Long runout landslide or fluidized ejecta on the Moon: the Tsiolkovskiy flow feature?

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Introduction: Since its discovery, the origin of the Tsiolkovskiy flow feature found on the west side of Tsiolkovskiy crater (Fig. 1) has been controversial, with some researchers proposing that it is a fluidized ejecta deposit [1-5] and others contending that it is a long runout landslide [6-10]. The arguments for both alternatives were mainly based on its proximity to Tsiolkovskiy crater and its surface morphology [11] that suggests it was emplaced by ground-hugging flow similar to the fluidized ejecta of Martian crater 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.

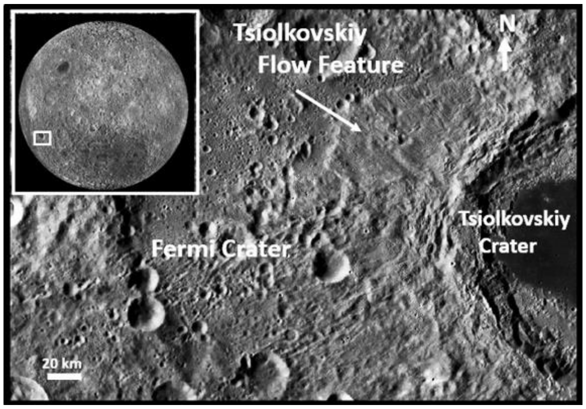

Figure 1. Location of the 185 km diameter Tsiolkovskiy crater (20.1°S, 128.6°E) and its flow feature on the western side of the crater. Insert mosaic of the lunar farside hemisphere show location of this image (white box). Both images are LROC WAC mosaics).

Fluidized ejecta: The strongest case for this feature being fluidized ejecta is that it exhibits some morphologic similarities with Martian fluidized ejecta (e.g., lobate terminations, radial grooves). However, these similarities are also consistent with those of long runout landslides.

Why Not Fluidized Ejecta: Other features that could be interpreted as fluidized ejecta deposits are not observed anywhere else on the Moon, although landslides are common [12, 13]. In addition, there is considerable evidence that ejecta fluidization to the degree required to produce the long runout distance of the Tsiolkovskiy features requires the presence of substantial volatiles. The surface of the Moon is generally regarded as including only small amounts of any volatile because of the lack of morphologic, seismic or spectral evidence of the presence of abundant volatiles in the area containing Tsiolkovskiy, especially in the central latitudes where Tsiolkovskiy is located. This suggests that processes and conditions responsible for producing landslides commonly allow them to develop on the Moon, but not fluidized ejecta. Furthermore, no convincing quantitative model for the development of Martian-like fluidized on the Moon has been proposed to explain the occurrence of this feature. However, in the case of landslides, no special model for their formation is need as evidenced by their common occurrence on the Moon.

Landslide: In contrast, most lines of evidence suggest that this feature is not ejecta. For example, previous researchers [1, 3-6] found that the ejecta deposits of Tsiolkovskiy crater are asymmetrically distributed around the crater (Fig. 2), likely caused by oblique impact that produced Tsiolkovskiy crater. This asymmetry of ejecta produced an ejecta forbidden zone that is centered at ~315°, with its boundaries diverging outward at ~60º angle from this center line [5, 6].

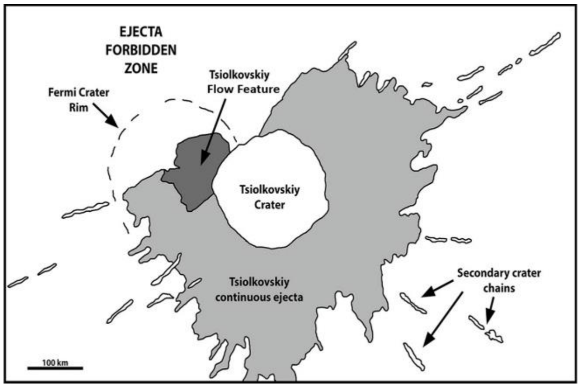

Figure 2: Sketch map of the distribution of ejecta around Tsiolkovskiy crater and the Tsiolkovskiy landslide. Ejecta boundaries and secondary crater chains derived from [6]. North is at the top

The Tsiolkovskiy flow feature is **(1)** located mostly within this ejecta forbidden zone, **(2)** it traces from its distal edges back to a ~90 km long, low (~2.4 km lower than the rest of rim) section of the rim of Tsiolkovskiy (Fig. 3) that is likely a landslide scar, and the source of material for the Tsiolkovskiy flow feature (10), (3) no ejecta facies, such as secondary craters and thin discontinuous ejecta deposits (see 17, 18] are observed beyond this flow feature, but such ejecta facies are found beyond the ballistically emplaced continuous ejecta deposits around the rest of Tsiolkovskiy crater, as well as observed around fresh ejecta craters on other planets (e.g., see14-16), **(4)** the ejecta mobility (EM) of this feature is 0.77, considerably less than the ~2.3 for ballistic ejecta from gravity dominated craters and for Martian layer ejecta craters, where the average EM of their inner ejecta layers is ~ 1.5, and ~ > 3.0 for their outer ejecta layer [19], and **(5)** its mobility is, instead, more comparable to long run-out landslides on Mars, and dry long run-out landslides on Earth (Fig. 4).

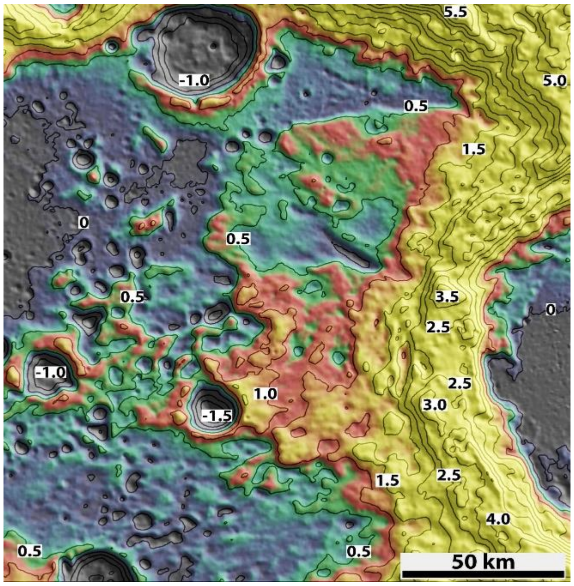

Fig. 3: Contour map of the slide, derived from Kaguya DTMTCOs01_03240S197E1243SC. Contour interval is 500 m with numbers indicating elevations (in km) relative to local datum, i.e., the lowest elevation portion of the floor of Fermi crater. Color rainbow displays low elevations in blue and high points in yellow. North is at the top.

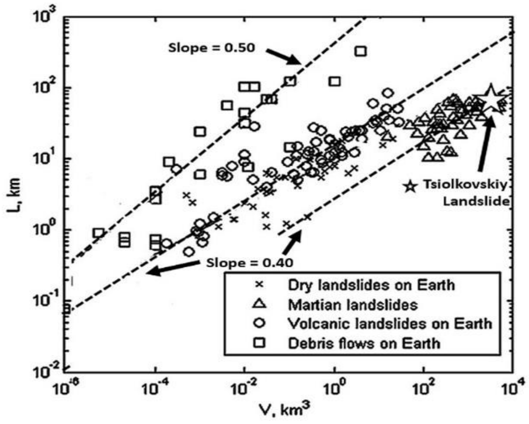

Fig. 4. Runout distance, *L*, verses volume of geophysical flows [20 and references therein].

Conclusion: Considering that (1) the morphologic attributes of this feature fits 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, (4) it shows no lateral continuity with the rest of the ejecta of Tsiolkovskiy, and (5) its mobility is most consistent with dry long run-out landslides, we suggest that the evidence is overwhelming that this feature is not ejecta of any type, but most likely a long runout landslide caused by collapse of the rim of the parent crater. This is in agreement with the origin proposed by [3, 7, 8, 10, 14], and many others.

References: [1] Guest and Murray, 1969 Planet. Space Sci. 17, 121–141; [2] Guest, 1971 Elsevier, London, pp. 93–104; [3] Howard 1973, Lunar Sci. Conf. III, p. 386-387; [4] Schultz, 1978, U. Texas Press, 626 pp; [5] Wilhelms, 1987, USGS Professional Paper, 1348; [6] Morse et al., 2018, Lunar Plant Sci. XXXXIX Abstract 2083; [7] El Baz and Worden, 1972, in Apollo 15 Prelim. Sci. Rept., NASA SP-289, 25-1 to 25-26; [8] El Baz, 1973, Lunar Sci. Conf. III, 1, p. 39-61; [9] Howard, 1974; [10] Boyce et al., 2016, Lunar Plant Sci. XXXXVII Abstract 2471; [11] Barnouin-Jha et al., 2005, J. Geophys. Res. Planets 110, 4, 1–22; [12] Brunetti et al., 2015, Lunar Plant Sci. XXXXIV. Abstract 1066; [13] Scaioni et al., 2018, Europe J. Remote Sensing, 51, 47-61 [14] Schultz and Singer, 1980, Lunar Plant Sci. I Geochem. Cosmochim. Acta, 3, 2243– 2259; [15] Barlow et al., 2014, Icarus 239, 186-200; [16] Boyce, et al., 2015, Icarus, 245, 263-272; [17] Melosh, 1989, Oxford University Press, New York; [18] Housen and Holsapple, 2012, Icarus 211, 856–875; [19] Barlow, N., 2006, MAPS; [20] Boyce, and Mouginis-Mark, 2019, Icarus submitted.