NUMERICAL MODELLING OF IMPACT CRATERING ON THE MOON AND ICY SATELLITES. V. J. Bray, G. S. Collins and J. V. Morgan. Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom. veronica.bray@imperial.ac.uk

There is growing evidence of a brine ocean beneath the ice crust of Europa. The possibility of this ocean hosting the development of simple life depends on the interaction of the ocean with the satellite's surface where oxidants and organic compounds are believed to be formed by the breakdown of H_2O and CO_2 ices [1]. Transfer of these organics is considered possible if the ice crust is thin, making the determination of Europa's crustal thickness an important exobiological issue.

For planetary bodies on which geophysical profiling is not viable, one of the most powerful means of investigating the interior is the study of impact craters as they offer direct probes of a body's subsurface. Providing that the underlying process is understood, craters allow crustal structure to be inferred on the basis of their morphology.

Simple craters on the Moon and icy satellites display similar morphology, implying a comparable near-surface rheology; and cratering models used for the terrestrial planets have been successfully applied to icy bodies [2, 3]. The differences of complex craters on the icy satellites and the Moon are probably the result of the relative weakness of ice. Crater morphologies seen only on the icy satellites are believed to also be affected by the presence of subsurface oceans [4]. This work describes numerical simulations of cratering on the Moon and icy satellites with the specific aim of inferring the thickness of Europa's ice crust

Acoustic Fluidization: This work used the iSALE hydrocode, a multi-material, multi-rheology extension of the SALE hydrocode [5], to simulate impact crater formation in its entirety within an acoustically fluidized target. Acoustic fluidization [6] involves the weakening and fluid flow of a target (planet or satellite) when subject to strong vibrations. These vibrations are transmitted as sound waves via rock to rock contacts acting to locally increase or decrease the overburden pressure. This initiates sporadic, localised slips that allow the material to act fluidly on a macroscopic scale.

A simple mathematical approximation of acoustic fluidization, known as the block model [7] has been implemented in iSALE in which the amount and longevity of acoustic fluidization is controlled by two parameters: the kinematic viscosity of the fluidized region, η, and the decay time of the block vibrations, τ [8]. Using a simple mechanical argument, Ivanov and Artemieva [9] suggested that both τ and η are directly proportional to the characteristic size B of blocks that comprise the sub-crater material. The exact equations they derive are of the form:

$$\eta = \frac{CB}{\chi} \tag{1}$$

$$\tau = \frac{2\pi\chi B}{QC} \tag{2}$$

where C is the sound speed of the breccia between blocks, χ is a constant related to the relative size and density of blocks and the surrounding breccia (assumed to be ~ 0.2 - 0.5) and Q is the 'quality factor' (the energy retained per oscillation divided by the energy lost per oscillation). Consequently, the ratio η / τ can be considered constant for impacts into the same material.

$$\frac{\eta}{\tau} = \frac{C^2 Q}{2\pi\chi^2} \tag{3}$$

Lunar Simulations: As the best observational data set for impact craters is for the Moon, and the compositional data is also relatively well known, simulation of lunar impact was a viable first check of iSALE's capabilities before applying the model to ice. We used the Tillotson equation of state and typical rock strength parameters for Gabbro [10] employing an impact velocity of 15 km s^{-1} to simulate impact on the Earth's Moon. The simulations were axis symmetric, considering only vertical impact.

Wünnemann & Ivanov [8] found good agreement between similar simulations and lunar observational data by assuming that B was proportional to the projectile radius, R_p. This is supported by drilling at terrestrial impact structures that shows a general increase in B with crater diameter [9] Rather than assume a scaling law, this work employed the following procedure to find the relationship between B and R_p:

1. η and τ were determined for a specific impact event such that the modelled crater morphology agreed with observational data ('best-fit' was based on comparison of depth-diameter measurements and to actual crater profiles).

2. The ratio of η and τ was fixed; η was varied for different crater sizes, and the block

model applied to a range of impact sizes, so that η as a function of R_p could be found.

3. $\eta = f(R_p)$ relationship was then combined with Equation 1 to find B as a function of R_p,

$$B = \frac{\chi}{C}\eta(R_p) \qquad (4)$$

Following this process, η values for a range of simulated crater sizes were obtained and η was defined as a function of projectile size:

$$\eta\left(ms^{-2}\right) = 194.86(R_p) + 177558 \qquad (5)$$

Hence, by Equation 4, the average block size B is proportional to projectile radius R_p:

$$B(m) = \frac{\chi}{C}(194.86R_p + 177558) \qquad (6)$$

This supports results that $B \propto R_p$ [8].

Icy Satellite Simulations: Before assessing the effects of sub-surface layering on crater morphology, the outlined process was repeated for impacts into pure ice to determine if a similar set of acoustic fluidization parameters could be found. Material differences to impactor and target were taken into account. As crater morphology on Europa is considered to be heavily affected by the presence of a subsurface ocean, comparison to Europan craters was unsuitable. Instead, initial work on the icy satellites focused on recreating craters in Ganymede's bright terrain as it is thought to predominantly consist of water ice [11]. As transitions in crater shape at diameters of 26 and 150 km on Ganymede are thought due to the satellite's internal layering [4], simulations were performed for crater diameters of 1 – 20 km to limit the effect of these rheologic variations. Results produce a block equation of:

$$B(m) = \frac{\chi}{C}(1.5778R_p + 551.79) \qquad (7)$$

Use of a blocksize derived from Equation 7 did not reproduce the size-morphometry progression for craters above 26 km in diameter, demonstrating that craters of this size are affected by factors other than those inherent to the cratering process.

The relationship between B and R_p in Equation 7 was used for simulated impact into a layered ice and water target. The ice thickness was varied and the modelled crates compared to actual crater profiles to find the 'best-fit' conditions. The most promising results were obtained using an ice crust at least 8 km thick. This ice thickness was then used in later simulations of different sized impacts and successfully reproduced the depth-diameter progression from craters 1 – 30 km (figure 1).

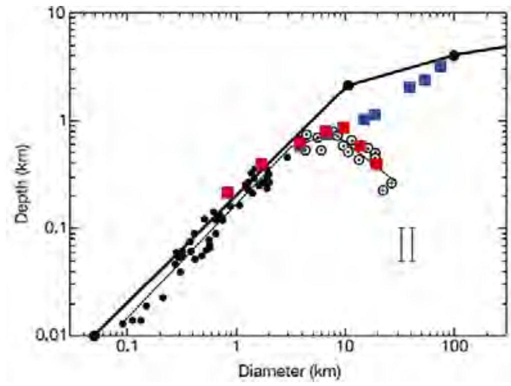

Figure 1: depth-diameter measurements of Europan craters. Thick line marks trend of Lunar craters, black circles represent simple craters, open circles are complex (central peak and pit) craters, error bars mark anomalous dome craters. Blue squares mark craters simulated in pure ice. Red squares represent modelled craters created with an ocean at 8km depth.

Discussion: Using equations 6 and 7, characteristic block sizes beneath a 10 km crater were found to be of the order of 1 and 100 m for Ganymede and lunar craters, respectively. The value for lunar craters is in line with current theory; however, such a small block size for craters in ice was unexpected. It is possible that the simulated ice was too strong, necessitating an increased amount of additional weakening during impact.

Europa's crust is not globally uniform, therefore the best-fits and ice thickness estimates were based on the average cratering trend over the whole satellite surface. As the ice crust is assumed to be generally growing with time as the satellite cools, estimates of upper-crustal thickness derived from this work should be seen as a minimum value. However, it has been suggested that that the mean position of a subsurface ocean on Europa can be maintained due to the tidal heating of the satellite's interior, involving depth oscillations over time [12]. Taking this into account, results of this work indicate that Europa's ocean has been positioned beneath an ice crust of ≥ 8 km depth, averaged over the moon's recorded geological history.

References: [1] Chyba (2000), Nature 403, 381-382 [2] Bray et al. 2005, LPSC Abs. #1889 [3] Turtle .& Ivanov (2002), LPSC Abs. #1431 [4] Schenk (1993), J. Geophys.Res. 98, 7475–7498 [5] Amsden et al. (1980), LANL Report LA-8095, 101, Los Alamos, New Mexico [6] Melosh (1979), J. Geophys. Res. 84, 7513 – 7520 [7] Melosh & Ivanov (1999), Ann. Rev. Earth Planet. Sci. 27:385-415 [8] Wünnerman & Ivanov (2003), Planetary and Space Science, 51, 831-845 [9] Ivanov & Artemieva (2002), GSA Special Paper 256, 619-630 [10] Melosh (1989), Impact Cratering: a geological process. Oxford Univ. Press, London [11] Showman et al. (2004), Icarus 172, 625–640 [12] Hussmann & Spohn (2004), Workshop on Europa's Icy shell abs. #7012.