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# Forming the Tiger Stripe Fractures with eccentricity tides

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## Abstract

Enceladus has a young, tectonically active south polar region, including a prominent set of fractures called Tiger Stripes. No comparable activity is observed at the north pole, which is heavily cratered with relatively limited tectonism. Given the many lines of evidence supporting a global ocean under Enceladus' icy shell, the reason for the dichotomy in geologic activity is unclear. We examine the magnitudes of tidal stresses with different ice shell structures, and compare the tidal stress orientations with the prevailing orientations of the Tiger Stripe Fractures (TSFs), to explore how eccentricity-driven tidal stresses might explain their formation and the dichotomy in tectonic activity between the two poles. Assuming that Enceladus' ice shell has a similar strength to Europa's, we find that differences in ice shell structure can produce a change in tidal stress magnitude that could lead to fracturing at the south pole and no comparable fracturing at the north pole. We also find that the prevailing orientations of the TSFs are highly correlated with the current eccentricity-driven tidal stress field when we apply a threshold failure condition rather than assuming the ice fails at the maximum daily stress. We conclude that 1) eccentricity-driven tidal stresses played a dominant role in determining the orientations of the TSFs and 2) the hemispheric dichotomy in geologic activity is due to a difference in shell thickness between the two hemispheres.

## 1. Introduction

There is now a substantial body of evidence to support a global ocean under the ice shell of Enceladus [1-6], but the thickness of the shell is not well-constrained and is likely non-uniform. Attempts to match Enceladus' librations and gravity have resulted in estimates for the thickness of the ice shell at the south pole that range from >10 km to <1 km. The north pole is thought to be ~10 km thicker than the south [1-4].

The two hemispheres differ greatly in the extent of geologic activity preserved on their surfaces: the south polar region is crater-free, riddled with overlapping fractures, and has sustained eruptions from the TSFs, while the north polar region is heavily cratered [5][6]. The origin of the TSFs is a mystery. Eruptive output along the TSFs varies with the tidal cycle, suggesting that tides raised by Enceladus' eccentric orbit are modulating the eruptions [7]. However, eccentricity-driven tidal stresses are expected to be an order of magnitude lower than the tensile failure strength of ice derived from laboratory tests [8-10]. Forming the TSFs from these stresses is, thus, challenging, although tidal stresses of similar magnitude are strongly correlated with the orientations of fractures on Europa [11][12] – another ocean-bearing moon in an eccentric orbit.

## 2. Methods

We measured the orientations of the most prominent branches of Alexandria, Baghdad, Cairo, and Damascus (i.e. the Tiger Stripes) at over 2000 points along their lengths in a coordinate system that is appropriate for polar features (clockwise from the 0° longitude line). We then fit Gaussian curves to the distributions of observed orientations for each individual TSF to determine its prevailing orientation.

We computed tidal stresses using the approach of [13], which enabled us to specify a thickness and set of material parameters for a rocky interior overlain by an ocean and two-layer ice shell (brittle over ductile). We varied the total thickness of the ice shell, the depth of the outermost brittle ice layer, and the viscosity of the ductile ice layer, using constraints derived from the literature [8-10]. At each location, we calculated principal tidal stresses through an orbit.

To quantify the differences in tidal stress magnitude introduced by differences in ice shell thickness, we identified the largest magnitude tensile stress ever achieved across all locations and times to determine a peak regional tensile stress for each interior structure model. We made the assumption that fractures only form in models with peak regional stress that exceeds the range implied by fractures on Europa (> ~50 kPa). We also computed the orientations of the principal tidal stresses at each location throughout an orbit. We then assumed that fractures will form perpendicular to the most tensile principal stress when the failure criterion is reached. We tested two criteria: 1) failure at a given location occurs when the tidal stress has reached its daily peak value, regardless of its magnitude and 2) all locations will fail at the same threshold of stress, regardless of how large the stress might become later in the orbit. We produced histograms and Gaussian fits to the distributions to compare the predicted orientations with observations.

## 3. Results and Discussion

We find that ice shells ≤ 5km thick can produce tidal stresses much larger than those on Europa (170 – 415 kPa), even with high viscosity ductile ice. Thicker shells with a low viscosity ductile layer ($10^{13}$ Pa*s) produce tidal stresses that are comparable to Europa's (37 – 102 kPa). Only in thick shell cases with ductile ice viscosities $>10^{13}$ Pa*s do the stresses drop below values inferred from fits to Europa's fractures (16 – 43 kPa). Even the largest tidal stress magnitudes we find are lower than the strength of ice determined from laboratory testing (~1MPa) by about a factor of 2. If the interior is cooling, and the ocean is freezing out, additional stresses could be combining with tidal stresses to achieve failure [14].

If we assume Europa-derived failure thresholds, we find two scenarios that can explain the hemispheric dichotomy in tectonic activity: 1) the ice shell is thin (≤5km) at the south pole and ~10 km thicker at the north pole or 2) the ice shell is of order 10 km at the south pole and at least 20 km at the north pole. In the latter case, the ice shell at the south pole would have to maintain a relatively low viscosity to achieve high stresses, which may be possible if the shell is convecting. In both cases, the ice shell at the north pole would have to have a higher viscosity to suppress stress magnitudes. Due to the higher overall magnitudes of tidal stress in the thin shell cases, along with other *Cassini* measurements that suggest a thin shell at the south pole, we favor that scenario.

Looking now at the formation of the Tiger Stripes, when we assume that failure will always occur at the daily peak stress, the predicted and observed orientation distributions were not well matched for any of the TSFs (differing by 25 – 35°). However, when we assumed a consistent threshold for failure (i.e. 100 kPa), the peak in the predicted distribution of orientations matched almost exactly with the peak in the observed orientations. This result is consistent across significantly different interior structure models. The exact value of the stress threshold we assume will alter the distribution; we find that a threshold of $^2/_3$ to $^3/_4$ of the peak regional stress for a given interior model provides the best fit to the observations. The uncertainty in the failure threshold makes it challenging to constrain the structure of Enceladus' ice shell; both thick shell and thin shell models can match the prevailing orientations of the TSFs by adjusting the threshold.

Using the threshold failure criterion, we achieve an excellent match between the present-day stress field and the observed orientations of the TSFs. Hence, we see no need to invoke non-synchronous rotation to explain the orientations of the TSFs [c.f. 15]. However, we cannot rule out the potential for NSR to have affected the formation of previous sets of fractures, as suggested by [16].

The tidal stress model predicted a much narrower range of orientations than we identified over our 2000+ data points, which suggests that the nucleation and propagation of fault segments was complex, with tidal stresses governing the overall orientation but not the details. More sophisticated modeling of the fracture process could enable stricter constraints.

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