STRESS RISERS IN ENCELADUS' CRATERED TERRAIN. Mallory J. Kinczyk[1], Paul K. Byrne[1], Geoffrey C. Collins[2], Gerald W. Patterson[3], DelWayne R. Bohnenstiehl[1]. [1]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, [2]Wheaton College Norton, MA 02766, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

Introduction: Enceladus is among the most enigmatic icy satellites in the outer Solar System. From its combination of extremely young and heavily tectonized terrains to its ancient, heavily cratered surfaces, the interior dynamics of Enceladus' ice shell remain poorly understood. In this study, we focus primarily on the ancient cratered terrains and the characteristics of the ice shell in this region.

The leading model of Enceladus' subsurface composition and structure consists of a likely porous silicate core, a global subsurface ocean, and a conducting or convecting ice shell ~30–40 km thick [1]. Although the detailed structure of the ice shell interior is unknown, there are numerous surface features that hint at spatial and temporal variations in the processes acting on the shell. These features include viscously relaxed craters [2], ancient fault regimes that predate even the oldest craters in the cratered terrains [3], as well as ridges and troughs in the youngest and most active terrains (situated in the leading and trailing hemispheres, and the South Polar Terrain (SPT)).

However, the evolution of the ancient cratered terrain remains poorly understood. An interesting finding in this region is that crater catalogs for Enceladus [4,5] indicate a dearth of craters >1.5 km in diameter along the equatorial region of the sub-Saturnian compared with the anti-Saturnian cratered terrain (at 0° W and 180° W, respectively). In addition to the large, viscously relaxed craters observed across all of the cratered terrains, this paucity of equatorial craters may reflect periods of intense heat flux at Enceladus that could plausibly have reset the local crater retention ages of these units [4]. These observations indicate an active cratered terrain, with potential implications for the nature of the interior.

Crater–Fracture Interactions: Notable in the cratered terrain are systems of fractures (**Figure 1**) that crosscut many of the craters in this region and, in some instances, have orientations that change in proximity to, and so appear influenced by, the underlying crater. These fractures appear to be mode I fractures (e.g., joints) and/or high-angle normal faults resulting from extension [6].

The relatively sharp scarps of these fractures suggest that they are geologically young, having not yet had their forms tempered by impacts or other processes subsequent to their formation. Structural studies of Enceladus to date have focused primarily on the SPT because of its enigmatic and unique morphology, and because of the presence there of active jets [7]. However, the ubiquitous presence of the fresh fractures observed in Enceladus' cratered terrain therefore suggests recent tectonic activity in these regions as well.

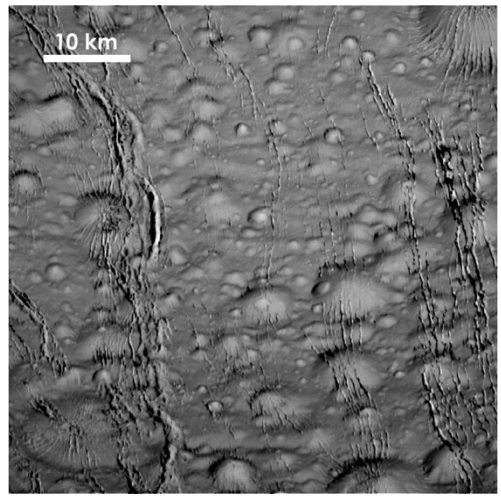

Figure 1. Cratered terrain centered at 55°N, 168°W. Image was acquired during the last Cassini encounter of Enceladus in 2015. Both linear fault segments and radial fracture trends are shown. (Image N1823513436_1)

Previous studies of the nature of fracture reorientation proximal to large craters on Enceladus and elsewhere have proposed a variety of causal mechanisms including the evolution of crustal stresses [8], topographic loading of the crater rim [9], and thermally induced upwelling of ice beneath the impact site [10]. We investigate whether the apparent change of fracture orientation with proximity to craters is possible *without* the influence of these additional mechanisms.

Stress Risers: Much research has been done to quantify the influence of stress concentrators, or "stress risers," on the strength of engineered materials. A stress riser is a local region of high stress in a body that can act as a zone of weakness, and which can take on a variety of shapes [11]. For Enceladus, we consider a model that treats craters as stress risers where stresses are spatially concentrated, resulting in a higher probability of fracturing and consequent modification of the stress field than in areas without craters. A 1953 study [12] developed analytical methods to study the influence of a hemispherical pit in a free surface on the local stress field—a method that has been refined and applied by numerous workers since [e.g., 11,13,14]. The aforementioned study used methods first developed to determine the sensitivity of the stress field to the presence of a

notch in a 2-dimensional space, such as the one depicted in **Figure 2**, to calculate the same sensitivity of the stress field to the 3-dimensional representation of a hemispherical pit in a surface. By testing this model with boundary conditions analogous to those expected at Enceladus, we may better understand whether large craters are simply points of weakness (stress concentrators) or if there is an additional process happening at the craters themselves (such as those described earlier).

Preliminary Results: We first focus on statistically verifying the nature of the observed change in fracture orientation. Rather than characterizing the orientations of individual fault traces as in previous investigations [e.g., 8–10], we take a 2-dimensional approach by comparing the spread of fault strikes at given radii from the crater rim. Using our catalog of morphologically fresh fractures in the cratered terrain as well as the global crater database [5], we identify craters within the anti-Saturnian cratered terrain that are cross-cut by fractures that themselves appear to change orientation closer to the crater rim. To statistically verify that fracture orientations do indeed change (and to what degree they change) as a function of distance to craters, we compare the spread of fault strikes at 0.5 radius from the crater rim (r_c), and again at 0.5–1.0 r_c, 1.0–1.5 r_c, and 1.5–2.0 r_c (**Figure 3**). Using a circular statistical method [15] to compare azimuths at different radial distances from the crater rim, we find that fracture strike does change in a statistically significant manner with distance near several large craters in the anti-Saturnian cratered terrain.

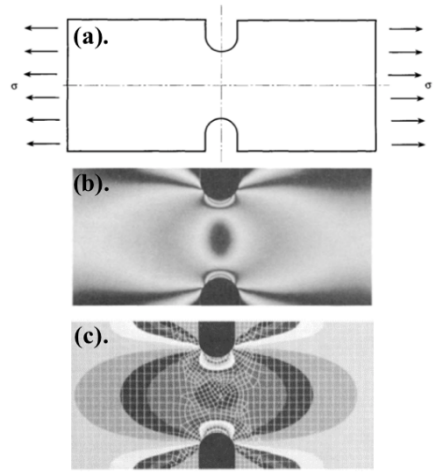

Figure 2. Tension bar with notches acting as stress risers: (a) schematic; (b) photoelastic fringe photograph; (c) finite element solution. Figure from [11].

Outlook: We are currently developing a finite element model to replicate a stress field capable of producing the pattern of strain we observe at large craters on Enceladus. When the differential stress exceeds the elastic limit of the brittle portion of the ice shell, the strikes of the fractures so formed are influenced by the relative orientations of those stresses in the horizontal plane (i.e., σ_2 and σ_3 for extensional fractures). A comprehensive comparison of predicted fracture orientations from model stress fields with our observations will help determine if crater depth/diameter (and/or the presence of an associated damage zone) has a systematic controlling effect on fracture strike.

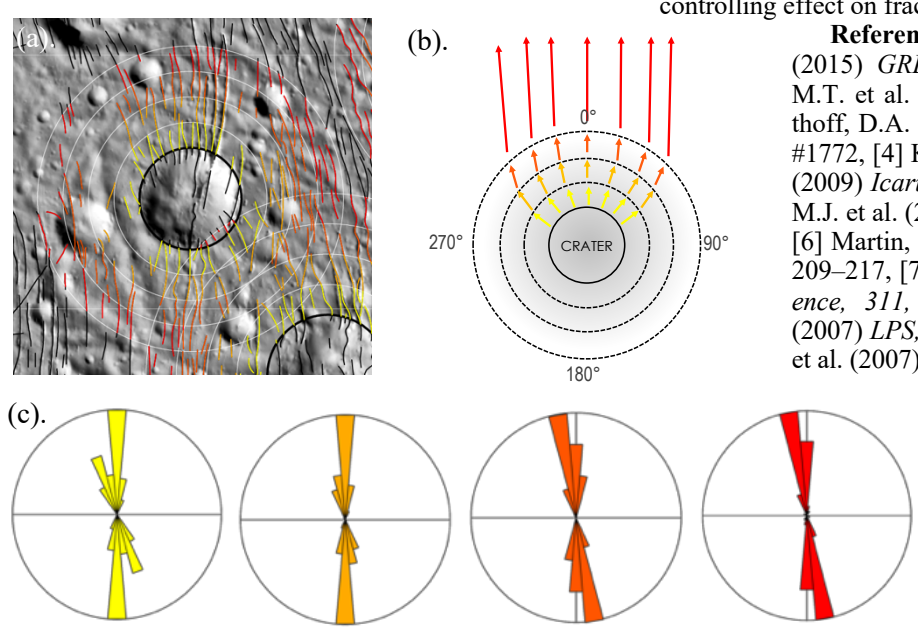

Figure 3. Example of strike analysis. (a) 6.8-km diameter crater centered at 6.6°N, 162.3°E. Zones of analyzed fault fragments are outlined in white. (b) Conceptual model of fracture reorientation proximal to crater. Strike orientations have a broader spread close to the crater and more uniform farther from the crater. (c) Rose diagrams of strike orientations for each zone ordered in ascending distance from rim.

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