MASSIVE ICE AVALANCHES ON IAPETUS, AND THE MECHANISM OF FRICTION REDUCTION IN LONG-RUNOUT LANDSLIDES.

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Introduction: Long-runout landslides are debris flows that have travelled unusually long distances, thus exhibiting friction coefficients much lower than either the static or sliding values generally accepted for geologic materials [1]. Such landslides or rock avalanches (sturzstroms) are notable on Earth [2] and Mars, there especially associated with the steep canyon walls of the Valles Marineris system [3-5] (Figs. 1 and 2). The mechanics of long-runout landslides are poorly understood, and mechanisms proposed for friction reduction include riding a cushion of trapped air [6,7], lubrication by released groundwater, wet debris, or mud [8], sliding on ice [9] or frictionally generated basal melt layers [10,11], and acoustic fluidization [12,13]. We report here numerous long-runout landslides on an icy satellite, Iapetus, and the extremely cold, airless surface there provides an excellent control on landslide friction reduction compared with Earth and Mars, as there is little obvious role for either trapped atmosphere or groundwater [14].

Overview: Landslides on Iapetus are among the largest in the Solar System, with Iapetus' exceptional topographic relief [15,16] and unconsolidated surface likely accounting for the frequency of landslides there. The drop height-to-runout length ratio, H/L (an approximation for the friction coefficient of landslide material [4,5,13] falls between 0.1 and 0.3 on Iapetus, but does not follow the trend of decreasing H/L with increasing length seen on Earth and Mars. This lack of dependence of H/L on L is not consistent with a role for a gravity-independent yield strength, such as predicted by Bingham or acoustic fluidization models [4,17], but is consistent with rheological control by modest dry friction within ice rubble that has been frictionally heated such that surfaces are slippery [18,19]. Energetics are favorable for this mechanism on Iapetus. Moreover, fault friction on icy satellites may likewise be similarly reduced, in a manner similar to that proposed for faults in rock [20,21].

Landslides Everywhere: Mass movements in the form of landslides or avalanches at some scale are ubiquitous in the Solar System (among solid bodies), but large mass movements, in the form of long-runout landslides, are less common. Beyond Earth, Mars, Iapetus, and possibly Rhea, long-runout landslides have also been observed on Venus [22], Io [23], and possibly on the Moon [24] and Phobos [25]. With re-

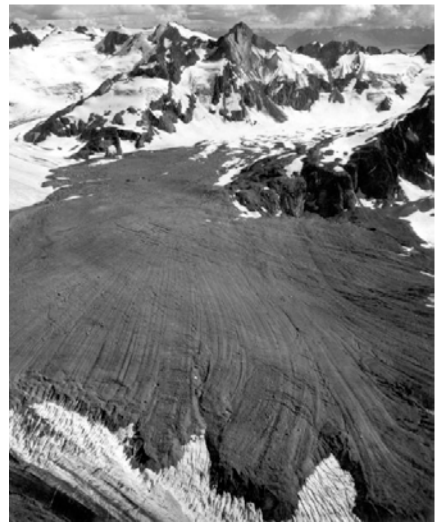

Figure 1. Sherman Landslide, Alaska. Triggered by the 1964 earthquake, this longitudinally furrowed rock mass slid across Sherman glacier. Distance from toe at bottom to rock spur at upper mid-right is ~2.5 km.

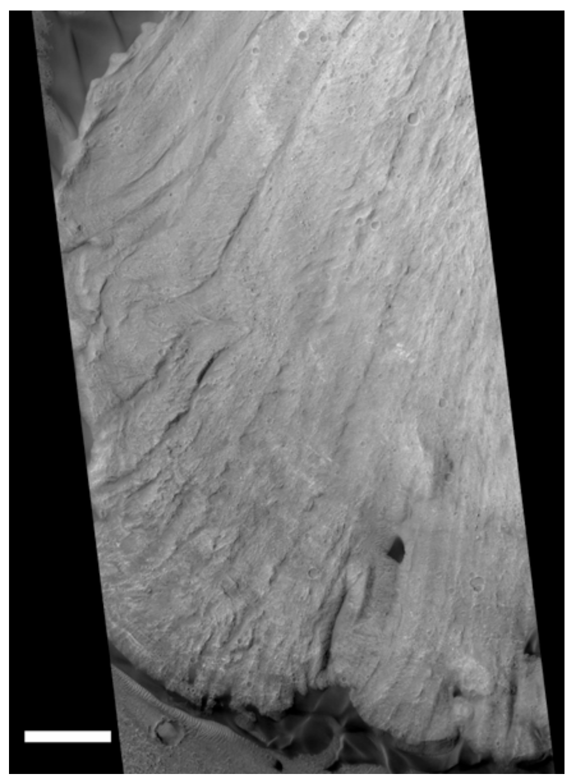

Figure 2. Toe of landslide in Ganges Chasma, Mars. MRO HiRISE ESP_024267_1720 (scale bar = 1 km).

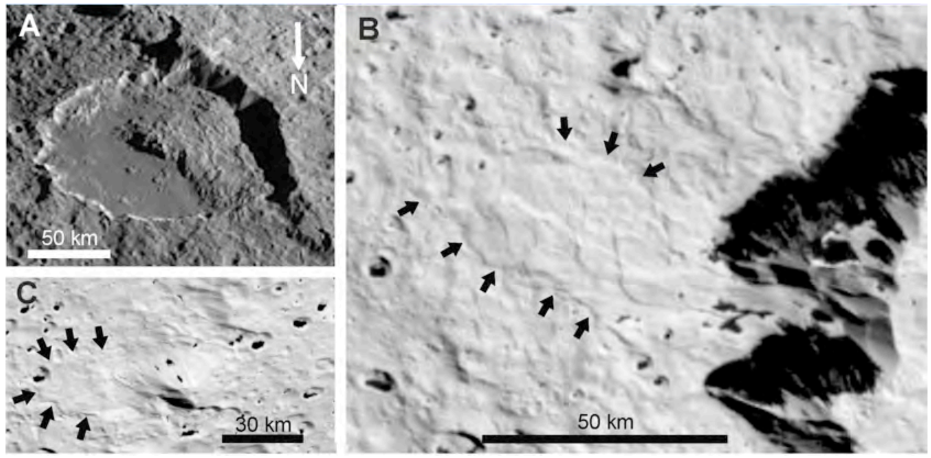

Figure 3. Long-runout landslides on Iapetus [14]. A) "Famous" Malun crater blocky landslide (*H/L* = 0.16); **B)** Multiple lobate landslide in Engelier Basin (*H/L* = 0.13); **C)** Lobate landslide in Gerin Basin (*H/L* = 0.15). North up unless otherwise noted.

spect to icy worlds, mass movements of modest scale have been detected on Callisto [26], and instances are known on Phoebe [27].

Iapetus' value in this context is due to the large number (at least 30) and scale of landslides observed there (Fig. 3), and the lack of complicating factors. For example, only a single example has been cited on Io (though there are certainly more), the lunar landslide in [17] is a regolith slide triggered by Tycho ejecta, and the "example" on Phobos is based on variation in impact crater density, not primary geomorphology. Clear examples exist on Venus, but the high surface density of the Venus atmosphere (65 kg/m^3) implies an important role for atmospheric support.

Implications for Iapetus: The sculpting of Iapetus' topography by mass wasting, both along the equatorial ridge and the rims of large impact basins, is remarkable. One implication is that the surface and upper crust of the satellite is largely unconsolidated. This is consistent with overwhelming dominance of impact cratering, as opposed to other resurfacing processes over geological history, and the non-volatile nature of the volumetrically dominant crustal mineral (water ice) at the low temperatures and pressures of the subsurface. The strongly backcut and fluted impact basin rims on Iapetus are particularly unusual, and similar morphologies are generally not seen around large impact craters and basins in the solar system. In terms of comparably sized structures on other midsized icy satellites, the degraded basins on Rhea bear some resemblance, but the relatively young and undegraded Odysseus basin on Tethys does not. We note that the most crenulated portions of the Engelier basin wall are associated with a depression, likely related to Engelier forming over an older, large basin (Gerin). The majority of landslides in Engelier occur in this eastern section (Fig. 3B) and may be related to a reduced structural integrity due to the Gerin impact.

Regarding the equatorial ridge, the ridge shows diverse morphologies where it is visible. The mountainous peaks on the ridge are variable, sometimes sharp and steep, and at other places rounded, flat-topped or exhibiting multiple parallel smaller-scale ridges. Landslides and alcoves are most prevalent in the tall, steep sections. Along with cratering, much of this variability, and variable preservation along strike, can be attributed to mass wasting altering the appearance of the ridge over time. No matter how the ridge originally formed [28], it has since been considerably altered. Ridge flank slopes are neither pristine, nor in the long term, stable. Arguments against an exogenic origin for the ridge based on slope angles [15] should take these observations into account.

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