THE THEORETICAL PLAUSIBILITY OF CENTRAL PIT CRATER FORMATION VIA MELT DRAINAGE. C. M. Elder[1], V. J. Bray[1], and H. J. Melosh[2] [1]Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd. Tucson, AZ 85721, USA, [2]Department of Earth, Atmospheric, and Planetary Sciences, Physics and Aerospace Engineering Civil Engineering Building, 550 Stadium Mall Drive, Purdue University, West Layfette, IN 47907, USA.

Introduction: Central pit craters occur most commonly on Mars and Jupiter's icy moons, Ganymede and Callisto. They have terraced rims, flat floors and a pit at or near the center [1]. Central pit craters are not found on all icy satellites, so they are not considered to be a consequence purely of cratering in ice [1]. However, the lack of central pit craters on most rocky bodies besides Mars implies that some ice is required. Understanding why central pits form in some impact craters but not all may thus provide insight into the quantities and location of ice in the solar system.

Several mechanisms have been proposed to explain the formation of central pits [1], [2], [3] [4]. Here, we focus on the feasibility of impact melt drainage [4]. Central pits could form by drainage of melt if the volumes of fracture space beneath the central peak and of melt generated by impact both exceed the volume of the observed pit and if a large enough volume of melt can drain before the fractures freeze shut [5]. Furthermore, if drainage of impact melt is a viable central pit formation mechanism, it must form pits in craters in ice or ice-rock mixes but not in volatile-poor targets.

Melt Volume: The volume of material that melts during an impact depends on the impact angle, temperature of the target, target porosity, target material, impactor material, impactor size, and impactor velocity [e.g. 6]. Direct observations of impact melt deposits are only available on Earth through detailed field work [e.g. 7]. This type of data are not available for the icy satellites and so we turn to hydrocode modeling of impacts into ice for our calculations. To compare the volume of melt generated during an impact to observed central pit volumes [8] on Ganymede, we estimate the volume of melt as a function of final crater diameter. We combine scaling laws relating melt volume to projectile size [6], transient crater diameter to projectile size [9; 6], and transient crater diameter to final crater diameter [8]. The volume of melt remaining in a crater of final diameter, D, on Ganymede is

$$V = (4.8x10^{-4})D^{3.1}(1+0.2\log(D)) \qquad (1)$$

where D is in km and V is in km^3 [5].

Fracture Volume: Impact induced fractures and voids are inferred beneath terrestrial craters based on negative gravity anomalies [e.g. 10]. Such data do not exist for the Galilean satellites, and numerical modeling studies are only beginning to estimate the volume of fracture void space [11]. We use Gauss's law, the gravity anomalies above 58 Terrestrial impact craters [10], and an assumed target density to calculate the mass of rock that could fill the empty space implied by the negative gravity anomaly [5]. These observations suggest that a terrestrial crater with a diameter D (km) would have a sub-crater fracture volume, V_f (km^3) of approximately:

$$V_f = 0.01D^{2.5} \qquad (2)$$

Based on Weibull parameters, we expect the fracture size distribution and number of fractures in ice and rock to be similar [5].

Melt Drainage: We estimate the size and number of fractures by combining a size distribution similar to that observed at Vredefort [12] with equation 2 to calculate the number of fractures [5]. Next we estimate the depth at which draining melt would freeze. As melt flows through a fracture the liquid advects heat along the channel while at the same time heat is conducted out of the channel into the colder surroundings [13]. This could result in either the fluid releasing its latent heat, solidifying against the fracture walls and blocking the channel, or in the flowing liquid heating and melting the fracture walls and widening the fracture. The outcome depends on the relative temperatures, fracture width, and material properties. Accordingly, we compare the results of liquid water flowing through water ice on Ganymede, and molten rock flowing through solid rock on Earth and the Moon. Because of water's low viscosity the flow of water in fractures on Ganymede will be turbulent and the flow of molten rock in fractures on Earth or the Moon will be laminar [5]. We calculate the time it takes for the fractures to freeze shut using equation (5a) in [14] and integrate the velocity over this length of time to find the depth of solidification, d, for both laminar flow:

$$d = \frac{\rho_l g b^4 S_\infty^2}{288\mu\kappa} \qquad (3)$$

and turbulent flow:

$$d = \left(\frac{g}{0.073}\right)^{4/7}\left(\frac{\rho_l}{\mu}\right)^{1/7}\left(\frac{49S_\infty^2}{456\kappa}\right)b^{19/7} \qquad (4)$$

where ρ_l is the fluid density, g is gravity, b is fracture width, S_∞ is the Stefan number, μ is the fluid viscosity, κ is the thermal diffusivity. We also compare rates of solidification and meltback at a range of different liquid and solid temperatures to determine when a fracture will freeze shut and when its walls will meltback [5]. In the case where the fractures freeze shut, the total volume able to drain is equal to the volume that could drain into a fracture of a certain width times the number of fractures at that width summed over all fracture widths.

Results: Central pits can only form via melt drainage into sub-crater fractures if the melt volume, fracture volume, and volume of melt able to drain before freezing fractures shut all exceed the observed volumes of central pits on Ganymede. Figure 1 compares these volumes for craters with diameters ranging from 5 km to 200 km. These volumes all exceed the observed central pit volumes which implies that a central pit could form even if some melt remains in the crater and some fractures remain empty. Such excess melt could explain the flat floors observed in large central pit craters.

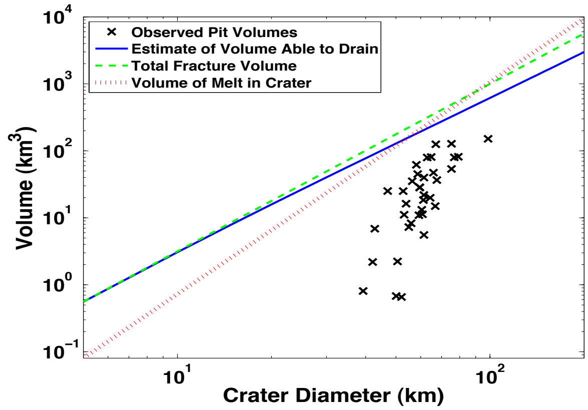

Figure 1: Melt volume, fracture space volume, and the estimated volume of melt able to drain compared to the observed volume of central pits on Ganymede [8].

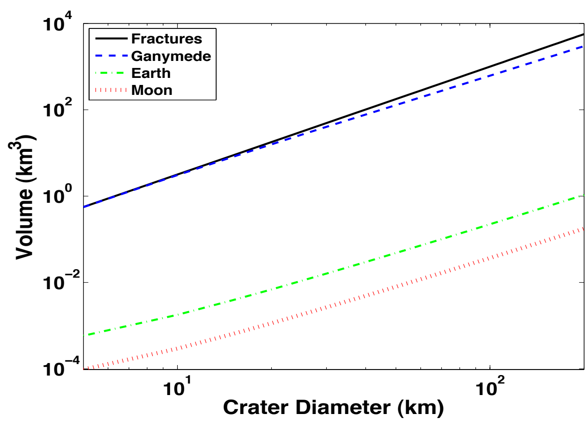

Figure 2: The volume of melt expected to drain on different bodies compared to the total fracture volume expected for craters of different diameters.

We do not observe central pits on most rocky bodies, so if the melt drainage hypothesis is correct, it must not be able to form central pits on Earth or the Moon. Figure 2 compares the volume of liquid water able to drain through solid ice fractures on Ganymede to the volume of molten silicate rock able to drain through solid rock fractures on Earth and the Moon. The volume of impact melt able to drain on Ganymede exceeds the volume able to drain on Earth and the Moon by several orders of magnitude. The volume of melt able to drain on the Earth and the Moon is very small even at large crater diameters, so we do not expect central pits in craters on Earth or the Moon [5].

Conclusions: We investigate the hypothesis that central pits form when impact melt drains through fractures beneath a crater. Both the expected volume of void space and the expected melt volume exceed the observed volume of central pits on Ganymede. We find that the volume of melt able to drain into fractures on Ganymede also exceeds the volumes of the pits. We conclude that melt drainage is a plausible formation mechanism for central pit craters on Ganymede.

Water drains readily through fractures on Ganymede (ice) before it can freeze, but very little molten rock is able to drain on Earth and the Moon (rock), mainly as a consequence of differences in viscosity between liquid water and molten silicate. This suggests that if the impact target contains a sufficient amount of ice and the ice melts during the impact, a significant amount of the water can drain into fractures beneath the crater and leave behind a central pit. A central pit will not form if the target is dry rock because only a small volume of melt will drain into fractures beneath the crater. This is consistent with the presence of central pits in craters on icy satellites and Mars but not other rocky bodies.

Acknowledgements: This work was funded by Grant #NNX08BA96G from NASA's Outer Planets Research Program.

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