IMPACT MELT INDUCED FRACTURE PROPAGATION ON OCEAN WORLDS

K. L. Craft[1], M. Kinczyk[1], A. E. Chen[1,2], A. R. Rhoden[3]

[1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD (Kate.Craft@jhuapl.edu),(Mallory.Kinczyk@jhuapl.edu); [2]Johns Hopkins University, Baltimore, MD, (achen126@jhu.edu); [3]Southwest Research Institute, Boulder, CO (Alyssa@boulder.swri.edu)

Introduction: Europa and Enceladus are two ocean worlds that are ice covered, with ice shells potentially 10s of kilometers in thickness. The two moons orbit large parent bodies, Jupiter and Saturn, respectively, that induce tidal heating and enable their underlying oceans to remain liquid. Therefore, it is possible that impacts on their surfaces have produced liquid melt-water and non-water compositional interactions. Potentially, with the creation of melt during impact, a fracture originating in the subsurface could be reached, fill, and refreeze, further pressurizing the crack causing it to propagate deeper into the interior. Here we present initial numerical modeling work to consider such a scenario at Europa building on initial work by Chen et al. [1,2], and consider future work for more complex models including variations on ice shell thicknesses, multiple fractures, and compositional variations at Europa and other ocean worlds.

2D Model Set-Up: The initial 2D-model considered a crater in place at 10-km width and 1-km depth (Figure 1) based on craters that have been observed on Europa [3]. A crack was emplaced in the center of the crater, reaching from the crater bottom to a depth of 4-km (crack length = 3-km), based on models for crack lengths formed from cooling and thickening shells on Europa, when the ice shell is 9-km thick, calculated by Rudolph et al. [4]. The overall model dimensions were set at 30-km width x 9-km height, to represent the ice shell region of interest, and to ensure that the model boundaries do not affect the physical behavior of the crater and crack. This portion of the ice shell was assumed elastic considering the cryogenic temperatures present (~100K at the surface). Material properties were specified for water ice (Young's Modulus = 9.1 GPa; Poisson's Ratio = 0.3; Density = 920 kg/m^3 [e.g. 5]). Model boundary conditions set the bottom of the ice shell as fixed in X and Y, while the surface was free. We next applied a stress field to represent the profiles simulated by [4]. These values include the vertical compressive stress from gravity on Europa, -1.3 m/s^2. Under these conditions the initial crack width was calculated at 0.2-m.

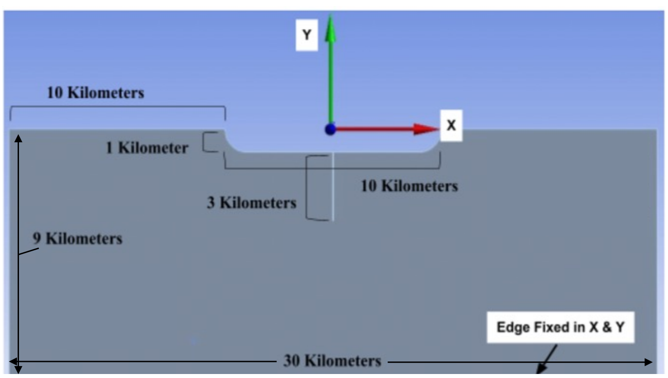
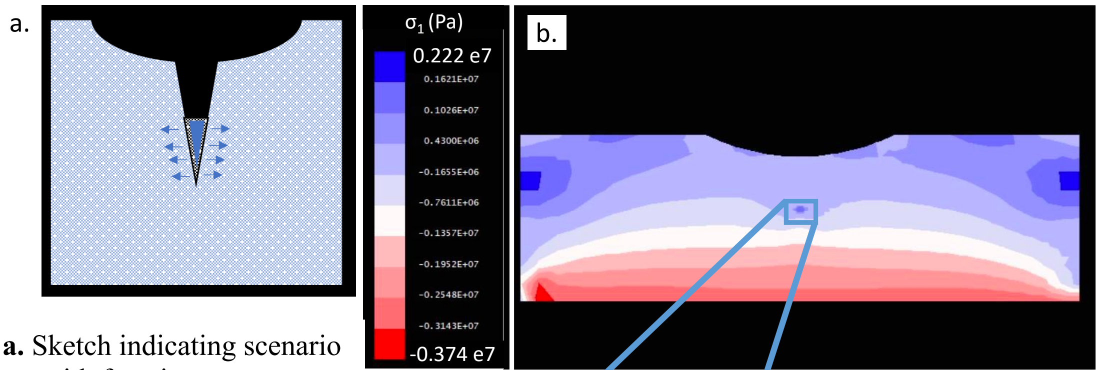


Figure 1. 2D Model setup: 30-km x 9-km, 2D block representing a section of Europa's ice shell showing boundary conditions, feature positions, and crater and crack dimensions.

We modeled two scenarios: (1) Cooling and thickening stresses under Europa conditions, and (2) Outward movement of crack edges induced by impact produced melt-water infill into the lower 1-km region of the crack and subsequent refreeze (Figure 2).

2D Model – Crack Propagation Results: Figure 2a provides a sketch that represents the Scenario 2 conditions where fluid intrusion and subsequent refreezing in the crack causes a small outward pressure (5e4 Pa) to the fracture edges due to volume expansion. This pressure could cause up to 0.9 cm of outward movement on each side of the crack, increasing the tensile stress there and enabling further propagation. Figure 2b and c show the resulting stress surrounding the crack tip. Stress values at the crack tip are tensile and greater than the estimated tensile strength of ice (10^4 – 10^6 Pa [6,7]) indicating that the crack would propagate. We then allowed the crack to propagate until the tensile stress at the tip no longer exceeded the strength of the ice. Under these conditions it was determined the crack could propagate a further 700 meters vertically downwards (Figure 2d).



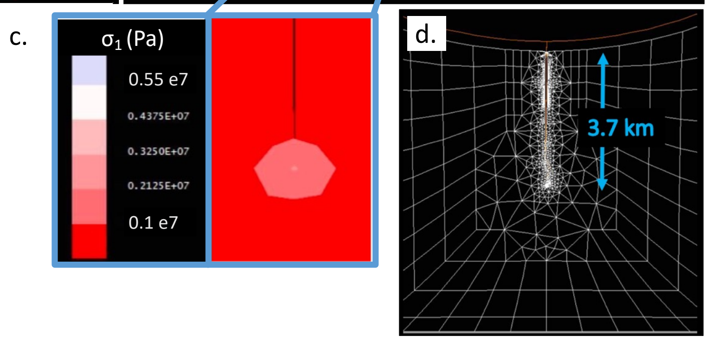


Figure 2. a. Sketch indicating scenario 2 conditions, with freezing water within the crack and subsequent outward motion due to the volume expansion. **b-c.** Stress results at the crack tip for scenario 2, with values over the strength of ice (10^4 - 10^6 Pa) in pink to white in inset c. **d.** Propagation profile of crack. Final crack length reached was 3.7-km below crater bottom.

Discussion and Further Work:

Work by Chen et al. [1,2] indicates that a crack formed in the subsurface due to cooling and thickening of the ice shell at Europa, beneath a region where an impact removes material from above, can propagate to further depths. Additionally, if melt-fluid fills into the crack after the impact, the subsequent refreezing of the fluid can enable the crack to propagate further (Figure 2). This propagation may allow cracks to connect with deeper fracture networks that potentially connect to the ice-ocean interface, which would facilitate surface-ocean compositional mixing.

Further work will include modeling in 3 dimensions in order to consider more realistic crack dimensions and stress effects (Figure 3). Additionally, we plan to apply different conditions for Enceladus and other ocean worlds and explore how variations in these environments (ice shell thickness, tidal stresses, layers/pockets of different densities, initial stress conditions, proximity to multiple cracks, impact damage zone, etc.) may alter crack growth and the resulting implications for habitability.

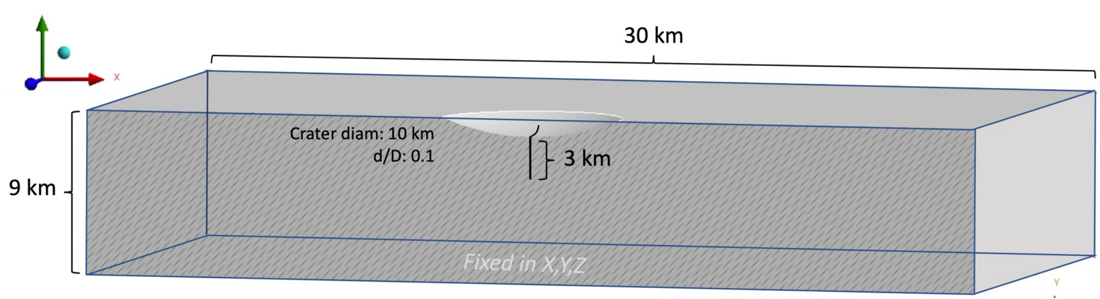


Figure 3. 3D model setup (cross-section view)

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References: [1] Chen et al. (2022), *53rd LPSC*, # 2932. [2] Craft et al., *Ices in the Solar System,* # 4037. [3] Turtle et al. (2001), *Science, 294,* 1326. [4] Rudolph et al. (2022), *GRL, 49(5).* [5] Craft et al. (2016), *Icarus, 274,* 297. [6] Dempsey et al. (1999), *Int. J. Fract. 95*. [7] Lee et. al. (2005), *Icarus, 177.*