DEVELOPMENT OF A HYDROCODE STRENGTH MODEL FOR LARGE IMPACTS IN PURE WATER ICE.

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Introduction: The constitutive model incorporated in many hydrocodes is comprised of a static strength and an additional target weakening mechanism designed to recreate the apparent reduced target strength during large-scale impacts. Our work uses the iSALE hydrocode [1,2,3] and incorporates the weakening mechanism of acoustic fluidization (AF), in which a mass of fractured blocks acquires the macroscopic rheology of a viscous fluid when subject to strong vibrations [4]. In iSALE the amount and longevity of AF is controlled by two parameters: the dynamic viscosity of the fluidized region, η, and the decay time of the block vibrations, τ_v [5].

As crater diameter increases, average crater wall slopes shallow on both the Moon and Ganymede, indicating a progressive weakening of the target material [6, 7]. Numerical modeling of the formation of different sized impact craters must therefore incorporate a means to scale the effectiveness of the weakening mechanism with event size. [8] found a good fit of simulation results to lunar crater depth/diameter ratios by assuming that η and τ_v were proportional to the projectile radius (R_p). We performed a series of impact simulations into unlayered water ice to determine a similar scaling relationship for crater formation on Ganymede, using newly available topographic profiles and scaling trends [7] to improve upon our previous work [9].

Method: We used a simple spherical and homogeneous water ice projectile, with an impact velocity of 20 km s^{-1} and an impact angle of 90°. The Ganymede surface was approximated as a homogeneous, unlayered constant temperature half-space. The equation of state and static strength properties used in these simulations are detailed in [7] and references therein.

Suites of simulations were performed for a range of projectile sizes in which the AF parameters were varied for each simulation. The resulting crater profiles were then compared to Ganymede crater scaling trends of [10, 11] to determine a best-fit combination of η and τ_v for each crater size. Best-fit AF parameters were determined primarily by fit to observed crater wall slope, as the position and dimension of the modeled crater rims is a noted weakness of the AF model [7]. With these best-fit simulations established, the relationship between decay time and viscosity with impactor radius was assessed and used to determine a scaling law for the AF parameters with event size (Eq 1 and 2).

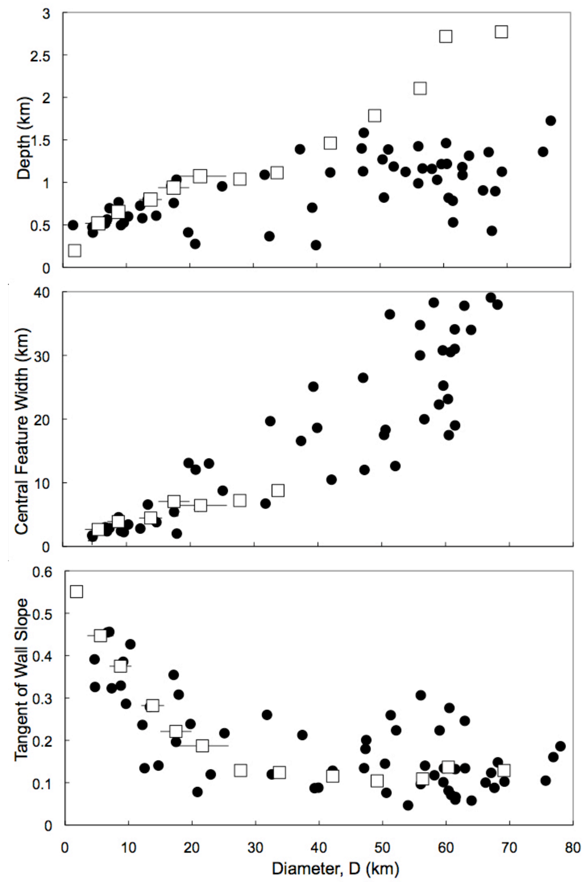

Figure 1: Simulation results (White squares) plotted over observational data from [10] of crater depth, central feature width, and the tangent of wall slope for different crater diameters on Ganymede (Black circles)

As craters larger than ~ 26 km in diameter on Ganymede are considered to be affected by rheological changes that occur with depth [11], only craters smaller than 26 km were used to develop a pure ice strength model. Due to long run times, craters smaller than ~ 3 km were not attempted until the main trend had been established;

Results: Crater depth, wall slope and peak width of the best-fit simulations are a good fit to observational data for craters up to 34 km in diameter (Fig 1) This was achieved using η and τ_v which increase with R_p following power laws:

$$\tau_v(s) = 4.86 R_p^{0.46} (R_p \text{ in meters}), \qquad (1)$$

$$\eta(m^2 s^{-1}) = 55.48 Rp^{1.32}, \qquad (2)$$

We note, however, that simulations using these AF-parameter scaling laws cannot recreate appropriate rim heights while still maintaining correct internal morphology [7].

Simple-Complex Transition Recreated: The strength model presented in this work successfully recreates the simple-to-complex transition at a crater diameter between 1.5 and 3.5 km, consistent with the observed transition for Ganymede craters of ~ 2 km [11]. The change in depth-diameter ratio associated with the s-c transition was also achieved, although the simulated crater is shallower than expected for simple craters on Ganymede (Fig 1), possibly due to the onset of crater floor uplift at too small a crater size. The overly shallow depth of the crater therefore suggests that the effect of AF in this simulation was too large, excessively weakening the sub-crater material.

Central Peak Collapse Modeled: Observational data suggests that between crater diameters of 32 and 39 km on Ganymede central uplifts become unstable, collapsing to form a two-tiered peak [7]. The height and width of central peaks in the simulated 27 and 34 km diameter craters are consistent with observations (Fig 1). The central uplift of the 34 km crater at t=200s is much larger and collapses to form a broader shorter central peak than the 27 km diameter crater, whose peak is formed solely by uplift of the crater floor (Fig 2). The critical diameter for this style of peak collapse in the models is thus between 27 and 34 km, similar to that suggested by observations.

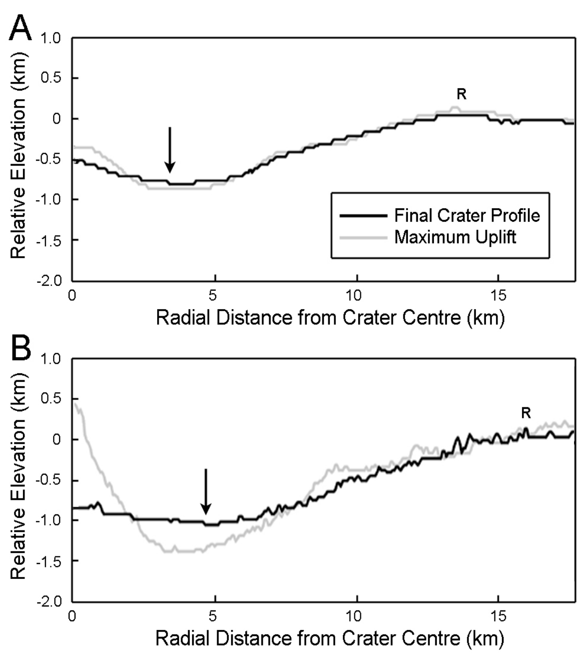

Figure 2: Simulation profiles of a 27 (A) and 34 km (B) diameter crater. Grey profile shows the simulation at the point of maximum transient central uplift. Black profile shows the final crater Location of the final crater rims is marked with 'R' and the final central peak edge indicated with an arrow.

The Need for Target Layering: Our simulated craters above 40 km in diameter have wall slopes of ~ 0.12, consistent with observations (Fig 1), but are flat-floored and up to 150% deeper than Ganymede craters. The inability of the pure ice strength model to recreate the correct depth-diameter ratio for larger craters is an expected result as craters above 51 km in diameter on Ganymede are thought to be affected by the additional weakening influence of a sub-surface ocean [11]. However, the lack of internal morphology is considered a model flaw as AF decay times calculated using Eq 1 and 2 for projectiles with $R_p >$ 860 m (leading to craters with D > 40 km), were in excess of 112s allowing the material at the centre to remain weakened long enough to prevent the retention of topography. The larger quantity of melt produced during these larger impacts, often comprising the majority of the central uplift, also contributed to loss of central topography, replaced instead by a central melt pool.

Melt Pool to Pit Formation: Central pits on Ganymede may form via drainage of a structurally confined centre of melt water into fracture space [12, 10]. Consequently, although the lack of surrounding topography indicates a flaw in the strength model, the central melt pools that remain after acoustic fluidization of the rock mass has subsided are still of interest. The simulated melt pool of the 50-km diameter crater is ~10 km across, similar to the diameter expected for a central pit in craters of this size on Ganymede [e.g. 10]. Consequently, although central pit formation has not been directly simulated using the current iSALE strength model, simulation results may provide starting conditions for theoretical investigation or further numerical modeling of central pit formation on Ganymede [e.g. 13]. Simulations including different near-surface temperature gradients, target layering and a new equation of state for water/ice are ongoing, from which we hope to better determine the amount of melt available for theoretical pit formation via sublimation or drainage.

References: [1] Collins et al. (2004) MAPS 39:217-231. [2] Amsden et al. (1980), LANL Report LA-8095, 101, Los Alamos, New Mexico. [3] Wünnemann et al. (2006). Icarus 180:514-527. [4] Melosh (1979), JGR 84:7513-7520 [5] Ivanov & Kostuchenko (1998), 29th LPSC pp1654. [6] Pike (1977), 489-509 of Impact and Explosion Cratering, Pergamon Press. [7] Bray et al. (2008). MAPS 43:1979-1992. [8] Wünnemann & Ivanov (2003), Planetary and Space Sci., 51:831-845. [9] Bray et al. (2005), LPSC Abs. #1889 [10] Bray (2009), PhD Thesis, Imperial College London. [11] Schenk (2002), Nature 417:419-421. [12] Croft (1981), LPSC pp196-198. [13] Elder et al. LPSC 2010.