IMPACT CRATERS AND THE STRUCTURE OF EUROPA'S ICE SHELL. E. A. Silber[1], B. C. Johnson[1], [1]Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI, USA, 06912 (elizabeth_silber@brown.edu).

Introduction: Europa, one of the Galilean moons of Jupiter, may harbor simple life forms in its subsurface ocean, making it one of the highest priority targets in the search for extraterrestrial life. To better understand conditions conducive to formation of life on Europa, one of the crucial steps is to constrain the thickness of its ice shell, depth of the subsurface ocean, and the boundary conditions at the interface between the ice and subsurface ocean (warm convective ice vs. a purely conductive shell). Despite recent developments in remote sensing [1] and numerical modelling [e.g. 2], the aforementioned attributes of Europa's ice shell remain poorly constrained. Among techniques used in an attempt to estimate the thickness of Europa's crust, meteorite impacts remain the most cost effective probes of ice shell thickness and likely conditions at depth. Impact craters are produced by hypervelocity cosmic collisions and are one of the most ubiquitous geological features on solid planetary surfaces. The final size and morphology of an impact crater depend on both the impactor (e.g. size, velocity) and target properties (e.g. rock, ice) [3].

Observations of the Galilean moons (Europa, Callisto, Ganymede) reveal the depth-diameter (*d/D*) relationship that exhibits three distinct transition regimes [1]. On Europa, these regimes correlate to: simple-to-complex transition (I), anomalous crater dimensions and morphologies (II), and abrupt transition from modified central peak to multi-ring morphologies (III) [1]. Regimes II and III, however, occur at much smaller diameters than on the other two satellites, and may correspond to the presence of warm convecting ice at depths of 7-8 km and a liquid ocean at 19-25 km, respectively [1]. Recent numerical studies placed the ice shell thickness at 7 km [2] and 10 km [4]; however, neither study considered the possible presence of warm convective ice.

In this study, we perform numerical modeling of impact cratering on Europa to probe the internal structure. Our study is different in that we consider the both fully conductive ice shell and warm convective ice regime to discern the boundary conditions at the interface between the ice and the underlying ocean.

Modeling: We model formation of impact craters on Europa using iSALE-2D, a multi-material, multi-rheology shock physics code [5,6]. Due to the axial symmetry of our models, only vertical impacts are considered. Although the average impact velocity (v_i) for Europa is 26 km/s, we use v_i = 15 km/s to reduce the simulation time and to maintain the consistency with previous work [2]. Following [2], we implement the ANEOS [7] and Tillotson [8] equations of state to represent the ocean layer and ice Ih, respectively. The strength and damage models for ice shell correspond to [2], as well as the parameters for the block model of acoustic fluidization [9]. Furthermore, we consider a full viscoelastic-plastic ice rheology, as described by [10], to account for any viscous contribution to material deformation. This implementation allows for modeling and full treatment of an ice shell with warm convecting ice.

Our study consists of two parts. First, we model the fully conductive 7 km thick ice shell over the ocean, as presented by [2], to investigate the influence of a fully viscoelastic-plastic ice rheology. The impactor radii are identical to those in [2], R_i = 70 – 405 m.

Second, we perform simulations implementing a conductive-convective layering, where conductive ice overlays a region of convective warm ice. We start with the heat flow (q = ~70 mWm^{-2}) and thermal conductivity (k = ~3 J/m/s) for a purely conductive 7 km layer, corresponding to a thermal gradient (dT/dz) of 24.6 K/km, as given in [2]. To account for a variety of possible scenarios, we vary both the conductive layer thickness (3 – 7 km) and the temperature of the warm ice (255 – 270 K). Using surface temperature of 100 K, the temperature-depth profile switches from conductive to convective regime at some depth, defined by the region at which the linear thermal gradient reaches the given temperature (255 – 270 K). Since the lithospheric thickness is derived using a thermal gradient appropriate for a given layer thickness (e.g. 5 km), the actual thickness is always slightly less (e.g. 4.5 – 4.9 km), as the maximum temperature corresponding to the warm convective ice is below the melting point of water. However, for simplicity, here we refer to the conductive layer thicknesses, rather than lithospheric thicknesses.

Preliminary Results: Figure 1 shows the depth-diameter relation for the observed data [1] (the gray circles), impact model results of [2] (the black circles) and the preliminary results from our study (the purple circles and colored squares). The *d/D* trend corresponding to the ice over ocean scenario [2], with implementation of the full viscoelastic-plastic ice rheology (the purple circles), is consistent with observations for smaller craters (R_i = 105 m and 230 m, D = ~6 km and ~11 km). Large craters (R_i = 320 m and 405 m, D = ~16 km and ~21 km), however, are systematically shallower. Such behavior could be attributed to the fact that our model accounts for viscous contribution to material deformation. Thus, a simple conductive crust overlaying the liquid ocean might not appropriately describe the actual conditions on Europa. However, [2] show that the crater morphology in size range is quite sensitive to changes in ice shell thickness. It is conceivable that a slightly thicker ice shell and inclusion of the viscoelastic-plastic ice rheology will produce good fits to observed crater *d/D*. This will be the subject of future work.

The colored squares in Figure 1 represent various conductive-convective ice layer scenarios, with thermal gradients (dT/dz = 57.7, 34.6 and 24.6 K/km) corresponding to 3, 5 and 7 km conductive layer overlying warm convecting ice at temperatures of 255, 265 and 270 K. While the crater diameters produced by a given impactor size are insensitive to these changes in pre-impact thermal structure, the depths are significantly different and strongly dependent on the temperature gradient. Simulations with warm convecting ice at 255 K and 265 K for a 7 km conductive layer result in craters that are too deep (Figure 1, orange and pink). Conversely, the crater depths for simulations with warm convecting ice at 265 K for 3 km conductive layer (Figure 1, yellow) and 270 K (Figure 1, blue) for a 5 km crust are too shallow (R_i = 405 m).

However, there appears to be a 'Goldie locks' region, roughly corresponding to a warm ice temperature of 265 K and the thermal gradient for a 5 km conductive layer (Figure 1, brown). Although our results are preliminary and more simulations are pending, the 255 K with 5 km conductive layer also remains a viable candidate (R_i = 405 m).

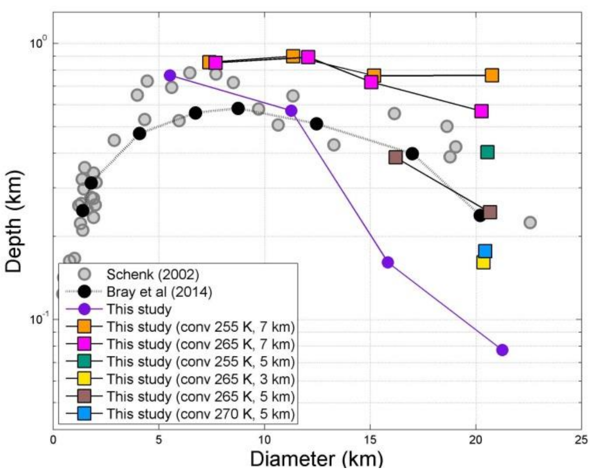

Figure 1: The *d/D* relation for Europan craters. The gray circles are data from [1] and the black connected circles are simulation data from [2]. The purple circles and colored squares represent the results for the simulation in this study (see the legend and main text for details).

Conclusions and future work: The implementation of the viscoelastic-plastic rheology of ice in iSALE has allowed us to consider the formation of Europan craters for a range of possible ice shell structures. Consequently, this allows us to better decipher the internal structure of icy bodies based on crater morphology. Our preliminary results suggest that Europa's crust is likely composed of conductive ice overlying warm convective ice, or at the very least that such a structure can reproduce Europan crater morphologies as well as a completely conductive ice shell. We are currently running several suites of simulations, which will better illuminate the thickness and rheologic composition of ice shell of Europa. Lastly, we note that the mode by which the largest craters can break any degeneracies as ring structures should be very sensitive to the difference in rheology between warm convecting ice and liquid water [11]. The aim of future work will be to model these largest craters.

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