A FIRST ORDER MECHANICAL ANALYSIS OF THE STRESS REGIME DRIVING TECTONIC ACTIVITY IN THE SOUTH POLE OF SATURN’S MOON ENCELADUS.
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Introduction: Enceladus is a small moon of Saturn, distinguished by its uniquely active south pole. The moon’s geological activity is expressed as cyclic eruption of plumes, composed of gas and water-ice particulate, sourced from a series of parallel “tiger-stripe” fractures (TSF) [1]. The cyclic nature of the plume’s eruption has been attributed to diurnal variations of tidal stresses acting on the moon, possibly inducing phases of opening and closing along the TSF [2]. The diurnal stresses, at least in part, are understood to be a consequence of Enceladus’ eccentric orbit around Saturn. There is, however, a mismatch in timing between Cassini’s observations and the theory of tidally modulated cracks opening and closing as driven by orbital eccentricity [3].

Physical libration due to Enceladus’ non spherical shape would produce diurnal oscillation in the longitude of Enceladus’ tidal bulge as it orbits Saturn, and could perhaps have a profound effect on the diurnal tidal stresses experienced by the surface of the satellite [4]. Nimmo et al. 2014 suggests that a 1:1 resonant between physical librations and the orbital period of Enceladus could potentially be responsible for the ~5 hour delay in expected plume eruption [3]. Another model to explain the eruption delay relates to the ice shell itself experiencing a lag in response to the perturbing tidal potential, and may be a natural consequence of the viscosity structure in the south-polar region and the size of the putative subsurface ocean [3] [4].

Methodology: The goal of our stress tensor analysis is to provide a simple model with which to conduct a first order mechanical analysis of the stresses acting on Enceladus’ south pole and the implications this might have on constraining the physical parameters of the icy substrate of the south pole.

We attempt to derive the pre-stressed (non-tidal) conditions operating on the south pole of Enceladus with the simplified understanding that

\[
\text{Total } \sigma_{xx} = T_0
\]

where \( T_0 \) is the tensile strength of ice, and is equal to \( \sigma_{xx} \) (primary) + \( \sigma_{xx} \) (tidal).

Our analysis incorporates diurnal tidal stresses that follow the expression for varying stress acting on a hypothetical tiger stripe fault, as described by the Vening-Meinesz Equations for a decoupled, thin shell. [5] [6] Our mathematical framework incudes contributions from physical librations to the overall diurnal tidal stresses acting on Enceladus’ ice shell, as well as optical librations owing to the eccentricity of Enceladus’ orbit around Saturn [5].

Implications: With an understanding of the primary stress conditions of the south pole, we can build a simple framework to relate pre-stressed conditions to mechanical properties of the south polar ice substrate, as well as to the thickness of the brittle fracture layer. We operate with the assumption that normal stress on the fault and potential failure shear planes are comparable to the lithostatic pressure [7]. Given the high topographic relief (> 1 km) around the SPT, topographic and/or gravitationally induced stress is important and perhaps even dominant in the ice shell.

This is a simple but important start in understanding the mechanical evolution and driver of the tiger stripe fractures; understanding how the tiger stripes were initiated, and the subsequent maintenance of their motion via brittle deformation, is essential for determining the controlling mechanisms of active geologic processes and plume eruption on Enceladus [8].