat Pre-Nectarian plains in the floor of Fermi that are in the ejecta forbidden zone of Tsiolkovskiy crater (Fig. 6). This superposition relationship, combined with the topographic data from LROC and Kaguya, allows calculation of thickness and volume of each part of the landslide superposed on these plains (Table 1). However, calculation of these parameters for south slide that sits outside the ejecta forbidden zone require an additional step that takes into account the presence of a layer of continuous ejecta from Tsiolkovskiy crater deposited on the Fermi plains and overran by the landslide. The surface of the continuous ejecta deposits from Tsiolkovskiy crater in Fermi crater outward of south slide is ~500 m higher than the surface of the nearby plains in Fermi crater. This suggests that the thickness of these ejecta deposits outward of the slide, and likely buried by south slide, is ~500 m. In addition, the average surface elevation of south slide is ~500 m higher than the surface of the continuous ejecta deposits of Tsiolkovskiy crater and ~1000 m higher that the Fermi plains in the area. This also suggests that the continuous ejecta deposits from Tsiolkovskiy crater is ~500 m thick and that south slide is ~500 m thick, as well.

The slope generally has the characteristics that, starting at the rim of Tsiolkovskiy crater, the surface of each part of the slide slope relatively steeply away from the rim. This slope likely mimics the slopes of the topography of the rim uplift buried beneath. About 15 km outward from the rim, the surfaces of these slides dramatically change slopes to become relatively level and flat, out to a distal rampart ridge where they terminate in a scarp. This rampart ridge varies in height along the edges of the slides, but is typically ~10% higher than the adjacent body of the slide (Boyce and Mouginis-Mark, 2018). Large blocks are uncommon on the surface of the landslide, as well as on the rampart ridge, probably a result of their age and lack of steep slopes (Ghent et al., 2014).

### 3.1. North slide

North slide is the largest of the morphologically different parts of the Tsiolkovskiy landslides that make up the main slide (Fig. 7). It has an area of ~2540 km², average thickness is ~800 m, and volume of ~2032 km³. It originates from the northernmost part of the low section of Tsiolkovskiy rim, and extends ~65 km outward. It has a triangular shape in map view with its widest dimension at the base of the rim (~50 km).

As mentioned above, parallel sets of slump blocks with long axes transverse to flow direction of north slide are developed on the slopes extending down from the rim. In addition, several low, broad ridges and troughs also trending transverse to landslide flow and parallel to the crater rim are found on the relatively flat, hummocky, horizontal surface of north slide. Several large nearly circular pits (4 to 6 km diameter) are found in the western part of the slide that could be buried impact craters or unusual flow features.

The surface of north slide is crossed outward by closely-spaced furrows that formed longitudinal to the direction of flow, and radial to the crater rim (Fig. 7). These furrows are similar to grooves common on terrestrial (Shreve, 1966, 1968; Bull and Marangunic, 1968) and Martian landslides (Lucchitta, 1979), as well as some types of layered ejecta deposits (Dufresne and Davies, 2009; De Blasio, 2014; Boyce et al., 2014) (Fig. 3). These features are typically ~<~50 m deep, up to ~300 m wide, and as long as ~40 km. They tend to widen and curve outward near the outer edge of the slide, most likely indicating extension and pulling apart of the flowing debris in that area of the slide as it spreads. The presence of these features on this slide indicates that the development of such furrows did not require ice, water, or clay minerals at their base to act as a lubricant to enable flow because the Tsiolkovskiy landslide was dry when emplaced, and formed in a historically dry environment (e.g., Dufresne and Davies, 2009; De Blasio, 2014; Watkins et al., 2015).

North slide terminates in a raised ridge (i.e., a rampart ridge) at the contact with Fermi Crater plains along its outer edge. It connects continuously with the distal edge of middle slide, and it is therefore likely that they formed at the same time. This rampart ridge is typically ~1.5 to 3 km wide, and has ~10% higher relief than the body of the slide behind it (measured from the terrain outward of the slide). Remarkably, this ridge also bifurcates where it meets middle slide’s distal ridge and extends back toward the pinnacle of the crater rim. This ridge borders north slide and middle slide and is likely a lateral rampart ridge produced as the thicker north slide expands against the thinner middle slide during its formation. Along the edge facing Fermi crater plains, this...
ridge is not a long smooth continuous feature, but is a series of small lobate sections commonly 2 km to 5 km wide. This gives the outer edge of north slide a scalloped appearance. The individual lobate sections are separated by relatively wide (i.e., ~1 km) radial grooves that extend all the way through the rampart. De Blasio (2014) proposed that such morphology indicates a dry, thick landslide, consistent with the Tsiolkovskiy landslide. Such rampart ridges are also found on distal edges of terrestrial and Martian landslides, as well as some types of layered ejecta deposits. These ridges are thought to be due to particle separation processes and shear in the flows that result in the accumulation of coarse particles at their leading edges (e.g., see Savage and Hutter, 1989; Iverson, 1997; Major and Iverson, 1999; Pouliquen and Vallance, 1999; McSaveney and Davies, 2007; Barnouin-Jha et al., 2005; Wada and Barnouin-Jha, 2006; Campbell, 2006; Boyce and Mouginis-Mark, 2006, Iverson et al., 2010; Johnson et al., 2012).

Like the rest of the Tsiolkovskiy landslide, the surface of north slide has accumulated numerous impact craters. These craters are generally circular, in close proximity to one another but generally do not overlap, and have a small range in sizes and a morphology that indicates similar stages of freshness. Judging from their interior shadows that suggest that they are relatively deep for their diameter, these craters appear to have nearly fresh crater depth-to-diameter ratios, and hence are relatively young. We believe that these small craters are secondary craters produced by a relatively young large crater (e.g., Necho) and that these craters were produced by impact of high-velocity, high-ejection angle ejecta thrown a great distance (see Preblich et al., 2007). In addition to these small secondary craters, many of the small craters on north slide (and the other slides) also appear to be fresher than expected for the age of the surface as noted by El Baz and Worden (1972) and El Baz (1973). This age relationship is discussed in more detail in Section 4.4.
3.2. Middle slide

Compared with north slide, middle slide (Fig. 8) has a substantially smaller surface area (~1290 km²), is thinner (~350 m), and has a smaller volume (~452 km³). Middle slide extends to ~72 km from the western rim of Tsiolkovskiy crater. The surface of this slide gently slopes away from its distal rampart back to the break in slope below the crater’s rim. In plain view, the middle slide is triangular shaped with its widest dimension at its distal edge. It narrows toward the crater to below the pinnacle in the middle of the low section of the crater’s rim.

The presence of this pinnacle probably indicates that collapse in this area of the rim was less extensive compared with other parts of the low section of the rim, and most likely accounts for the relatively small volume of middle slide compared with north slide. Middle slide and north slide are separated by a ~5 km wide trough and a ridge (mentioned earlier). The close proximity of these two features supports the idea that they may be related in some way. The long axis of the trough is on a line that points toward the pinnacle on the rim. The border between middle and south slides, on middle slide’s south side, is a topographic step up (i.e., subdued scarp) of ~500 m, unlike a terminal rampart ridge that slopes downward from its summit in both directions.

The surface of middle slide is morphologically similar to north slide. It is only moderately hummocky and exhibits a pattern of furrows that formed longitudinal to the direction of flow. The furrows are about the same size as those found on north slide, but are less well developed and less frequent. Similar to north slide, middle slide terminates in a rampart ridge composed of lobate sections typically 2 km to 5 km wide separated by radial furrows that extend all the way across the rampart. This rampart is continuous with that of north slide, consistent with the idea that they formed at the same time and likely as part of the same flow.

The crater population of middle slide is similar to that on north slide. Crater counts indicate that middle slide is the same model age as north slide, or ~3.55 ± 0.1 Ga (Michael and Neukum, 2010). Middle slide also exhibits numerous small fresh impact craters that have the same characteristics as those on north slide. Like on north slide, some of these are clearly secondary impact craters similar to those formed by high velocity, high ejection angle debris from a distant crater.

3.3. South slide

South slide (Fig. 9) has a run-out distance of ~50 km, i.e., two-thirds of that of north or middle slides. It has a surface area of ~2415 km², and its surface is ~500 m higher than the continuous ejecta from Tsiolkovskiy crater outward from it, and averages ~1000 m higher than the nearby plains in Fermi on which these ejecta deposits are superposed. Assuming that south slide was deposited on top of the continuous ejecta deposits of Tsiolkovskiy crater and that these ejecta were deposited on the Pre-Nectarian plains in Fermi crater, then the thickness of south slide...
is ~500 m with a volume of ~1208 km$^3$ for south slide.

The surface of south slide is morphologically different than north or middle slides; it is hummocky and lacks furrows. On the slopes of south slide leading up to the rim of Tsiolkovskiy crater, relatively large sets of parallel ridges and troughs concentric with the rim crest have formed. These ridges and troughs are probably large slump blocks composed of rim material and landslide debris. Outward from these features the surface of the slide becomes nearly flat, but quite hummocky. Some hummocks have as much as ~500 m relief. A rampart ridge has developed on the western and southern edges (up to near the crater rim) of south slide (Fig. 9). On its west side this rampart ridge connects continuously with the distal rampart of middle slide suggesting they formed as part of the same flow, and at the same time, i.e., 3.55 ± 0.1 Ga (Michael and Neukum, 2010). On the south side of south slide, the rampart ridge appears to extend continuously crater-ward to the break in slope below the rim. This geometry suggests that the flow that produced this rampart likely came from that area. However, on its north side, the boundary with middle slide is not a rampart, but a ~600 m high east-west trending subdued scarp that steps-down to separate the lower elevation middle slide from the higher elevation south (Fig. 5). The trend of this scarp points in the direction of the pinnacle on the rim and is coincidental with the boundary of the ejecta forbidden zone (Morse et al., 2018). Assuming that middle slide is ~350 m thick (see Section 3.2) and that the Tsiolkovskiy continuous ejecta deposit and south slide together average ~1000 m thick, then this difference in elevation is ~650 m. However, the topographic step up from middle slide to south slide at the boundary between the two slides is ~650 m, meaning that either the buried Tsiolkovskiy ejecta deposit or south slide (or both) thin along their edges, a reasonable expectation. This is most likely an indication that south slide is superposed on these ejecta deposits as well as on its west side (see Section 3.6).

Furthermore, the hummocky nature of south slide is likely due to the effects of the landslide debris flowing over buried hummocky ejecta deposits. This is in contrast to north and middle slides that were emplaced over the relatively smooth Pre-Nectarian plains in Fermi crater and are much less hummocky. South slide also lacks radial furrows found on the other parts of the Tsiolkovskiy landslide. The rough surface of the hummocky ejecta most likely disrupted the flow processes that produced the furrows, and hence prevented their production (e.g., see Dufresne and Davies, 2009; De Blasio, 2014). Furthermore, the lobate, digitate segments, like those along the distal ramparts of north and middle, are absent along the distal ramparts of south slide, probably because the furrows are not present on south slide.

The crater population on south slide is similar to that on north and middle slides. Based on crater counts the model age of south slide is 3.55 ± 0.1 Ga (Michael and Neukum, 2010). Within error limits, this is the same age as north slide and middle slide. South slide also exhibits numerous small fresh impact craters. Some occur in clusters that can be traced off the slide. The small craters in these clusters have the same characteristics as those on the rest of the slide and are likely secondary impact craters formed by high velocity, high ejection angle debris from a distant young crater.

### Table 1

<table>
<thead>
<tr>
<th>Slide</th>
<th>Max run-out from rim, km</th>
<th>Avg. thickness, km</th>
<th>Volume, km$^3$</th>
<th>Approx. surface area, km$^2$</th>
<th>Height of drop, km</th>
<th>Coefficient of friction, H/L</th>
<th>Mobility L/V</th>
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<tr>
<td>North slide</td>
<td>65</td>
<td>0.8</td>
<td>2032</td>
<td>2540</td>
<td>3.5</td>
<td>0.054</td>
<td>18.6</td>
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<td>72</td>
<td>0.35</td>
<td>452</td>
<td>1290</td>
<td>3.5</td>
<td>0.049</td>
<td>20.6</td>
</tr>
<tr>
<td>South slide</td>
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<td>0.5</td>
<td>1208</td>
<td>2415</td>
<td>3</td>
<td>0.060</td>
<td>16.7</td>
</tr>
<tr>
<td>West Slide</td>
<td>90</td>
<td>0.1</td>
<td>55</td>
<td>546</td>
<td>3.5</td>
<td>0.039</td>
<td>25.7</td>
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<tr>
<td>Total slide</td>
<td>71</td>
<td>0.49</td>
<td>3746</td>
<td>6791</td>
<td>3.5</td>
<td>0.049</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### 3.4. West slide

West slide is a small area (546 km$^3$) located outward from the western edge of the distal rampart of middle slide (Fig. 10). West slide, starts abruptly at the edge of the distal ramparts of middle and south slides. It exhibits many of the same morphologic characteristics as north and middle slides, such radial furrows, and high density of small fresh craters. Its average thickness is ~100 m, and hence its volume is only ~55 km$^3$.

The boundaries between west slide and the surrounding terrain are different than those of the other parts of Tsiolkovskiy landslide. For example, the exact location of the western and northern edges of west slide are ill-defined because they thin continuously outward and disappear, instead of ending in a distal rampart ridge as do the other parts of the Tsiolkovskiy landslides. The northern third of this slide thins from an average thickness of ~100 m to zero, i.e., to the elevation of the
Fermi plains. This part of west slide is separated from the southern two-thirds of the slide by a subdued ~300 m high scarp that runs east-west. This scarp is on the same trend line as the boundary between middle and south slides and may have been caused by overriding and burial of continuous ejecta deposits from Tsiolkovskiy by west slide. The surface of the southern two-thirds of west slide is more hummocky than middle slide, but less hummocky than south slide. The surface of this part of west slide is inclined, rising westward from ~200 m (above the elevation of the nearby plains in Fermi crater) at the base of the rampart of middle slide to ~400 m where it intersects, and in places (its southern half) overrides, the north trending chain of large (averaging ~5 km diameter) craters to the west. In the places where west slide overrides these craters it appears to be quite thin, <100 m and may extend out for over 5 km from these craters. On its south side, west slide terminates against a northeast trending chain of relatively large (also averaging ~5 km diameter) craters that separates west slide from south slide.

West slide is crossed by shallow furrows that approximately parallel those on middle slide (Fig. 11). These furrows start abruptly at the outer edge of middle slide’s rampart, so that either the west slide was overriden by middle slide or that west slide may be a facies of middle slide and originated from it. The furrows can be traced westward across the southern part of the chain of large secondary craters on the western side of west slide. These craters do not appear to be appreciably filled with slide debris, indicating that the distal part of the western side of this slide is quite thin and overrode these craters without filling them. Like on the north side of this slide, a discernable rampart is not apparent on the west...
margin of the slide although the hummocky nature of the southern part of west slide may have made a rampart in such a thin deposit difficult to identify.

The crater population of west slide is similar to that on the other slides. Crater counts indicate that west slide is approximately the same age as other parts of Tsiolkovskiy landslide, or $3.55 \pm 0.1 \text{ Ga}$. In addition, like the other parts of the Tsiolkovskiy landslide, west slide appears to have a high density of small (less than a few hundred meters diameter) fresh craters superposed on its surface. These are even found on the surface of the relatively large elongate craters on the southwest side of the slide that are crossed by the grooves. Many of these small craters are circular, but in places occur in clusters and are likely to be

Fig. 8. Middle slide with the perimeter of the slide delineated by a dashed line. North is at the top. Image is an LROC WAC mosaic.

Fig. 9. South slide with the perimeter of the slide delineated by a dashed line. The radial furrows common on north and middle slides are absent on south slide. North is at the top. Image is a LROC WAC mosaic.
secondary craters from a distant source.

West slide is the only segment of the Tsiolkovskiy slide that does not extend back to the rim. The western edge of this slide is ~90 km from the rim of Tsiolkovskiy crater, but its eastern edge contacts the distal rampart of western edges of middle slide and south slide 71 km from the rim of Tsiolkovskiy crater. This abrupt contact with the distal edge of middle and south slides suggests that, if west slide is, indeed, a part of the Tsiolkovskiy landslide, it is (1) an outer facies of middle slide emplaced at the same time as middle slide, (2) an earlier slide that was overridden by middle slide, (3) a later thin, highly fluid slide that overrode parts of south and middle slides, or (4) possibly a thin ejecta facies (see Boyce et al., 2015a, 2015b; Tornabene et al., 2019) produced along the edge of the forbidden zone that was emplaced before the slides. However, there is no morphologic evidence that provides clues to which alternative is valid. While all are possible, no other similar thin deposit is found outward of north or south slides. We therefore conclude that the origin of west slide remains speculative.

4. Discussion

Recently acquired high-resolution data (especially LROC images, as well as Kaguya and LOLA topographic data) are used here to support a
A detailed analysis of the morphology and morphometry of the Tsiolkovsky landslide and its geologic setting to better understand its origin and emplacement, as well as its relationship with other terrain in the immediate vicinity. In this section, we discuss the age relationships between the different morphologic parts of the landslide and their age relationship to nearby terrain, as well as address some of the open questions, including (1) the origin of this feature, (2) why it formed where it did, (3) how its mobility compares with other natural geophysical flows, and what does that tell us, and (4) what causes the apparent high density of small craters on its surface reported by El Baz and Worden (1972) and El Baz (1973).

4.1. Age relationships from crater counts

Understanding age relationships between units are key for placing constraints on the origin of this feature as well as placing it in the context of the geologic history of its surrounding. A variety of techniques are used here to establish age relationships between geologic units, such as superposition relationships, intersection relationships, and the density of superposed impact craters on a surface (from crater counts). Of these techniques, crater counts, provide a reasonably reliable means of determining relative age, and with certain assumptions provide a means of estimating the feature’s absolute (model) age (see Michael and Neukum, 2010). For this reason, in this study, crater counts are the primary tool used as a way of determining the chronology of events at Tsiolkovsky crater.

LROC NAC images were used as the primary data base for measurement of crater diameter for performing the crater counts. Cumulative size-frequency distribution (CSFD) curves were constructed from the crater count data collected for each sample area. Crater model ages were calculated based on the CSFD curve using the craterstats2 program of Michael and Neukum (2010). Error bars, based on the statistical error inherent to the number of craters counted (assuming a Poisson distribution of values), were calculated for the number of craters in each diameter bin (N) (calculation included in craterstats2 program). The lunar production function and lunar chronology of Neukum et al. (2001) were used to estimate model crater age for each CSFD curve. Care was taken to ensure that each sample area contained enough area to be confident that their impact crater production function could be confidently determined, and that these areas were flat and horizontal enough to insure that the effects of slope and mass wasting on the crater population were not significant (e.g., see Ghent et al., 2014, van der Bogert et al., 2015). While generally all impact craters greater than a particular diameter (which is dependent on area size and image resolution) were included in the counts, rimless and irregular-shaped craters and craters occurring in chains or tight clusters were excluded because they may be either endogenic (i.e., volcanic) or are secondary impact craters. However, even with their exclusion, their effects on the CSFDs are generally predictable, which itself could provide valuable information about the history of the surface (Schultz and Singer, 1980; Hartmann et al., 1981; van der Bogert et al., 2015).

Craters were counted in the areas shown in Fig. 12 (i.e., the four morphologic parts of the Tsiolkovskiy landslide discussed above, the cratered plains in Fermi crater, continuous ejecta deposits in an area on the northwest rim of Tsiolkovskiy crater on the boundary with the ejecta forbidden zone, and the continuous ejecta in southwest Fermi crater). In addition, craters were also counted in an area near the southeast rim of the crater, as well as a highlands region 483 km northwest of Tsiolkovskiy crater in its ejecta forbidden zone. The intent of these counts is to determine the model age of Tsiolkovskiy crater, its relationship to the formation of the landslide as well as the volcanism that has occurred in its interior, and its effects on the other surrounding terrain.

The CSFD of craters on north, south, middle and west slides are plotted in Fig. 13a and show that all approximately follow the lunar production function with a model age of ~3.55 ± 0.1 Ga (see Neukum et al., 2001; Michael and Neukum, 2010). On south, middle and west slides, craters > ~100 m diameter were counted to avoid the effects of crater size saturation that, for this age surface, should occur at ~80 m diameter (see Moore et al., 1980, p. 86). However, on north slide, craters were counted down to ~19 m diameter as a test to investigate the population of small craters on these slides. We found, as predicted, that below the crater saturation size, the CSFD of craters on this slide exhibits a bend to a shallower negative slopes compared to the lunar impact production function. We interpret this shallowing of slope to be due to the effects of the crater saturation size for this age surface (e.g., see Hartmann et al., 1981). Alternatively, the roll-over of this curve at ~80 m diameter could be partially a result of the properties of the surface materials, such as a thick regolith, that effects small craters more than large craters in these areas.

To determine the temporal relationships between the formation of the landslide and the formation of Tsiolkovskiy crater, craters were counted on the continuous ejecta deposits of Tsiolkovskiy crater that occur on the floor of Fermi crater west of south slide, the ejecta on the southeast rim of Tsiolkovskiy crater, the ejecta 110 km east of craters rim, and the ejecta deposits on the northwest rim of Tsiolkovskiy crater located immediately outside the ejecta forbidden zone boundary (Fig. 12). The CSFD of these counts are shown in Fig. 13b. The CSFD for crater in the first three of these areas approximately follow the lunar production function with a model age of ~3.55 ± 0.1 Ga (see Neukum et al., 2001; Michael and Neukum, 2010). However, while the CSFD of craters < ~300 m diameter in the area on the northwest rim of Tsiolkovskiy crater also follows the 3.55 ± 0.1 Ga production function, craters > ~1 km diameter in this area follow the lunar production function with a model age of ~4.10 ± 0.1 Ga. This CSFD curve indicates that the small crater population was partially reset at ~3.55 ± 0.1 Ga (from ~4.10 ± 0.1 Ga), most likely by the Tsiolkovskiy formation event.

In an effort to put the landslide and formation of the crater into a temporal context with nearby units, craters were also counted on the Pre-Nectarian plains in Fermi crater in the ejecta forbidden zone, and the Pre-Nectarian age highlands terrain in the ejecta forbidden zone northwest of Tsiolkovskiy crater (Fig. 14a). In addition, preliminary
kovskiy crater. We favor this interpretation for the structure of these
production function with a model age of ~3.55 Ga. The CSFD curve for
these craters are plotted in Fig. 14 a. The CSFD curve for
the large area exhibit similar structure to the craters
on the northwest rim of Tsiolkovskiy crater. In this large area, craters < ~350 m diameter follow a crater production function for a model age of
~3.55 ± 0.1 Ga, while craters with diameters > ~1 km follow a
production function with a model age of ~4.10 ± 0.1 Ga (see Neukum
et al., 2001; Michael and Neukum, 2010). Like with the data for
the craters on the northwest rim of Tsiolkovskiy crater, this also indicates
partial resurfacing of 4.10 ± 0.1 Ga terrain by the formation of Tsiolkovskiy crater. We favor this interpretation for the structure of these
craters erasure at ~3.55 ± 0.1 Ga is likely the formation of Tsiolkovskiy crater, and that
the reason that not all craters in these areas were obliterated is they are
located in or near the ejecta forbidden zone. These CSFD curves suggest
that some process, such as seismic shaking or possibly erosion by small
secondary particles, operated in this zone.

In an effort to understand the events that unfolded around the
development of the Tsiolkovskiy landslide, we have counted craters on
the west and south sides of the mare fill in the Tsiolkovskiy crater. In
addition to placing these in the context of the formation of the landslide,
the timing of flooding by basalt in the floor of Tsiolkovskiy crater may
provide deeper insight into whether these volcanic deposits are related
to the formation of the crater. There is some debate about the age of the
mare inside of Tsiolkovskiy crater. Wilhelms and El-Baz (1977) and
Wilhelms (1987) proposed that the age of this mare fill is Upper to Later
Imbrium age or > 3.2 Ga. While crater model ages from impact crater

Craters were counted on the floor of Fermi in two places (Fig. 12); a
relatively flat, small area between large (> ~10 km diameter) craters
and a larger area (where large craters were counted and a sub area
where smaller craters were counted) including large circular craters.
The CSFD for these craters are plotted in Fig. 14a. The CSFD curve for
craters in the small area (in a spot between large craters) follow the
production function with a model age of ~3.55 ± 0.1 Ga. However, the
CSFD of craters in the large area exhibit similar structure to the craters
on the northwest rim of Tsiolkovskiy crater. In this large area, craters
< ~350 m diameter follow a crater production function for a model age of
~3.55 ± 0.1 Ga, while craters with diameters > ~1 km follow a
production function with a model age of ~4.10 ± 0.1 Ga (see Neukum
et al., 2001; Michael and Neukum, 2010). Like with the data for
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Wilhelms (1987) proposed that the age of this mare fill is Upper to Later
Imbrium age or > 3.2 Ga. While crater model ages from impact crater

Fig. 13. (a.) CSFD of craters on the four different parts of Tsiolkovskiy landslide. (b.) CSFD of craters on continuous ejecta deposits of Tsiolkovskiy crater within
approximately a crater radius of the rim on the northwestern (two areas), southeastern and eastern sides of Tsiolkovskiy crater, and the floor of Fermi crater outward
of south slide. The crater population on the northwestern crater rim is near the boundary with the ejecta forbidden zone and shows evidence (i.e., knee in the CSFD curve)
of partial resurfacing of a ~4.10 Ga surface at ~3.55 Ga (presumably the Tsiolkovskiy formation event). The counts are based on the following data where
N = number of crater counted in each area, A = the area counted in km², and R = range of diameters in km. Graph on left (a.), north slide (low Resolution), N = 32,
A = 118, R = 0.440–0.786; north slide (Medium Resolution) N = 164, A = 4.2, R = 0.060–0.262; north slide (high resolution), N = 119, A = 0.32, R = 0.020–0.095;
south slide, N = 101, A = 27, R = 0.150–0.600; middle slide, N = 112, A = 29, R = 0.150–0.500; west slide, N = 81, A = 16, R = 0.130–0.470. Graph on right (b.),
Tsiolkovskiy ejecta in Fermi Floor, N = 115, A = 39, R = 0.180–0.720; SE rim of Tsiolkovskiy, N = 31, A = 1346, R = 0.85–2.3; NW rim of Tsiolkovskiy (large area)
N = 100, A = 2752, R = 0.550–7.4; NW rim of Tsiolkovskiy (high-resolution, small area), N = 63, A = 52, R = 0.216–1.1; near rim east of Tsiolkovskiy, N = 19,
A = 334, R = 0.630–1.4.
counts are generally consistent with this idea, they range from ~3.19 Ga to ~3.8 Ga (Gornitz, 1973; Wilber (1978); Walker and El-Baz, 1982; Wilhelms, 1987; Tyrre, 1988; Greenhagen et al., 2016; Mouginis-Mark and Boyce, 2017), although Pasckert et al. (2015) found different areas ranging from 2.22 and 3.69 Ga. In addition, based on crater erosion morphology, Boyce et al. (1975) estimated the age to be ~3.35 ± 0.2 Ga for this mare fill. The crater counts we collected for this study are plotted in Fig. 14b and indicates an average model age of ~3.55 ± 0.2 Ga. This age and that of the landslide suggest that within the limits of error, the Tsiolkovskiy landslide and mare emplacement occurred at approximately the same time, i.e., soon after the formation of Tsiolkovskiy crater. In addition, it has been proposed by Wilber (1978) and Pasckert et al. (2015) that the scatter of model age values for the mare fill in these studies may indicate the presence of several mare units of nearly the same ages. The differences in our two counts could be interpreted as two mare units of slightly, though not statistically significant, different ages. More work is needed to resolve the issue of timing of mare emplacement in Tsiolkovskiy crater.

Tsiolkovskiy crater formed in Pre-Nectarian cratered terrain on the lunar farside (Wilhelms, 1987). To determine the model age of this terrain in the general vicinity of Tsiolkovskiy crater, we counted craters in an area ~380 km northwest of Tsiolkovskiy crater. We took special care to ensure that the sample area in this terrain is in the Tsiolkovskiy ejecta forbidden zone in order to avoid contamination by secondary craters from Tsiolkovskiy crater. We counted craters > ~22 km diameter in order to be confident that secondary craters from the nearby young 30 km diameter crater, Necho, were not included in the counts. The CSFD curve for these craters is plotted in Fig. 14c and follows a ~4.10 ± 0.1 Ga production function (Neukum et al., 2001). We assume this is approximately the age of the Pre-Nectarian farside highlands in the area of Tsiolkovskiy crater, which is consistent with the model age measured for the larger craters on the Pre-Nectarian plains in Fermi crater and the northwest rim of Tsiolkovskiy.

The crater count data presented here (Fig. 14c) indicate that Tsiolkovskiy crater formed at a model age of ~3.55 ± 0.1 Ga on ~4.10 ± 0.1 Ga Pre-Nectarian farside highlands. It should also be noted that none of the CSFD collected near the crater show a positive bump in their curves at smaller diameters (or any diameter for that matter) expected for contamination by self secondaries as proposed by Zanetti et al. (2017) and Plescia and Robinson (2019). Self secondaries were most likely produced by Tsiolkovskiy crater, they are smaller than the lower limits of our counts, and hence would not affect results from the counts. In addition, because Tsiolkovskiy crater was formed by an oblique impact an ejecta forbidden zone was produced on the west side of the crater. Small scale surface features, such as small craters, were obliterated in this forbidden zone, while larger features were preserved. This obliteration could have been done by seismic shaking. The Tsiolkovskiy landslide (and all its parts) formed soon after formation of the crater, also at ~3.55 ± 0.1 Ga. At nearly the same time, the mare basalts were emplaced in the interior of Tsiolkovskiy crater. However, the errors associated with crater counts are so large that the exact timing of the slides cannot be determined with respect to the formation of Tsiolkovskiy crater, but our crater counts demonstrate that there likely was only a relatively short period of time between crater formation and the landslides (i.e., a few seconds/minutes or thousands of years, but not tens of millions of years).

4.2. Origin: long runout landslide or fluidized ejecta?

Since its discovery, the origin of the Tsiolkovskiy landslide has been controversial, with some researchers proposing that it is a fluidized ejecta deposit (e.g., Guest and Murray, 1969; Guest, 1971; Howard,
Morse et al., 2018) found that the ejecta deposits of Tsiolkovskiy crater and its surface morphology (Barnouin-Jha et al., 2005), and inferred it was emplaced by a ground-hugging flow similar to the formation of the layered ejecta of Martian craters and long runout landslides. Considering the implications of these two alternatives to our understanding of mechanics of long runout landslides or lunar ejecta, it is important to resolve this controversy.

In considering the layered ejecta alternative, besides some morphologic similarities with Martian layered ejecta, most lines of evidence indicate that this feature is not ejecta. For example, previous researchers (Guest and Murray, 1969; Guest, 1971; Schultz, 1976; Wilhelms, 1987; Morse et al., 2018) found that the ejecta deposits of Tsiolkovskiy crater are asymmetrically distributed around the crater, and attribute this asymmetry to the effects of an oblique impact that produced Tsiolkovskiy crater. This asymmetry of ejecta deposits around the crater results in an ejecta forbidden zone. This ejecta forbidden zone, mapped by Wilhelms (1987) and Morse et al. (2018), is centered at an azimuth of ~315°, with boundaries diverging outward at ~60° angle from this center line (Fig. 4). This distribution of ejecta puts the Tsiolkovskiy flow feature mainly inside this ejecta forbidden zone, suggesting that it is not ejecta.

Furthermore, if this feature was ejecta, no matter whether Martian-type layered ejecta or ballistically-emplaced ejecta like all other lunar craters, then ejecta facies, such as secondary craters and thin discontinuous ejecta deposits should occur beyond its outer edge. No such ejecta features are observed beyond this flow in the ejecta forbidden zone. Their absence would be surprising if this flow feature was ejecta, especially considering that such ejecta facies are observed around fresh fluidized ejecta craters on other planets (e.g., see Schultz and Singer, 1980; Barlow et al., 2014; Boyce et al., 2015a, 2015b; Tornabene et al., 2019), and because such ejecta facies are produced as a result of hypervelocity impact excavation of consolidated materials whether the continuous ejecta deposits were emplaced ballistically or as a surface hugging flow (e.g., Schultz and Singer, 1980; Melosh, 1989; House and Holsapple, 2011). Moreover, these ejecta facies are found beyond the ballistically emplaced continuous ejecta deposits around the rest of Tsiolkovskiy crater.

In addition, if this feature is a layered ejecta deposit, then like the ejecta of the Martian crater Zunil whose ejecta blanket exhibits both fluidized and ballistic ejecta morphologies (Mouginis-Mark and Sharpston, 2016), this deposit should be laterally continuous with the rest of the Tsiolkovskiy continuous ejecta deposits surrounding Tsiolkovskiy crater, in spite of their differences in emplacement style. This is clearly not the case, particularly on the north side where there is a gap between this feature and the ballistically emplaced continuous ejecta deposits (Figs. 4 and 5). Furthermore, the deposit can be traced from its lobate distal edges on the plains in Fermi crater directly back and intersects with a ~90 km long, ~18 km wide, low (~2.4 km lower than the rest of rim) relatively flat section of the rim of Tsiolkovskiy. Boyce et al. (2016) proposed that this nearly missing section of the rim is likely a landslide scar, and the source of material for the Tsiolkovskiy flow feature (Fig. 5). Moreover, there is considerable evidence that the degree of fluidization of ejecta required to produce the long runout distance of the Tsiolkovskiy features requires the presence of substantial volatiles (Cintle and Greeley, 1978; Schultz, 1992; Barnouin-Jha et al., 2005; Barlow, 2006). The surface of the Moon is generally regarded as including only small amounts of any volatile, especially in the central latitudes where Tsiolkovskiy is located. Furthermore, there is no morphologic (e.g., sublimation pits) or remote sensing evidence of abundant volatiles in the area containing Tsiolkovskiy required for ejecta fluidization to the degree suggested by the dimensions of the Tsiolkovskiy feature. A similar situation is found on Mercury where there are a number of large craters whose rims intersect the floors of older flat floored craters similar to the intersection of Tsiolkovskiy crater with Fermi crater. On these Mercury craters, flow features that morphologically resemble the Tsiolkovskiy landslide originate from the rims of the younger craters and extend partly across the plains in the floors of the older craters (Figs. 15, Xiao and Komatsu (2013) interpret the flow features associated with Mercury craters to be fluidized ejecta. However, we believe that the same lines of reasoning outlined above apply to the Mercury features and that they are likely landslides because they are topographically-controlled and form only where the wall of a relatively young crater formed on the rim of an older crater.

Finally, while layered ejecta deposits are not observed anywhere on the Moon, landslides are common (Brunetti et al., 2015; Scano et al., 2018) (Fig. 16). This observation supports the idea that the processes and conditions responsible for producing landslides commonly allow landslides, but not fluidized ejecta. We believe that for this reason, it is unlikely, though not impossible, that fluidized ejecta could occur in one place on the Moon, and nowhere else. Furthermore, no convincing quantitative model for the development of Martian-like fluidized ejecta on the Moon has been proposed, but in the case of landslides, no unique model for their formation need be developed to explain their presence because they are common on the Moon.

Considering that (1) the morphologic attributes of this feature fit the criteria for a long runout landslide, (2) it formed in the ejecta forbidden zone where there is no evidence that substantial ejecta was emplaced, (3) it shows none of the features outward of it generally associated with impact ejecta, such as secondary craters, and discontinuous ejecta (4) it shows no lateral continuity with the rest of the ejecta of Tsiolkovskiy, and (5) there is no evidence for the volatiles in the area of Tsiolkovskiy crater required to produce the degree of fluidization observed, we conclude that the evidence is overwhelming that this feature is not ejecta of any type, but most likely a long runout landslide. This is in agreement with the origin proposed by El Baz and Worden (1972), El Baz, (1973), Howard (1973), Boyce et al. (2016), and many others.

4.3. Why only one giant landslide on the Moon?

The Tsiolkovskiy landslide is one of the best preserved examples of a long run-out landslides in the Solar System, but questions remain as to why this huge landslide formed, why it is the only one on Moon, and over what time frame did it form. It seems most likely that the answer to these questions is a combination of size and geometry, and that the landslide components (i.e., north, south, west and middle slides) formed almost simultaneously. Specifically, the formation of the Tsiolkovskiy landslide required that Tsiolkovskiy and Fermi craters both be relatively large so that (1) the segment of the rim of Tsiolkovskiy that crosses the floor of Fermi crater was sufficient voluminous when it collapsed to provided enough debris to produce a huge landslide; and (2) this rim segment collapsed in a place on the flat floor of Fermi crater that provided adequate space for its full development. In addition, the formation of this landslide in the relatively broad ejecta forbidden zone of Tsiolkovskiy crater enhanced its identification.

It is proposed that the large diameter of Tsiolkovskiy and Fermi craters was a key factor in development of the Tsiolkovskiy landslide. This is because their size provided both a relatively large flat, horizontal runout space on the floor of Fermi for development of such a huge landslide, and a guarantee of enough landslide debris from the source (i.e., rim of Tsiolkovskiy crater) to produce such a huge landslide. In particular, relatively large, old craters such as Fermi commonly have broad flat plains on their floors, and in Fermi, the distance from the rim of Tsiolkovskiy crater (the probable source of the Tsiolkovskiy landslide) to the edge of the flat floor of Fermi opposite that location is ~ 160 km. This is enough distance for the landslide to develop unrestricted until its kinetic energy dropped below the frictional resistance with the surface and it stopped.

Furthermore, the source of the Tsiolkovskiy landslide is likely the ~ 90 km low relief section of the ~140 km long segment of the rim of
Tsiolkovskiy that crosses the floor of Fermi crater. Assuming that this low area initially had approximately the same dimensions as the rest of the rim of Tsiolkovskiy crater (minus the ejecta), we calculate the volume of the material missing from this low area to be \(~2000 \text{ km}^3\). This estimate is based on the width at the base of the rim in this area to be \(~18 \text{ km}\), an initial height of \(~4.0 \text{ km}\) (i.e., approximately the average elevation of the rim elsewhere on Tsiolkovskiy crater) and \(~2.4 \text{ km}\) as its present average height above the Fermi plains. If the landslide originated from this location, then the volume of material missing from the low section of the rim should approximately equal the volume of the landslide (i.e., \(~3700 \text{ km}^3\), see Table 1). While our calculated volume of \(~2000 \text{ km}^3\) is nearly a factor of two less than the volume of the landslide deposit, considering a reasonable amount of bulking of material in the slide caused by fragmentation (i.e., \(~50\%–60\%\)), the volume of the collapsed rim material most likely roughly equals the volume of the landslide. While this suggests that no unusually high, voluminous rim segment needed to be produced to provide enough material to form the landslide, it also leaves open the question of what caused the landslide. We propose that the landslide formed by collapse due to gravitationally unstable, over-steepened outer rim slopes caused by the difference in relief between the relatively high, narrow rim and the low elevation of the adjacent plains in Fermi. In addition, it is also possible that added to this instability was the near lack of continuous ejecta deposit in the area of the forbidden zone that would have buttressed the rim slopes from failure.

In addition, the collapse of the rim along the low section left a pinnacle near the middle of this section. This pinnacle is coincidentally located where (1) the trough between north slide and middle slide intersected the rim, as well as (2) the southern boundary of the continuous ejecta deposits and ejecta forbidden zone. Although it is not clear why the pinnacle occurs at this location, it is clear that all the landslide debris originating from the section north of the pinnacle slid onto the flat, relatively smooth, Pre-Nectarian plains on the floor of Fermi crater that contained little to no high relief topography to disrupt flow. Whereas, landslide debris originating from the rim section south of the pinnacle slid onto both the flat, relatively smooth plains on the floor of Fermi crater, producing middle slide, and across the relatively rough, hummocky continuous ejecta of Tsiolkovskiy to produce south slide.
rough hummocky nature of the ejecta surface should result in comparatively higher friction and drag between the surface of the substrate and landslide. Hence, this should reduce the runout distance of the landslide on the continuous ejecta deposits, consistent with the comparatively shorter runout distance of south slide (see Table 1). The higher roughness (and increased friction) of the ejecta substrate should also inhibit formation of such surface features as radial furrows (De Blasio, 2014), while the formation of rampart ridges, like that at the edge of south slide, as well as the other slides, is likely unaffected by roughness of the substrate (Iverson et al., 2010). As a result, the morphology of south slide is different from that of the other parts of the Tsiolkovskiy landslides, lacking the radial furrows and more hummocky (see Section 3.3 for summary of evidence for it being a landslide). We believe that such landslides may be common in places on the Moon with similar large crater overlap geometry as with Tsiolkovskiy and Fermi craters, but because their landslides run over rough hummocky ejecta, they are usually misidentified as ejecta and not landslides.

As a result, a number of factors combine in order for the Tsiolkovskiy landslide to develop in the form we observe, in particular the geometry of the overlap relationships of Tsiolkovskiy and Fermi craters and their large size. A contributing factor also may have been the lack (or nearly so) of thick ejecta deposits outward of the uplifted rim of Tsiolkovskiy crater in the ejecta forbidden zone. This may have facilitated the ready collapse of the uplifted rim because such ejecta deposits may have help buttressed the weight of the rim. Although, if this were a factor then it contribution was only minor, judging by the landslide-like flow features in Mercury craters with symmetrical ejecta deposits. Alternatively, it is also possible that the oblique nature of the impact could have produced anomalously high rim uplift in the area of the forbidden zone. This could have resulted in a higher rim, substantially deepening the rim slopes and causing the ready collapse in that section of rim. However, there is evidence that the greatest rim uplift from an oblique impact is normal to the direction of the impactors path, indicating this was most likely also not a factor (Melosh, 1989; Schultz and Anderson, 1996; Pierazzo and Melosh, 2000). Considering the unlikeliness of these two possibilities, we conclude that the most likely reason for rim collapse to produce Tsiolkovskiy landslide was its location at the highest aspect ratio of the rim (rim relief to its base width), i.e., where the rim stood highest above surrounding topography. This is most likely where over-steepening of the rim slopes would occur that would result its failure under its own weight, probably immediately after crater formation. Most likely, the debris produced by collapse of the rim both spread onto a flat, horizontal, relatively smooth surface on the floor of Fermi crater as well as in places over Tsiolkovskiy ejecta (i.e., west slide). We also infer that if the ejecta forbidden zone had developed elsewhere on the crater, it is likely that this landslide would resemble south slide and be easily misidentified as part of the continuous ejecta deposit.

4.4. Landslide mobility/geometry

Understanding what controls the horizontal runout distance (L) and being able to predict L of rapid natural mass movements, such as of landslides, and rocksslides, is an important issues because of the obvious concern caused by their destructive power and the great distance over which they can travel, i.e., they can travel as much as 30 times their fall height (H) (Dade and Huppert, 1998). While this goal is beyond the scope of this paper, we recognize that because the Tsiolkovskiy landslide is a large, long run-out landslide emplaced under completely dry conditions (owing to its location on the Moon), its geometry provides a valuable end-member for testing hypothesis of the mechanisms of emplacement of such rapid natural mass flows. Our objective in this section is to use our new measurements of the dimensions of the Tsiolkovskiy landslide to estimate its flow efficiency (i.e., mobility and coefficient of friction) during emplacement and how they compare to other natural rapid geophysical mass movements.

The ratio L/H of natural flows is termed their “mobility” (M) and is a measure of their efficiency of movement, while the inverse (i.e., H/L) is the coefficient of friction (μ) that quantifies the macroscopic dissipative properties of the flow (e.g., see Hsu, 1975; Voight, 1978; Middleton and Wilcock, 1994; Iverson, 1997; Harrison and Grimm, 2003). These two parameters are traditionally used to describe the ability of such natural flows to flow. Furthermore, the runout distance of these natural flows is generally thought to be dependent on the volume V of rock mobilized by the slide (e.g., see Heim, 1932; Dade and Huppert, 1998; Legros, 2002). Heim (1932) originally advanced the hypothesis, prompted by an analogy with solid friction, that the whole of the initial potential energy of the mass is dissipated by the work of frictional forces along the topography. He proposed that an additional mechanism (e.g., some kind of enhanced lubrication) is required to explain the long runout distance of some landslides. Since his observations, numerous mechanisms have been proposed that would act to lubricate the movement of these flows. However, recently it has been proposed that the long runout distance of some natural flows can be explained without the need for a lubricating mechanism and that volume of the flow is irrelevant (Lajeunesse et al., 2006; Soukhovitskaya and Manga, 2006; Staron and Lajeunesse, 2009).

We plotted the dimensions of Tsiolkovskiy landslide (Table 1) on the traditional L/H (i.e., M) and H/L (i.e., μ) verse V plots (Fig. 17), and included for comparison data from other types of terrestrial mass movements as well as the landslides in Valles Marineris (VM) on Mars (from data previously published). As a result of concerns raised about the physical meaning of M (i.e. L/H) because L varies over a much wider range than H, so that the H could add nothing more than scattering to the dependence of L on V, we have also plotted L versus V for these data shown in Fig. 18 (Davies, 1982; Staron and Lajeunesse, 2009). As a result, Fig. 18 shows a modified measure of mobility. The morphologic parameters of the natural flows in these plots are all measured the same way, where L is the maximum runout distance, H is the maximum fall height from the where the slide began to where it ends, and V is the final volume (see Soukhovitskaya and Manga, 2006, page 349 for discussion). In addition, in these figures, parameters for the entire Tsiolkovskiy landslide are plotted (Table 1), and not for the different morphologic parts discussed earlier. This is because of the likelihood that the entire mass of the landslides was emplaced at roughly the same time, and that morphologic differences within the slide were likely caused by local conditions, such as roughness of the subsurface (see Iverson and Deninglier, 2001) or thickness variation caused by incomplete rim collapse that affected the thickness of middle slide.

These plots show that V, M, μ and L of the Tsiolkovskiy landslide are comparable to those of long run-out landslides on Mars in Valles Marineris (McEwen, 1989; Quantin et al., 2004; Soukhovitskaya and Manga, 2006), but different than any type of the long runout mass movement on Earth. Like the landslides in Valles Marineris, the Tsiolkovskiy landslide exhibits lower flow mobility (~29.6), and higher coefficient of friction (~0.0034) than any terrestrial mass flows.

Considering that the Tsiolkovskiy landslide was emplaced demonstrably dry, this plot is consistent with the contention of McEwen (1989) that the landslides in Valles Marineris were also emplaced dry.

Furthermore, as noted by earlier researchers, these plots show trends that suggest there may be different functions for the relationship for a given V of M, L and μ of Martian landslides and terrestrial natural flows (McEwen, 1989; Quantin et al., 2004; Soukhovitskaya and Manga, 2006; Staron and Lajeunesse, 2009). Fig. 18 also shows that there may be three distinct and different functions of L versus V describing (1) terrestrial materials that contain moisture, (2) those that are relatively dry, and (3) the landslides in Valles Marineris on Mars. The Tsiolkovskiy landslide on the Moon appears to be included in the Martian function. The differences in these functions have been attributed to differences in rheology of the different types of flows (e.g., yield strength), difference in gravity of Earth and Mars, and/or the dominate flow regime governing flow (McEwen, 1989; Harrison and Grimm, 2003; Quantin et al., 2004; Lajeunesse et al., 2006; Soukhovitskaya and Manga, 2006; Staron and Lajeunesse, 2009, Brunetti et al., 2015).
4.5. Anomalously high density of small craters

Previous investigators noted that there may be an anomalously high density of small (i.e., <∼300 m diameter) fresh craters on the Tsiolkovskiy landslide, and that these craters may be caused by drainage of fine-grained ejecta into voids (El Baz, 1972), degassing out of the slide (Guest, 1971), or that the absence of a thick regolith on the comparatively young landslide caused the small craters to appear to be fresh compared with a thick regolith on the surrounding terrain (El Baz and Worden, 1972). However, because no high resolution images were available and no crater counts were done on these different surfaces to test these hypotheses, the issue was left unexplored until now. Toward this end, we examined high-resolution LROC images and counted craters to search for evidence of these processes, or ones not considered.

Our crater counts (see Section 4.1) indicate that, while the small crater population on the landslide may visually appear to be higher density than the surrounding terrain, it is not. The CSFD curves for small craters on all parts of the landslide, Tsiolkovskiy ejecta, and those on the Fermi Plains are essentially the same (Fig. 13). Furthermore, high-resolution LROC NAC images provide observational evidence that eliminates the hypotheses that the small craters in question are either drainage or degassing pits. These images clearly show that most relatively fresh craters on the slide components have raised rims, hence are not drainage craters that would be rimless. In addition, these images also show that crater chains are not found along the furrows (higher porosity pathway for gas to escape) as expected if the small craters were caused by degassing, and, hence the small craters are likely not degassing pits either.

However, the proposal of El Baz and Worden (1972) that the apparent crater density differences may actually be an illusion caused by the effects of differences in the thickness of the regolith on the landslide compared with that on the adjacent plains may be at least part of the answer, but not all of it. This is because the differences in the age of these terrain could be due to differences in the thickness of their regolith, which in turn may have had an effect on crater morphology. Considering the landslide is ∼3.55 Ga, its regolith should average ∼5 m thick, while the model age of the Pre-Nectarian plains in Fermi crater (craters >~250 m diameter) is ∼4.10 Ga implying an average regolith thickness as much as ∼25 m (e.g., see Quaide and Oberbeck, 1968; Moore et al., 1980; Fa et al., 2015). We also note that even though the CSFD of craters on the Fermi plains indicate that the population of small craters (i.e., <∼200 m diameter) was reset by the Tsiolkovskiy crater formation event at ∼3.55 Ga, there is no evidence that the process that obliterated the small crater on the Fermi plains would also remove the regolith (i.e., no evidence of erosion, scouring, or mantling). Consequently, we assume that the average regolith thickness on the Fermi Pre-Nectarian plains is at least ∼25 m.

This factor of five difference in regolith thickness can have a substantial effect on the morphology of craters in the size range considered to be anomalous. A regolith (or ash mantle) can affect the morphology of craters whose depths are as much as five to ten times its thickness, causing them to be initially shallower, and appearing more degraded than if they formed on a surface with no regolith or a substantially thinner one (Quaide and Oberbeck, 1968; Melosh, 1989; Senft and Stewart, 2007). In the case of the Tsiolkovskiy landslide, where the regolith is relatively thin (i.e., ∼5 m), fresh craters >~50 m diameter should form with a higher depth to diameter (d/D) ratio (i.e., see Pike, 1980) than those <~50 m diameters. On the Fermi Plains, where the regolith is five times as thick, craters >~250 m diameter should also form with a high d/D ratio while craters <~250 m diameter should initially form with a more subdued shape (i.e., lower d/D ratio). This means that relatively young craters in the diameter range of 50 m to 250 m would appear sharper and morphologically fresher on the landslide compared with craters <250 m diameter of the same age on the plains in Fermi crater. Hence, as proposed by El Baz and Worden (1972), this would make the small crater population of the landslide to appear to have more small fresh craters than on the Fermis plains. Since fresh
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Large craters stand out visually, this could easily result in the illusion that small craters on the landslide are more abundant than those on the Fermi plains.

However, differences in regolith are likely not the only cause of the apparent anomalously high number of small craters on the landslide. The high population of secondary craters also adds to this perception of a high density of small craters. This is because there is a large number of secondary crater clusters occurring in this area, whose individual craters exhibit characteristics of secondary craters produced by high velocity debris thrown great distance from the primary crater (Preblich et al., 2007), i.e., small, individual, closely-spaced, fresh, and circular craters (Fig. 19). These secondary craters are typically <200 m diameter and appear fresh on the landslide, as well as on Tsiolkovskiy ejecta deposits where the regolith is only ~5 m deep. However, the crater clusters on old terrain (e.g., the plains in Fermi crater) commonly appear morphologically more subdued and degraded compared with those on the slide (Fig. 19). The long axes of most of the clusters are in the direction of several distant, relatively large, young impact craters northwest of Tsiolkovskiy crater (i.e., Necho, King and Giordano Bruno). We believe that these secondary craters likely originate from one of these distant craters, most likely Necho because it is closest and quite fresh (Fig. 20).

Consequently, we conclude that the apparent high-density of small craters on the Tsiolkovskiy landslide noted by the Apollo astronauts and previous workers is an illusion as suggested by El Baz and Worden (1972). It is the result of (1) the presence of the abundant young, secondary craters produced by high impact-angle, high-velocity debris, and (2) the effects of differences in regolith thickness on crater morphology.

5. Summary and conclusion

While this feature has been proposed to be layered (fluidized) ejecta, (1) its similarity in morphology to huge, long runout landslides found on Earth and other planets, (2) its location in the ejecta forbidden zone of Tsiolkovskiy crater, (3) the lack of other ejecta facies such as secondary craters and discontinuous ejecta deposits outward from it, (4) its lack of lateral continuity with the rest of the continuous ejecta deposits of Tsiolkovskiy crater that occur at the same distance from the rim, and (5) the lack of evidence that the lunar target materials include the quantity of volatiles required to produce the degree of fluidization demonstrated by this feature are conclusive evidence that it is a long runout landslide. Furthermore, we believe that, except for features resulting from the coincidental formation of this landslide in an ejecta forbidden zone, these criteria apply to landslides on other solar system bodies, such as Mercury (see Fig. 15), that originate from the rims of younger, relatively large impact crater where they cross the flat plains in the floors of older, large craters (Xiao and Komatsu, 2013).

Although landslides are relatively common on the Moon, this feature is unique in its enormous size. Its size is likely the result of the combination of several critical factors that coincidently came together in one place. These include (1) Tsiolkovskiy and Fermi craters are both huge craters; (2) the segment of the rim of Tsiolkovskiy that crosses the flat floor of Fermi crater was sufficient voluminous that when it collapsed it provided enough debris to produce an easily identified enormous landslide; (3) this rim segment formed in a place on the floor of Fermi crater where there was enough space for the landslide to flow outward unrestricted and fully formed, and (4) a relatively broad ejecta forbidden zone occurred in Fermi crater in a place where a substantial part of this landslide developed, indicating it is not ejecta and making it easier to identify.

We have identified three major parts (i.e., north, middle, and south slides), with a possible fourth (i.e., west slide) of the Tsiolkovskiy landslide that exhibit morphologic differences that are likely caused by local conditions. All of these parts of the slide originate from a 90 km
long, 18 km wide, low section (~2.4 km above the plains in Fermi crater, and ~1.6 km below the surrounding rim of Tsiolkovskiy crater) in the west rim of Tsiolkovskiy crater. This low section is probably the scar left after the rim collapsed under its own weight and slid outward as the landslide. In addition, these parts (except for west slide) of the Tsiolkovskiy landslide also terminate inward in a low, rampart ridge that extends continuously along their distal edges, consistent with the idea they were all emplaced at the same time. This also suggests that their individual morphological size is likely due to local conditions (e.g., roughness of the terrain).

The individual parts of this slide have essentially identical impact crater model ages of ~3.55 ± 0.1 Ga, so that all parts of the Tsiolkovskiy landslide either formed at one time, or alternatively, in sections very close in time. Crater counts on the ejecta of Tsiolkovskiy have a model age of ~3.55 ± 0.1 Ga, and hence, the landslide likely occurred soon after the crater formed. Crater counts in the ejecta forbidden zone of Tsiolkovskiy crater in the Pre-Nectarian Fermi plains on the northwest rim of Tsiolkovskiy crater (in the ejecta forbidden zone) show a model age of ~4.10 ± 0.1 Ga for craters >400 m diameter and ~3.55 ± 0.1 Ga for the population of craters <400 m diameter. Partial resurfacing probably occurred (i.e., erasure of craters <400 m dia.), as indicated by the CSFD and their resultant model ages for the Fermi plains and Tsiolkovskiy rim. Because there is no morphologic evidence for processes such as impact erosion, scouring or blanketing to have affected the smaller craters, we conclude that the partial resurfacing may have been a result of seismic shaking from the formation of Tsiolkovskiy crater. Furthermore, the ~4.10 Ga ± 0.1 Ga model age is the same model age as a sample area in the Pre-Nectarian crater terrain in the ejecta forbidden zone found ~380 km northwest of Tsiolkovskiy. In addition, none of the CSFD collected near the crater show a positive bump in their curves at smaller diameters expected for contamination by self secondaries as proposed by Zanetti et al. (2017) and Plescia and Robinson (2019). It therefore seems likely that self secondaries either were not produced by Tsiolkovskiy crater, or that they are all smaller than the lower limits of our counts, and hence would not affect results from the counts.

The dimensions of the Tsiolkovskiy landslide indicate that its mobility is ~20.3 and coefficient of friction is ~0.049. These values are consistent with those of terrestrial long runout natural mass flows emplaced by gravity. The landslides also extend for hundreds of meters and the surface with the thinner regolith appears to have more craters in this size range. Second, the presence of the abundant young, secondary craters adds to the impression of high crater density on the landslide. These relatively small (a few hundred meters diameter) craters were previously assumed to be primary impact craters, but are frequently found in elongate clusters and have the morphology of secondary craters produced by high impact-angle, high-velocity debris from distance sources. In the case of the small craters on the slide, many occur in elongate clusters whose long axis points to Necho crater, which may be their source.

We can infer that at least the northern, middle and southern slide segments formed at one time because they share a distal rampart. Had any segment formed prior to the other parts, then we would expect to see breaks in the distal rampart. The west slide, which may not be a landslide, may have formed first because it is over-ridden by the south and middle segments. The exact timing of the slides cannot be determined with respect to the formation of Tsiolkovskiy crater, but our crater counts (Section 4.1) demonstrate that there was only a relatively short period of time between crater formation and the landslides. It is therefore possible that these events were separated by seconds/minutes or by thousands of years, but not tens of millions of years. However, we postulate that the most likely time interval was at most a few days.

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