FIRST TECTONIC-STRESS MAP ACROSS ENCELADUS' SPT AND POSSIBLE DYNAMIC CAUSES

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Introduction: The outer solar system consists of a diverse population of icy satellites, but our understanding of their evolution remains in its infancy. Enceladus, a small (diameter ~500 km) moon of Saturn, provides a unique opportunity to explore the mechanical behaviors of icy satellites due to its unique geology, which is characterized by geysers erupting cyclically at the moon's south pole. The plumes of these geysers are sourced from a series of parallel ''tiger-stripe" fractures (TSF), and are composed of gas and water-ice particulate. Plume materials originate from a global water ocean beneath Enceladus' outer ice shell, making Enceladus a leading candidate in the search for extraterrestrial life [1].

The cyclic nature of the plume's eruption, the periodicity of which matches the orbital period of the satellite, has been attributed to daily variations of tidal stresses acting on the moon; stresses across the tiger stripes alternate from compressive to tensile over Enceladus' orbital period, allowing portions of the TSF to either open or close [2]. These daily stresses are thought to be a consequence of Enceladus' eccentric orbit around Saturn. The problem with this hypothesis is that there is an offset in timing between Cassini's observations of peak eruption and what is predicted by the theory of tidally modulated cracks as driven by orbital eccentricity [3].

Pre-stressed Conditions: Existing models have attempted to reconcile the plume timing discrepancy by invoking stress relaxation in a viscoelastic ice sell [3][4][5]. However, such an approach assumes the stress in the ice shell to be entirely induced by tidal stress, neglecting the role tectonically induced stress must play in order to support the high (>1 km) topographic relief around the moon's south pole [6]. With observational evidence to support tectonic stresses in the ice shell, the viscous relaxation model falls short. We propose to address this blind spot in previous models by relaxing the assumption of a tectonic stress-free ice shell and offering an analytical tensor analysis decomposing tidal and tectonic stresses. Tectonic stresses could be induced, for example, by lateral variation of ice-shell thickness [7][8] or warm ice convection below the brittle ice shell [9]. Pre-existing stress conditions from nonsynchronous rotation could also play a role in the stress regime governing plume eruption [10].

Methodology: We investigate the total stress as a result of three stress sources: tidal stress creating an averaged bulge figure, stress induced by physical libration, and tectonic stresses. We hypothesize that the observed delay in eruption is a result of the relative difference in magnitude of these three stresses. The mathematical framework we employ to calculate tidal stress follows the expression for varying stress as described by the Vening-Meinesz equations for a decoupled, thin shell. The total stress can be represented as such:

$$\sigma_{ij}^{D}(x,y,t) = \sigma_{ij}^{L}(x,y,t) + \sigma_{ij}^{B}(x,y) + \sigma_{ij}^{E}(x,y)$$

where σ_{ij}^{D} is the total diurnal stress tensor, σ_{ij}^{L} is the libration-induced stress tensor, σ_{ij}^{B} is the tidal bulge-induced stress tensor, and σ_{ij}^{E} is the tectonic stress tensor.

We are interested in the tectonic stresses in the South Polar Terrain (SPT) where the tiger-stripe fractures (TSFs) are at the critical state of frictional instability. Thus, we assume the fault is at the critical stress of tensile failure (plume eruption), such that $\sigma_1^{D} = \rho g h/2$ and $\sigma_3^{D} = -T_0$**,** where T_0 is tensile strength of the brittle ice shell, ρ is the ice-shell density, and g is gravity on the surface (Figure 1). Our goal is to determine the magnitude of σ_3^{E} and thus the tectonic stress tensor. This can be achieved by solving first for the tensor components of $\sigma_{ij}^{D}(x, y)$, and then for the tensor components of $\sigma_{ij}^{E}(x, y)$.

We built a MATLAB code with the aforementioned framework, and use this approach to deduce the magnitude and direction of tectonic stress tensors at numerous sites along the active TSFs. The points selected correspond to active jets as observed by Cassini [11]. The code is run for various points along Enceladus' orbit: at periapsis, five hours past periapsis (preliminary results), apoapsis (when peak plume eruption is predicted), and five hours past apoapsis (when peak eruption is observed). For each of these points along the orbit, ice shell thickness (h = 3 km, 7 km, and 13 km) and tensile strength of the ice shell ($T_0 = 10^6$ Pa, 5×10^6 Pa, and 10^7 Pa) is varied to see how these parameters effect the calculated stress field.

Preliminary Results

i) Maximum Shear

We ran the code for an ice shell 13 km thick, with a tensile strength of $T_0 = 10^6$ Pa, 5 hours past periapsis. The preliminary results for maximum shear are plotted on an ISS mosaic of Enceladus' SPT in Figure 2. The results indicate that the magnitude of maximum shear varies systematically across the TSF: it appears generally higher on the right side of the mosaic (trailing edge), and generally lower on the left (leading edge), with local variability at fault branching points. The areas of higher maximum shear are found adjacent to regions of compressional faulting along the Trailing Edge Margin (TEM), while the lower magnitudes are found adjacent to regions of extension within the Leading Edge Margin (LEM) [8].

ii) Orientation of Sigma 1

The preliminary results for orientation of σ_1^E are plotted on an ISS mosaic of Enceladus' SPT in Figure 2. Results indicate a general trend of sinusoidal rotation across the TSF, the orientation of σ_1^E oscillating across the SPT, trending from the LEM to the TEM. Results once more indicate local variability within fault branches. The overall trend of these results suggests toroidal motion, and are consistent with regional clockwise rotation across the SPT and left-slip bookshelf faulting along the TSFs. Non-synchronous rotation (NSR) between the solid ice shell and underlying liquid ocean could be one possible cause of toroidal flow beneath the SPT; deformation induced by NSR could be accommodated by viscoplastic shear in the warm SPT ice. Alternatively, localized warm ice convection could be one cause, answering the question of why activity is focused on the south pole. A final possibility is a two step model: plume heating underneath the SPT followed by viscous spreading that produces a torque, inducing SPT rotation.

Discussion: The work that we've presented here is a first order attempt to tackle the validity of assuming a tectonically stress free ice shell when modeling the opening and closing of the TSFs. We find tectonically derived stresses to be non-trivial; while these results are perhaps not surprising, the need for a more comprehensive plume eruption model, one that includes both tidal and tectonic stresses in its mathematical framework, is evident. We posit that perhaps the fundamental questions of eruption timing may lie in cultivating this understanding.

This work is just the first step in a greater exploration of ice-shell deformation and tectonics. We do not evaluate how stress interacts spatially within this simple mathematical framework; we are only evaluating singular points along the fault, without insight into how their locations are kinetically linked. In addition to this, we assume only that the shell has tensile strength, and for simplification purposes do not include rheological constraints. Eventually, we intend to build a numerical model with visco-elasto-plastic rheology in order to explore ice-shell deformation processes at various time scales; these tectonic calculations will offer a quantitative constraint for that model. There are three end-member geologic scenarios we are interested in exploring with these contraints: gravitation spreading, localized plume upwelling, and nonsynchronous rotation. While an elastic framework is valid for diurnal cycles, a viscoplastic approach would be more appropriate for exploring the evolution of stress over longer geologic times [7][8]. Tidal stressing no doubt drives short-term plume activities at the pole, yet we propose that non-tidal, pre-stressed conditions are perhaps primarily responsible for the observed delay in plume eruption.

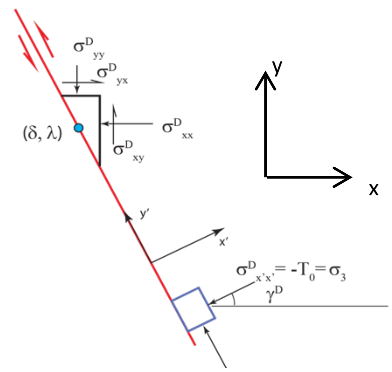

Figure 1: The geometry of stresses acting on the fault. (δ,λ) indicates the geographical coordinate of the point being evaluated, while γ is the orientation of the fault with respect to the normal.

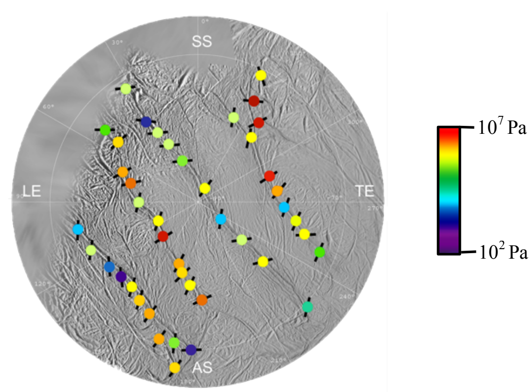

Figure 2: Magnitude of maximum shear (colored points) and orientation of σ_1^E (black line) plotted on an ISS mosaic of the SPT. TE stands for "trailing edge", LE for "leading edge", SS for "sub-saturnian", and AS for "anti-saturnian.

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