CENTRAL PIT FORMATION IN GANYMEDE CRATERS VIA MELT DRAINAGE. C. M. Elder[1], V. J. Bray[1] and H. J. Melosh[2], [1]Lunar and Planetary Lab., University of Arizona, Tucson, AZ 85721, USA, [2]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette IN 47907. cmelder@lpl.arizona.edu

Introduction: Central pit craters are seen most commonly on the icy Galilean satellites and Mars. 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 a consequence purely of cratering in ice. However, the lack of central pit craters on most rocky bodies besides Mars suggests that some ice is required.

Several mechanisms have been proposed to explain the formation of central pits including impact into a layered target [2], collapse of a central peak in weak ice [1], explosive release of volatiles [3] and drainage of impact melt [4], [5]. Central pits could form by drainage of impact melt if there is a sufficient volume of fracture space and a significant amount of melt can drain before the fractures freeze shut. Furthermore, if this process is the explanation for central pits, it must be able to form pits in impacts into ice or impacts into rock mixed with ground ice, but not in impacts into rock. We are investigating the hypothesis that central pits can form via melt drainage and present the results for a 50 km crater on Ganymede in this abstract.

Fracture Volume: The negative gravity anomalies observed over terrestrial craters can be caused by lower density post-impact sediments or lower density impact melt sheets, but the main cause of the low density region is the fracturing and brecciation of the target rocks [6]. This means the gravity anomaly should approximately equal the acceleration due to gravity of the mass of rock that could fill the empty space. As a result, the volume of impact generated fracture space into which melt could theoretically drain can be estimated for terrestrial craters from the observed gravity anomalies. Pilkington and Grieve (1992) compiled gravity anomalies for 58 Terrestrial impact craters [6]. These observations suggest that a 50 km terrestrial would have a fracture volume of approximately 3500 km^3 beneath it. Currently, we assume a similar fracture volume for craters on Ganymede.

The total volume of melt that will drain can be estimated by predicting the amount of melt that will drain through fractures of different widths and summing these values based on the expected number of fractures with a given width. We employ a Weibull distributions (see [7]) with Weibull constants for ice [8] to predict the number of fractures that will occur under a given amount of stress. Ahrens (2009) estimate the appropriate stress for an impact into ice as 3 MPa [9]. Using this tensile stress, we predict 4x10^4 fractures beneath the crater and approximate the range of fracture widths using a Poisson distribution.

Melt Volume: The volume of impact melt available for drainage can be estimated from scaling-laws based on observations of terrestrial impact craters and by modeling impacts. Grieve and Cintala (1992) compiled data to estimate the volume of impact melt in terrestrial craters formed in crystalline rocks [10]. These observations suggest that a 50 km crater on Earth would have ~ 170 km^3 of melt. Pierazzo et al. (1997) derived scaling laws for the amount of melt generated in an impact as a function of the volume of the projectile, the velocity of the projectile and the melt energy of the material [11]. Their scaling laws match the terrestrial observations, but can also be applied to ice targets with appropriate constants. The scaling law for an impact into ice predicts that a 50 km crater on Ganymede would have ~ 9700 km^3 of melt. Terrestrial observations and modeling results provide upper limits on the amount of melt available for drainage. The observed volumes of central pits can provide a lower limit on the amount of impact melt that must be able to drain into the ice beneath the crater, assuming that the pit was once entirely filled with impact melt water. Observations predict that a 50 km diameter crater would have a central pit with a volume of approximately 11 km^3 [5].

Melt Drainage: Impact melt can drain into the ice below the crater either by percolating through porous ice or by draining through fractures created by the impact. The speed of melt percolation, determined by Darcy's law, is much slower than the speed of melt draining through fractures. In addition, the surface area to volume ratio of ice to void space is much higher for melt percolation which facilitates heat conduction, so the amount of melt able to drain via percolation will be negligible relative to the amount able to drain through fractures.

We approximated melt drainage through fractures by considering water draining through a planar dike of width b which decreases with time as water freezes to the sides of the dike. Figure 1 shows the cross section of the dike at time, t=0, and a cross section of one side of the dike after a time t. y_m is the position of the dike wall at time t. At time t, the width of the dike will be $b - 2y_m$, so it has frozen shut completely when $y_m(z,t) = b/2$. Initially, the ice walls have a temperature of T_i, and the water has a temperature of T_m, but as the water freezes, latent heat is released and conducted away through the conduit walls, leading to a temperature gradient from T_m in the draining melt to T_i far from the boundary. If the melt has a temperature greater than the freezing point of water, the water will lose energy by cooling before freezes. We have assumed that the impact melt begins at the freezing point of water, so these calculations provide a lower limit on the amount of melt able to drain. Future calculations will account for melt starting with a temperature higher than the freezing point.

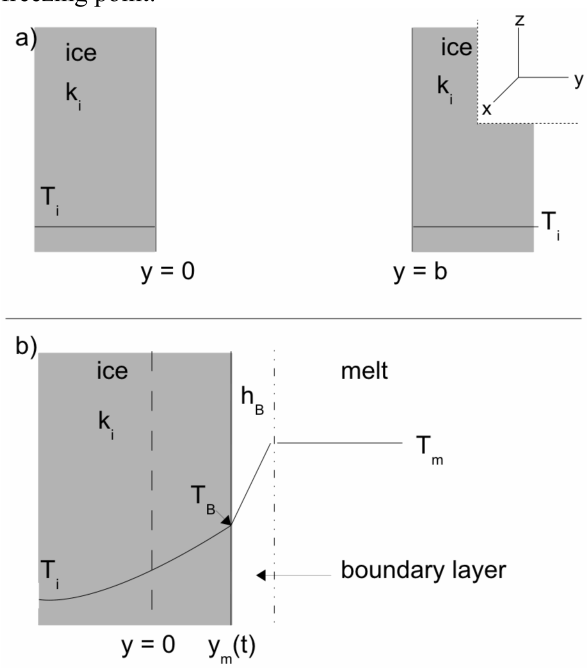

Figure 1: A cross section of (a) a fracture before impact melt (white) begins to drain through; and (b) one side of the fracture after impact melt has been draining through for a time t. The axes are labeled in the upper right corner of (a). y=0 and y=b are the initial positions of the fracture walls (grey). The position of the wall at time t is denoted by y_m. k_i is the coefficient of thermal conductivity for ice, and h_b is the heat transport coefficient in the boundary layer. T_i is the initial temperature of the ice, T_m is the temperature of the impact melt, and T_B is the temperature at the solid-melt interface (y_m).

We used conservation of energy to determine the rate at which the fracture freezes shut and thus the time at which it freezes shut. The velocity of a turbulent flow depends on the density of the fluid, the viscosity of the fluid, the pressure gradient of the flow and the width of the fracture which in this case is a function of time [12]. We assumed the pressure gradient is caused only by the weight of the water above. Integrating the velocity over the amount of time it takes for water to drain yields the depth to which the melt can penetrate (Table 1). By assuming a dike size distribution and estimating the available volume of fracture space, we found that for a 50 km diameter crater on Ganymede, 7 km^3 of melt can drain through fractures before they freeze shut.

b (m)	Depth (m)	Number
0.001	0.006	0
0.017	13.856	27
0.034	90.904	2835
0.053	303.347	19
0.068	596.782	0

Table 1: Fracture width (meters), b, depth (meters) to which melt can drain and number of fractures expected to have that width.

Discussion: We estimate that a total volume of 7 km^3 of melted water could drain through fractures in the ice beneath a 50 km diameter impact crater on Ganymede. This is of a comparable magnitude to observed central pit volumes (~11 km^3 for a 50 km crater [5]) suggesting that melt drainage is a plausible formation mechanism for central pit craters on Ganymede. It is expected that some minimal amount of melt may be able to drain through fractures in rock targets, as suggested by [13]. Calculations for water draining through rock, and for melted rock draining through solid rock are ongoing to investigate the efficiency of this possible pit formation mechanism in rocky targets such as the Moon and ice-rich terrestrial bodies such as Mars.

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