FRACTURE AND FLOW, POSSIBLE POST-IMPACT ACTIVTY ON ENCELADUS K. L. Craft[1*], J. Roberts[1], A. Stickle[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 are theorized to reach from the subsurface sea/ocean and open to the surface. Researchers have theorized that stresses acting on the moon as it orbits Saturn open and close the fractures enabling interior volatiles to release and form the plume observed [e.g. 3]. How, though, did the activity begin? We propose the possibly of an impact that initiated melt and fracturing to a liquid layer below with subsequent geyser activity.

Previous work modeled an impact into a 40 km think ice shell and predicted melt temperatures, volumes and penetration depth through the entire shell thickness (Figure 1, 2017 LPSC abstract by Roberts and Stickle). During and post impact fracturing would occur, the crater would collapse, water would begin to refreeze and subsequent fluid exchange would occur. Working from a point forward after freezing occurs and the ice shell reaches about 30 km thickness, we present here results of a finite element modeling effort to simulate the tiger stripe fractures and the stress regime and tidal forcing effects that would occur in order to understand the amount of opening and closing that is possible considering fracture interactions, tidal stress forcing with orbital location and ocean water pressurization.

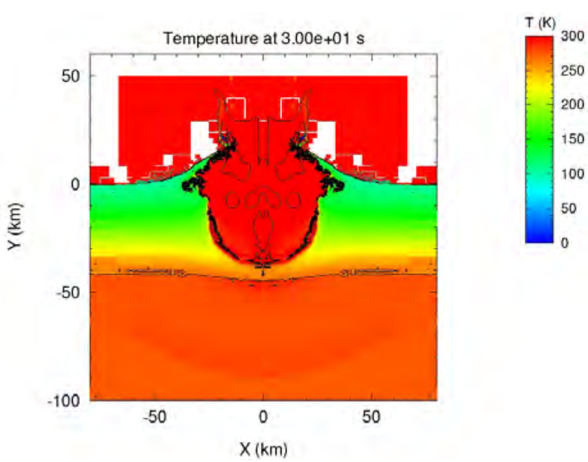

Figure 1. Melt and ice/water temperatures formed after a projectile impact into a 40 km thick Enceladus ice shell (see abstract by Roberts and Stickle, 2017 LPSC).

Methods: To investigate how tidal stresses act to open and close the tiger stripe fractures, we employed a finite element code, FRANC2d (FRacture ANalysis Code) [4]. FRANC2d calculates displacements/deformation 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 [5]. We began with a model space 150 km across and 30 km deep, representing an ice shell of density, ρ_{ice} = 900 kg/m^3, Poisson's ratio, v = 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, v = 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. We then emplaced 4 fractures, labeled the names given from left to right: Alexandria, Cairo, Baghdad and Damascus; from the base of the ice shell up to the regolith layer and pressurized the fractures hydrostatically (assumed pure water) plus pressure from the expansion of the ice shell as it froze to the simulated 30 km thickness, according to calculations by Manga and Wang [6]. Gravitational acceleration at Enceladus g = 0.11 kg/m^2 was also applied. Figure 2 shows the model set-up.

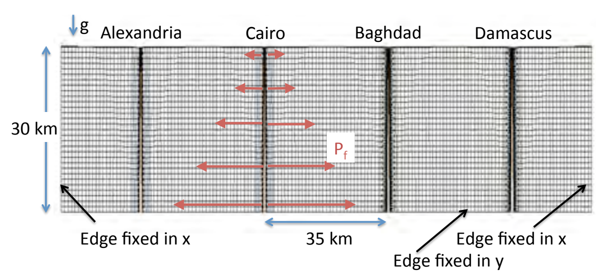

Figure 2. Tiger stripe fracture cross section deformed by gravity in a 30 km thick ice shell (deformation magnified 10x). Fluid pressure, P_f, applied at all fractures and calculated with depth. A 35 km spacing occurs between fractures. Boundary conditions are such that the left and right edges are held in x, the bottom edge is held in y and the top edge is free.

Tidal stresses were then calculated along fractures with the program TiRADE (Tidal Response And Dissipation of Energy) [7]. A variety of stressing conditions were employed to consider a range of possible original impact locations (latitude and longitude), orientation of the fractures relative to tidal stress forces, depth along a fracture and Enceladus true anomaly.

Results: To investigate the maximum opening and closing of the fractures that is possible, we first modeled stresses at a periapsis orbital location, with the fractures located along 120° and 300° longitude lines, crossing the south pole. This orientation is such that the Baghdad fracture is centered at the south pole, Alexandria and Cairo will be to one side of the south pole and Damascus to the other side (Figure 3). Due to symmetry effects, the fractures equal distance from the south pole (Cairo and Damascus) will undergo equal tidal stress forces.

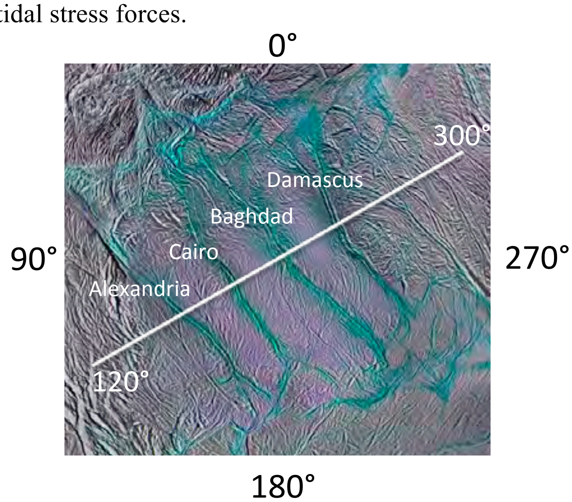

Figure 3. Orientation of tiger stripe fractures for first tidal stress application with Enceladus at periapsis. Tidal forces act perpendicular to fracture strikes.

Figure 4 shows the resulting stress regime for a 30 km thick ice shell under compressive tidal stresses on the order of a few kPa. Simulations determine fluid pressure can open fractures about 4-5 m and tidal stresses would only cause a small fracture opening change, ~1 to 3 cm of closure, with greater closure at increasing depth. Across the 4 fractures only a small difference in opening from fluid pressure and the closure due to tidal stress forces is observed.

Discussion and Future Work: These results indicate the fractures interact at a low level and do not appear to cause a large difference in fracture opening closing that occurs due to tidal stresses. However, further analyses will investigate the sensitivity of fracture interactions to a thinner ice shell case of 10 km (closer in time to post impact) as well as additional orbital locations and a scenario where the initial impact occurs away from the south pole.

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] Wawrzynek and Ingraffea (1987), *Theoret. App. Frac. Mech*., 8. [5] Craft et al. 2016, *Icarus*, *274*, 297-313. [6] Manga and Wang (2007), *GRL, 34.* [7] Roberts and Nimmo (2008) *Icarus, 194*, 675-689.

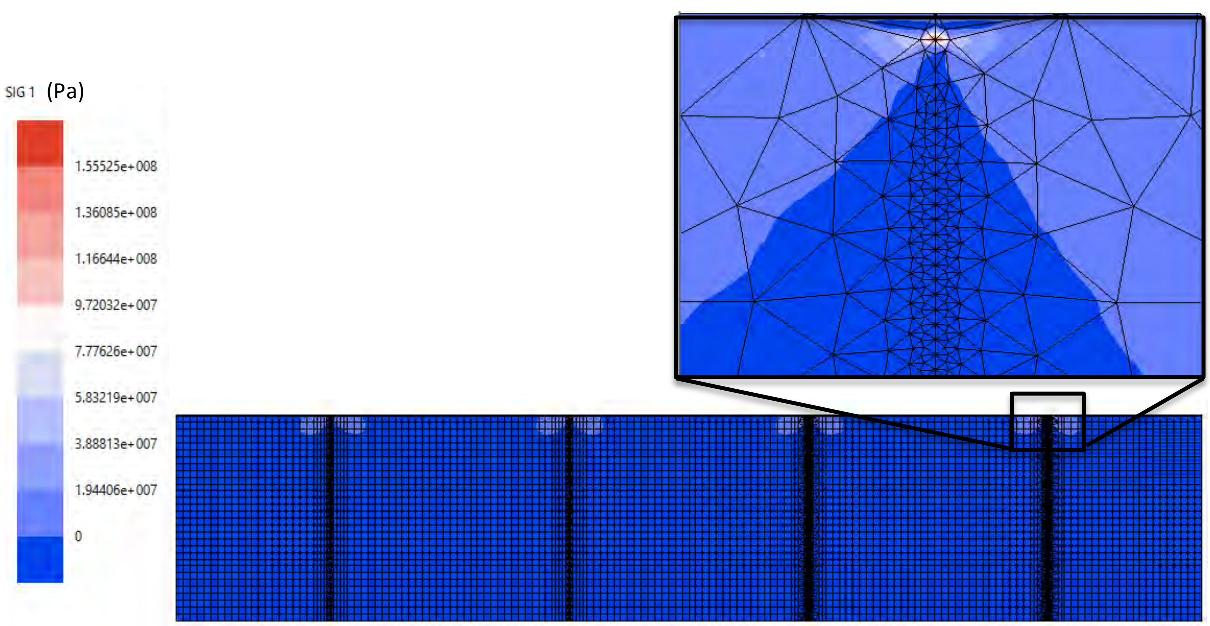

Figure 4. Stress regime results for 4 tiger stripe fractures, with Enceladus at periapsis, along 300°-120° longitude.