MOONQUAKE-TRIGGERED MASS WASTING PROCESSES ON ICY WORLDS. M. M. Mills[1,2], R. T. Pappalardo[2], M. P. Panning[2], E. J. Leonard[2], S. Howell[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, contact email: mackenziemills@arizona.edu, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

Introduction: Intense tectonism is evident on many outer solar system satellites. Some surface regions on icy satellites exhibit ridge-and-trough structures with characteristics suggestive of normal faulting [1-7]. In some cases, topographic lows between subparallel ridges are sites of textureless material displaying few craters (Figure 1) [2]. Satellite images from *Galileo* and *Cassini* also display scarps with faint textures on them—these resemble slope lineations commonly associated with mass wasting processes on Earth [8].

We consider whether smooth material can be generated by mass wasting triggered from local seismic shaking. We hypothesize that debris would flow from topographic highs into lows, initially mobilized by moonquake-induced seismic shaking during formation of tectonic ridges, covering and infilling older terrain.

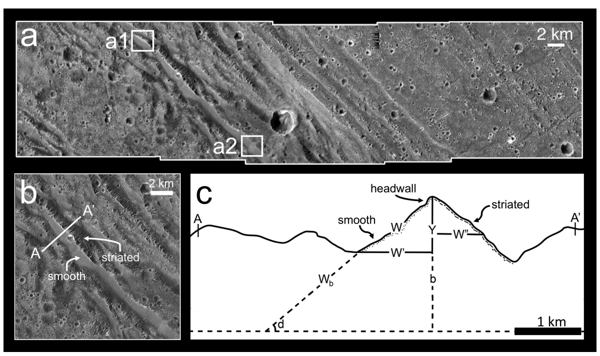

Figure 1: *(a)* Study site near Harpagia Sulcus on Ganymede. Two insets (a1, a2) display sites where faint lineations on slopes can be observed. North is toward the top. *(b)* Zoomed view of some studied ridges. Two types of material are labeled: smooth and striated. Transect A–A' is schematically illustrated in (c). North is toward the top. *(c)* A schematic cross-section of the ridge-and-trough terrain at transect A–A', with vertical exaggeration of ~3x. Surface topography is drawn as solid lines, and an inferred fault plane is drawn as dashed. Fault dimensions are labeled: smooth slope apparent width (*W'*), textured (i.e. striated) slope apparent width (*W''*), slope width (*W*), slope height (*Y*), slope angle (*d*), depth to the brittle-ductile boundary (*b*), and block width (W_b) which is the extrapolation of slope width to the brittle-ductile boundary along an inferred normal fault plane tilted at the slope angle. Vertical dimensions (*b*, W_b) are not to scale. Note, for this schematic, a west-facing fault scarp is assumed, but some scarps may instead face the opposite direction. In that case, apparent heave would be *W''*, and the striated slope would represent the fault face, facing east.

Methods: We map ridge features within high-resolution satellite images of three satellites: Ganymede, Europa, and Enceladus. Using mapped scarp dimensions and digital terrain models, we calculate quake magnitudes that may have accompanied observed scarp formation.

Mapping was performed in *ArcMap 10.8*, and all images were acquired from the *Planetary Data System*. For seismic estimates, the AxiSEM/Instaseis packages were utilized [9-11]. The structure models for seismic calculations on each satellite are from *PlanetProfile*.

Results: We analyze the feasibility of seismicity to trigger mass movements by estimating quake moment magnitudes (Eqs. 1, 2). Seismic moment (M_o) is defined as the energy release caused by a fault rupture and subsequent quake [12], and M_w is a logarithmic scaling of M_o [13], expressed as:

Eq. 1: $$M_o = \mu A_b p,$$

Eq. 2: $$M_w = \tfrac{2}{3}(log(M_o) - 9.1),$$

where μ is the shear modulus, here adopted as 3.5 GPa for ice [14]. Units of M_o are N·m, and p is the resulting scarp slip in meters. Because of the difficulties in estimating an accurate slip, we calculate quake magnitudes for a slip range for each fault. The resulting quake magnitude ranges are shown in Figure 2 (top). The inferred magnitude range is 4.9–8.4.

Estimated quake magnitudes are then fed into the AxiSEM/Instaseis numeric packages, and resulting seismic accelerations generated by quakes in icy satellite shells are returned. Resulting ranges are shown in Figure 2 (bottom). Where shaded areas exceed solid lines for a given satellite, seismic acceleration exceeds gravitational acceleration and mass wasting of unconsolidated surface material can occur.

Using estimates for seismic shaking, we apply two terrestrial coseismic landslide models to estimate mass wasting volumes produced in icy satellite quake events [15, 16]. We estimate volume ranges of 2.3×10^3–7.2×10^5 m^3 using methods of [15] and 5.0×10^7–2.8×10^{11} m^3 using methods of [16] Also, we calculate volumes necessary to infill idealized triangular troughs adjacent to ridges (6.0×10^6–1.6×10^{12} m^3). If troughs are completely infilled, then the surface would be fully "resurfaced" and smoothed, so it acts as a maximum volume bound for accumulated mass wasted material.

Discussion: We investigate the feasibility of coseismic mass wasting to create relatively smooth

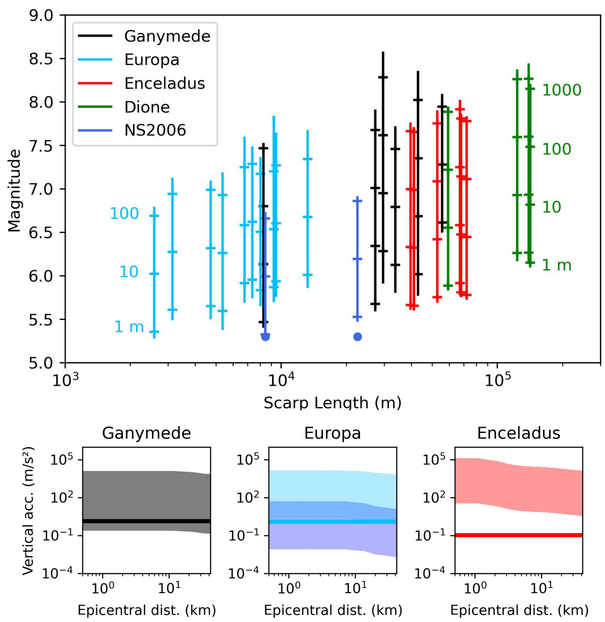

Figure 2: *(top)* Moonquake moment magnitudes necessary to generate ~1–1000 m slip on studied icy satellite scarps. Each vertical line represents an individual scarp, where the lowest tick mark assumes scarp slip p = 1 m, the next 10 m, then 100 m, and for scarps that achieve that dimension the uppermost tick mark assumes p = 1000 m. Two scarps studied by [17] are represented in dark blue (NS2006). *(bottom)* Modeled seismic-induced accelerations and velocities, to common axes for each satellite. For Europa, an ice shell of thickness 5 km (cyan) and 20 km (violet) are considered. Maximum (minimum) accelerations and velocities are represented on the upper (lower) edges of shaded polygons from maximum (minimum) estimated quake magnitudes. Horizontal lines represent surface gravitational accelerations for each satellite.

deposits within ridge-and-trough terrains of icy satellites Ganymede, Europa, and Enceladus (Figure 1). These terrains have been proposed as populations of normal faults created through tectonics, primarily lithospheric extension.

By measuring scarp dimensions, we aim to better understand fault formation and associated mass wasted deposits, given abundant evidence of past and/or recent tectonic and seismic environments on icy worlds. On Earth, quakes of similar magnitude commonly cause significant destruction. Occurrence of similarly large quakes on icy satellites, which have surface gravities less than Earth, implies that such quakes could induce significant seismic effects.

We adopt surface gravitational acceleration as the criterion which, if exceeded, implies that coseismic mass wasting is expected. In Figure 2 (bottom) we observe modeled seismic accelerations plausibly exceeding satellite gravitational accelerations on all satellites, particularly near quake epicenters. Therefore, we conclude that mass wasting is a feasible process for generating surface materials that could locally alter and resurface areas on icy satellites. Given that scarps may be shortened and shallowed by mass wasting, our estimates should be considered upper bounds.

Currently, existing image resolution, areal extent, and stereo coverage are severely constrained. A better understanding of tectonic and coseismic mass wasting processes will be possible when the Europa Clipper and JUICE missions provide high-resolution surface imaging, including stereo imaging, along with subsurface radar sounding, for both Europa and Ganymede. Future mission data will greatly improve our understanding of the tectonics, seismicity, mass wasting, and resurfacing of icy satellites.

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