NUMERICAL SIMULATIONS OF IMPACT CRATER EXCAVATION AND COLLAPSE ON EUROPA: IMPLICATIONS FOR ICE THICKNESS. E. P. Turtle and B. A. Ivanov, Lunar and Planetary Lab., Univ. of Arizona, Tucson, AZ 85721-0092; turtle@lpl.arizona.edu. Inst. for Dynamics of Geospheres. Russian Acad. of Sci., Moscow, Russian Federation 117334; baivanov@online.ru.

Introduction: Based on several discrete lines of evidence [e.g. 1-4], Europa is hypothesized to have a liquid water ocean under a thin ice shell. Although the total thickness of Europa's outer H2O layer is constrained by gravity measurements to be between 80 and 170 km [5], estimates for the thickness of the solid ice range from only a few kilometers [e.g. 6-9] to a few tens of kilometers [e.g. 10-12]. Turtle and Pierazzo [13] put a lower limit of ~4 km on the ice thickness based on melt production during impact cratering.

On Europa a total of 28 craters with diameters from 4 to ~50 km have been identified as primary impact structures [14]. Their morphologies are similar to those of impact craters on other planetary bodies. Craters, up to ~5 km in diameter are simple. Craters between ~5 km and 24 km in diameter have flat floors and several have central peaks [13,14], which give them the appearance of typical complex craters although they tend to be shallower. Six craters have well-defined central peaks: Brigid, Grainne, Cilix, Amergin, Maev, and Pwyll. Six others exhibit hints of central peaks, but they have not been observed at high enough resolution to be certain: Morvran, Govannan, Avagdu, Diarmuid, Uaithne, and Oisin. Two larger impact structures, Tegid and Taliesin, appear to have unusual morphologies, but both have been imaged only at low resolution so they are poorly understood. The two largest Europan impact structures, Callanish and Tyre, consist of flat, disrupted centers surrounded by concentric graben.

In lunar and terrestrial craters central peaks consist of deeply buried material that was uplifted during crater formation [15,16]. The central peaks in Europan craters are morphologically similar to those observed on the moon, so the simplest explanation is that they formed by the same mechanism. This requires that the ice shell not be breached during their formation. Therefore, we have simulated impact crater formation in ice layers of various thicknesses over deep water to determine how thick the solid ice shell must be to prevent complete penetration during impact crater excavation and collapse.

Modeling: We used the SALE–2D hydrocode [17] in Eulerian mode to simulate the vertical impact of an ice projectile into a two-layer (solid ice over liquid water) target. The hydrocode incorporates the Tillotson equation of state for H2O with thermal modifications [18]. The ice layer has a linear thermal gradient from 100 K at the surface to 273 K at the ice-water interface. We incorporated ice strength properties from published laboratory data [19] with a gradual decrease as the temperature approaches the melting point where strength is assumed to vanish. Consequently, the ice strength reaches a maximum at approximately half the ice thickness due to the increase in the overburden pressure. The simulation also incorporates Europa's gravitational acceleration of 1.3 m/s^2.

The median impact velocity for ecliptic comets on Europa is ~26.5 km/s [20]. However, modeling such high velocity impacts is problematic because the hot vapor that is produced requires short time steps, significantly lengthening the computation time. This problem can be avoided by modeling impacts with velocities of 10 km/s and using Pi-group scaling [21] to calculate the appropriate projectile size to produce a 10 km diameter transient crater. This transient crater diameter is within the range expected for the observed central peak craters on Europa; the final diameters of Europan central peak craters range from 8.5 to 23.7 km [14], so their respective transient crater diameters are 5.0 - 7.0 km and 12.0 - 18.5 km [Eq. 1 from 22].

Results and Conclusions: We have run several simulations of the excavation and collapse of ~10 km diameter transient craters in target ice layers between 5 and 11 km thick (i.e., ~0.5 to ~1.0 times the transient crater diameter).

Figure 1 shows cross sections from the late stages of six of the simulations and illustrates the strong dependence of crater morphology on ice thickness. The ice is not breached during crater excavation; however, for ice less than 7 km thick liquid water penetrates to the surface as the transient crater collapses. At ice thicknesses of 8 and 9 km, crater collapse produces a domed or flat crater floor as the water layer rises and longer simulations reveal that it eventually reaches the surface in the very late stages of collapse. So, ice less than 9 km thick is not sufficient to prevent an outburst of water during the collapse of a 10 km diameter transient crater. In thicker ice a normal transient cavity is formed. This series of simulations demonstrates that when the thickness of the ice is less than the diameter of the transient crater water can breach the crater floor, precluding the formation of a typical complex crater. When the ice thickness is greater than the transient crater diameter, central peak craters can be formed...
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and, at least for the short timescales of these simulations, maintained.

Implementation of additional factors, such as acoustic fluidization and creep of ice that is heated during impact, affects the shape of the final crater; the former produces central peaks and peak-rings [23], while the latter may be responsible for the shallowness of Europan craters. We have begun investigating the effects of acoustic fluidization; however, we find that the results of simulations with acoustic fluidization are strongly dependent upon model parameters. Incorporating acoustic fluidization with a relatively short decay time into the simulation with 9 km thick ice, results in slower uplift of the water layer. The ice is not breached, although the water layer is still rising very slowly at the end of the simulation. Using a longer decay time results in minimal uplift of the water layer for a simulation with 10 km thick ice. Although acoustic fluidization weakens the ice, which can facilitate penetration to the water layer, it also speeds crater collapse, which may work to prevent breaching. Further work to constrain this parameter is clearly necessary.

Our preliminary simulations imply a lower limit on the thickness of the Europan ice at the times and locations of crater formation: to prevent craters on Europa from penetrating to an ocean, the ice shell thickness must be roughly equal to the transient crater diameter. For the case of the smallest Europan complex crater the ice must have been between 5.0 and 7.0 km thick (the range is due to uncertainty in inferring diameter of the transient crater from the observed final crater diameter [22]). For the largest complex crater the ice must have been between 11.9 and 18.5 km thick. These results are consistent with simulations of melt production during the earliest stages of impact craters which predicted that a Europan ice shell must be at least ~4 km thick [13]. However, further investigation into the acoustic fluidization decay time for Europa's ice and into the longer term effects of creep will be necessary to more definitively constrain the ice thickness.


Figure 1: Final cross-sections of six simulations of impacts into ice 5, 6, 7, 8, 9, and 11 km thick. In the first three (top row) water breaches the ice early in the collapse stage. In 8 and 9 km thick ice the water rises more slowly, but eventually breaches the ice.