POSSIBLE FRACTURE FORMATION POST-IMPACT ON ENCELADUS K. L. Craft[1*], J. Roberts[1], [1]Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Rd., Laurel, MD 20723), *Kate.Craft@jhuapl.edu

Introduction: The small icy moon Enceladus, orbiting Saturn, was discovered to have jets of ice and vapor emanating from its southern polar terrain (SPT) by the Cassini mission [1, 2]. The fact that the activity only occurs at one region, and not also at other areas has not been well explained. Theories suggest a regional sea beneath the SPT or a global ocean that is thicker beneath the SPT feeds a group of fractures observed there called tiger stripes. These fractures may reach from a subsurface sea/ocean all the way to the surface. Researchers have theorized that the tidal stresses acting on the moon as it orbits Saturn open and close the fractures enabling interior volatiles to exit and feed the icy plume observed [e.g. 3]. How, though, did the fractures form initially? Possibly an impact occurred that completely melted a region and as the ice refroze, the continuing tidal stresses worked to form the tiger stripe fractures in the orientations we observe them today. We explore that possibility here.

Previous work by Roberts and Stickle [4] modeled an impact into an ice shell over an ocean and calculated penetration depth and melt temperatures and volumes through the entire shell thickness (Figure 1, [5]). During and post impact fracturing would occur, the crater would collapse, water would begin to refreeze and subsequent fluid exchange would occur. Working forward from a point after impact and as the ice shell begins refreezing, we performed finite element modeling to simulate the probable formation of fractures based on the resulting stress regime. Here we explore fracture formation for shells ranging from 1 km to 5 km thick (consistent with gravity and libration studies), to explore formation as the shell cools and thickens through time.

Methods: Activity at the impact site as the ice cools and thickens could be quite complex. Initial cooling would occur over several hours to tens of days, forming an initial m's thick layer. We began our modeling with a 1 km thick layer and investigated where tidal stresses would act to initiate fractures. The investigation employed a finite element code, FRANC2d (FRacture ANalysis Code, [6]) that calculates displacements/deformation and resulting stress due to imposed loads, specified boundary conditions, and material properties for a 2D body of certain geometry as shown previously in investigations of fracturing on Europa [7]. We began with a model space 150 km across and 3 km deep, representing an ice shell of density, ϱ_{ice} = 900 kg/m^3, Poisson's ratio, ν = 0.3 and Young's modulus, E= 5e9 Pa. A layer of icy regolith was represented in the uppermost 100 m by a material with ϱ_{reg} = 300 kg/m^3, Poisson's ratio, ν = 0.15 and Young's modulus, E= 1e7 Pa based on terrestrial sand values (with a lowered density). Boundary conditions were such that the bottom edge was constrained in the vertical, y, direction and right and left edges were held stationary in the horizontal, x, direction. A gravitational acceleration at Enceladus, g = 0.11 kg/m^2, was also applied. Figure 1 shows the impact, shell thickening and mesh for finite element models.

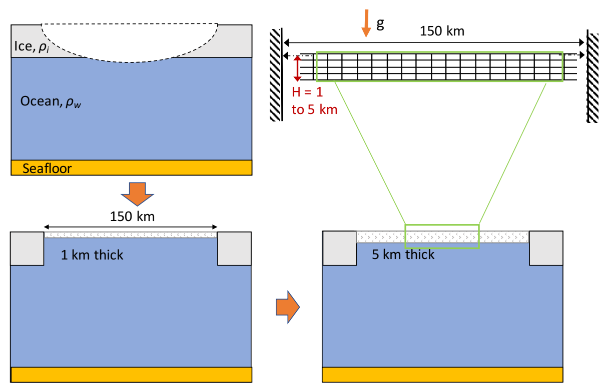

Figure 1. Layers of Enceladus showing initial crater in ice shell at upper left, then a cooling ice layer thickening from 1 to 5 km. Boundary conditions are as shown in zoomed in section at upper right, such that the left and right edges of the layer are held in x, the bottom edge is held in y and the top edge is free. Gravity, g, acts downwards and tidal and volume changes stresses are applied within the mesh area.

A variety of conditions are then employed to consider a range of possible stress regimes including different: original impact locations (latitude and longitude), orientations of the fractures relative to tidal stress forces, increasing stress with depth, and variations with the orbital true anomaly location. Tidal stresses were calculated with the program TiRADE (Tidal Response And Dissipation of Energy) [8]. We then explore where stresses would maximize, as possible fracture initiation locations, as the ice shell undergoes the periodic tidal forces and cooling and thickening stresses caused by the temperature and volume changes, respectively, for an ice shell increasing from 1 to 5 km thick. If tensile stresses are found to be above the strength of ice and lithostatic load, fractures can be initiated there and allowed to propagate as the stress field dictates, following fracture mechanics theory. The tensile strength of ice is approximated at 10^4 to 10^6 Pa according to laboratory and field measurements [8,9]. Fractures that propagate to the sea/ocean are assumed to allow water flow upwards and an outward hydrostatic pressure within the fracture, P_f, is applied that assumes an ocean pressurized by the lithostatic load: $P_f = P_0 - \rho_w g h$, where P_0 is the lithostatic load $=\rho_i g H$, ρ_i is the density of ice, H is the thickness of the ice, ρ_w is the density of water and h is the vertical distance of the water above the base of the ice shell (see Figure 1).

Initial Results: We investigate the stress regime in the ice shell of Enceladus for 3 km and 5 km thick ice shells for the 150 km region width assuming the same latitude and longitude as the current South Polar Terrain (shown in Figure 2) and tidal stresses acting at a periapsis Enceladus orbital location.

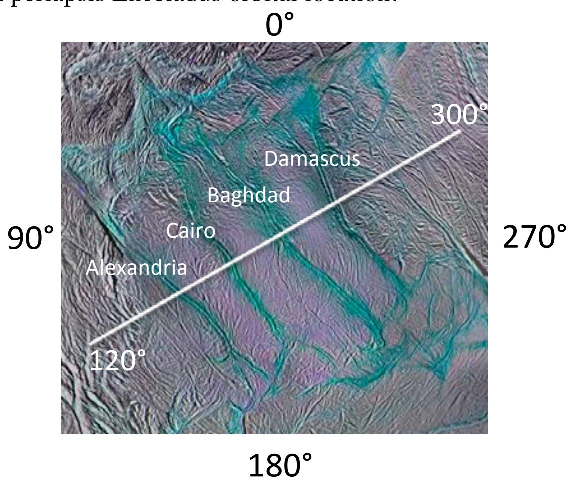

Figure 2. Orientation of tiger stripe fractures for first tidal stress application with Enceladus at periapsis. Tidal forces act perpendicular to fracture strikes and radially outward from center of Enceladus.

The maximum tidal stresses are calculated to act in the locations as shown in Figure 3. Although, total stress values will be a result of the lithostatic load of the ice, the rebound pressure of the ocean water beneath, thermal contraction as well as the volume change stresses of the ice as it freezes, these stresses would act fairly uniform across the shell, with variation resulting from the tidal stress variations. Maximum tidal stress is calculated at the South Pole at periapsis, indicating fractures may initiate at the location of the Bagdad tiger stripe within the shell where the tensional stress overcomes the compressional volume change stress. Further modeling will calculate the combined effects of these sources of stress.

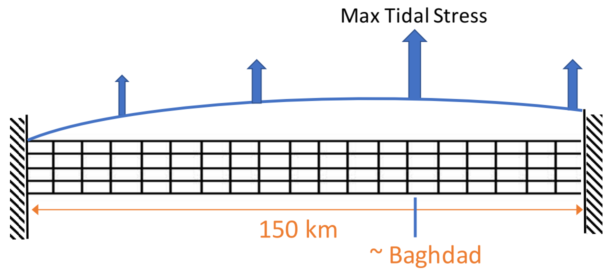

Figure 3. Radial tidal stress magnitude across ice shell with maximum calculated at South Pole at approximate location of the Baghdad tiger stipe across a 300° – 120° longitude.

Changing the impact location to occur at the equator of Enceladus rather than the polar region would alter the tidal stresses and resulting stress regime. Further investigations will employ a tidal stress field acting with the orientation of Longitude 0° (sub Saturn) and centered at Latitude 0° (equator). These additional results will be presented.

As shown in previous work [5] the tiger stripes alone are too far apart to cause interactive fracture effects on the stress fields around the fractures. Although, it is possible that there are fractures within the ice shell that do not reach the surface and are causing stress field changes due to weakening of the ice shell. Any basal fractures allowing water to flow towards the surface would have a similar effect and would also induce thermal stresses from the warmer seawater. Further work will explore these fracture interactions.

References: [1] Porco et al. (2006) *Science, 311*, 1393-1401. [2] Hansen et al. (2006) *Science, 311*, 1422-1425. [3] Hurford et al. (2007) *Nature, 447*, 292-294. [4] Roberts and Stickle, 2017, *LPSC* #1955. [5] Craft and Roberts (2017), *49th DPS*, #220.04. [6] Wawrzynek and Ingraffea (1987), *Theoret. App. Frac. Mech.*, 8. [7] Craft et al. (2016), *Icarus*, *274*, 297-313. [8] Roberts and Nimmo (2008), *Icarus, 194*, 675-689. [9] Dempsey et al. (1999), *Int. J. Fract. 95,* 347–366. [10] Lee et al. (2005), *Icarus 177*, 367–379.