FORMATION OF IMPACT CRATERS ON GANYMEDE AND CALLISTO AS A CONSTRAINT ON ICE SHELL STRUCTURE.

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Introduction: Ganymede and Callisto are both thought to have oceans underlying outer ice shells, but the thickness estimates of these ice shells are poorly constrained and range from 50-200 km [1]. Additionally, the thermal profiles of the ice shells are unknown, leaving questions unanswered regarding the strength of these shells, if the moons are still geologically active, and if there is material transfer between the surface and oceans. While we cannot directly measure the properties such as temperature and composition of the ice shells, we can use impact crater morphologies on their surfaces as a means to probe thermal properties of the ice.

Impact cratering is arguably the most pervasive geologic process in the solar system and crater morphologies are highly dependent on the physical properties of the target body [2]. Measurements of impact crater depths (*d*) and diameters (*D*) show three transitions of crater morphologies on Ganymede, thought to indicate characteristic properties of the thermal structure and thickness of its ice shell (Fig. 1) [3]. Transition I separates simple craters from complex craters. Transition II is an inflection point at which complex craters go from increasing depth to decreasing depth with increasing diameter. Transition III marks a shift from anomalously shallow complex craters to multiring basins. Consequently, we can test different physical properties of Ganymede by comparing modeling results to these transitions. Callisto shows similar *d-D* ranges for the three transitions, implying that the thermal profile of its ice shell is comparable to Ganymede's, whereas these transitions on Europa occur at smaller diameters and suggest it has a thinner ice shell [3].

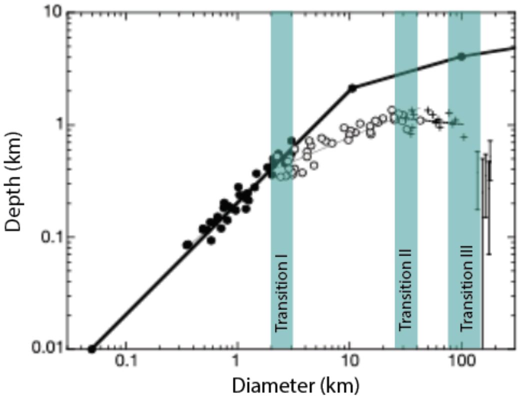

Figure 1: Log-log plot of impact crater depths and diameters on Ganymede [2]. Transitions between quasilinear depth-diameter provinces are highlighted.

Numerical models have been narrowing in on possible thermal profiles of the Europan ice shell. Initial ice shell thickness estimates ranged from several kilometers to tens of kilometers while recent estimates are 7-10 km thick if the shell is a single, conductive layer [4–6]. When considering a conductive lid over top a convecting layer, [6] determined a layer of conductive ice 5-7 km thick is consistent with transitions I and II. Work on Ganymede by [5] considered an unlayered ice shell and was able to reproduce transition I but did not match transition II. Our preliminary results discussed here are consistent with both transitions I and II and build upon this previous work by implementing a visco-elastic-plastic ice rheology as well as a layered ice shell. Eventually we plan to model transition III by including an ocean layer underneath the ice.

Methods: We modeled impact craters using the shock physics code iSALE-2D [7–9]. The models are comprised of ice impactors striking ice targets vertically at 15 km/s and have axial symmetry about the point of impact. Ganymede's ice shell is modeled as a conductive layer of predetermined thickness overlying an infinitely deep convective ice layer. Following [5], both the impactor and target material are modeled using the Tillotson ice equation of state and acoustic fluidization parameters, and we implement a visco-elastic-plastic rheology of ice consistent with [6].

We have run four suites of simulations thus far. In all cases the surface temperature is 120 K with thermal gradients in the upper layer (conductive ice) of 5 K/km and 10 K/km and lower layer (convective ice) temperatures of 240 K and 250 K. Fig. 2 shows representative temperature profiles for the aforementioned scenarios.

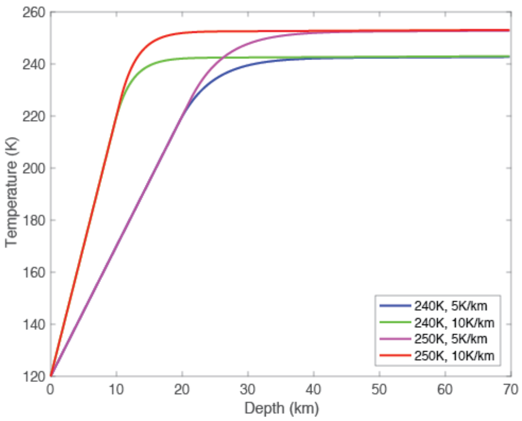

Figure 2: Temperature gradients for our four suites of simulations.

Each suite consists of eight impactor radii varying logarithmically between 20 m and 2000 m. Simulations with 5 K/km thermal gradients result in conductive ice lids 24 km thick whereas simulations with 10 K/km thermal gradients result in conductive ice lids 12 km thick.

Preliminary Results: Fig. 3 shows our modeled impact crater depth-diameter relations plotted with observations from [3]. All our simulations agree with observations when crater diameters are less than approximately 11 km. For craters larger than 11 km in diameter, simulations diverge dependent on the thickness of the conductive layer; 24 km thick conductive lids (5 K/km thermal gradient) result in craters which are deeper than observed and 12 km thick lids (10 K/km thermal gradient) result in craters that are consistent with observations. The combination of 12 km conductive lid and 250 K convecting ice gives the closest agreement with observations thus far.

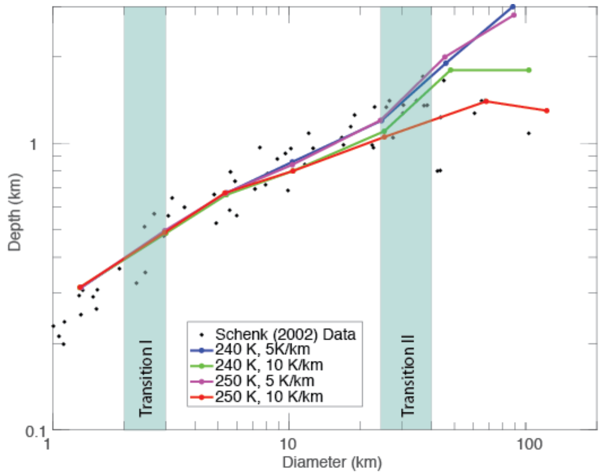

Figure 3: Log-log plot showing the modeled crater depth-diameter relation with observations from [3].

These results build upon the previous work by [5] which matched transition I but produced craters which were too deep to match transition II on Ganymede. Our models differ by testing a variety of thermal profiles as well as implementing a visco-elastic-plastic ice rheology. This viscous contribution in the strength models has an amplified effect for larger impacts [10] and we consider a major factor in why our models agree with a wider diameter range compared to [5]. We will test this conclusion by running large-diameter impacts without the visco-elastic-plastic ice rheology and determine what the effect it has in the resulting crater *d-D* measurements.

Conclusions and Future Work: Our initial results for Ganymede are encouraging and show that an ice shell composed of conductive ice overlying convective ice is consistent with observed depth-diameter measurements of impact craters. Furthermore, we show that a conductive ice shell 12 km thick over convecting ice is consistent with observations whereas a 24 km thick conductive shell is not. Future work will involve expanding our parameter space to various conductive temperature gradients as well as a wider range of convective ice temperatures. Eventually we will utilize even larger impactors to model Valhalla-class multiring basins.

Given the similar physical properties of Ganymede and Callisto, we expect our findings will agree with *d-D* measurements on both bodies. We will confirm this by running a suite of models using slightly different surface gravity and surface temperature appropriate for Callisto to verify that our results remain consistent with observations of both moons. With these findings we are now able to place some initial constraints on the thickness of an upper conductive ice shell above convective ice on Ganymede and Callisto, beginning to shed light on the interior structures of these bodies.

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