COMBINING STRESSES FROM DIURNAL TIDES AND A PRESSURIZED OCEAN ON ENCELADUS.

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Introduction: Enceladus is a geologically active icy satellite of Saturn with a radius of only 252 km. The south polar terrain (SPT) is a heavily fractured, geologically young region that contains the source of the active jets erupting from the largest fissures in the region [1,2]. The fractures and activity at the SPT may provide insight into the sources of stress on Enceladus both current and past. The sources of stress typically proposed to explain the tectonic activity of Enceladus are related to tidal activity or ice shell thickening [3]. These models provide valuable insight into the geologic setting on Enceladus but commonly assume a uniform ice shell thickness, which would not be the case if there is a regional sea [4] or ocean thickening beneath the SPT [5,6].

A regional sea has been proposed based on the observed active plumes, heat flux [7] and depressed topography of the South Pole [4]. The presence of liquid water beneath the ice shell has important implications for the tidal stresses [8] in the ice shell. A regional sea on Enceladus can either be positively pressurized (crystallizing) or negatively pressurized (melting) relative to the hydrostatic pressure state. Previous models of the global stresses arising from ocean pressurization [9] exclude tidal stresses and therefore are axisymmetric.

The stresses from diurnal tides and a pressurized ocean can be complimentary stresses. Here we combine the stress fields from these models to gain insight into the interaction of the stresses and the origin of tectonic activity on Enceladus.

Models: *Pressurized Ocean.* For calculating the stresses resulting from a pressurized ocean we use an axisymmetric elastic model developed using COMSOL Multiphysics™. The models considered here has a 40km thick cryosphere that is allowed tangential movement relative to the rigid interior (Figure 1). It predicts faulting at Enceladus' poles, as is observed. A buoyant restoring force is imposed on the surface to account for the density contrast of any uplifted material. A thicker cryosphere (80 km), bonded cryosphere-interior interface, and a range of ocean sizes are also considered. An overpressurization of 10 kPa is applied to simulate progressive crystallization in a confined ocean. Stresses at the surface of the ice shell are extracted and combined with the stresses from the diurnal tidal stress model.

Diurnal Tides. The diurnal tidal stresses are calculated using SatStressGUI [10], which uses a 4-layer viscoelastic satellite model where the outer 2 layers are divided into an upper more-viscous ice layer and an inner less ice viscous layer. The third layer is a global liquid ocean, and the fourth is the core. We assume the satellite has the constitutive propers shown in Table 1. Only stresses from diurnal tides are considered for the results shown here.

Layer	ρ (kg/m^3)	*E* (Pa)	ν	*T* (km)	μ (Pa s)
Upper Ice	917	9.107x10^9	0.330	38	10^{22}
Lower Ice	917	9.107 x10^9	0.331	1	10^{13}
Ocean	100	0	0.000	1	0
Core	3660	10^{11}	0.300	212	0

Table 1. Input parameters for SatStressGUI modeling. (ρ is density, *E* is Young's modulus, ν is Poisson's ratio, *T* is layer thickness and μ is viscosity).

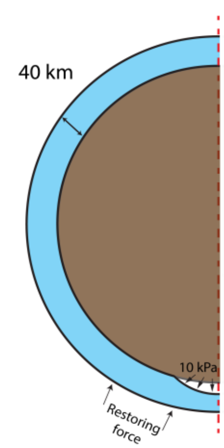

Figure 1. Pressurized ocean model. The cryosphere is 40 km thick and is allowed tangential movement (roller boundary). An over pressure of 10 kPa is imposed to simulate the presence of a pressurized ocean.

Results: Figure 2 shows the maximum principal stresses at periapsis. (A) Includes only the stresses from the diurnal tides, (B) includes the stresses from the diurnal tides and small regional sea, and (C) includes the stresses from the diurnal tides and a larger (deeper and wider) pressurized ocean in the southern hemisphere.

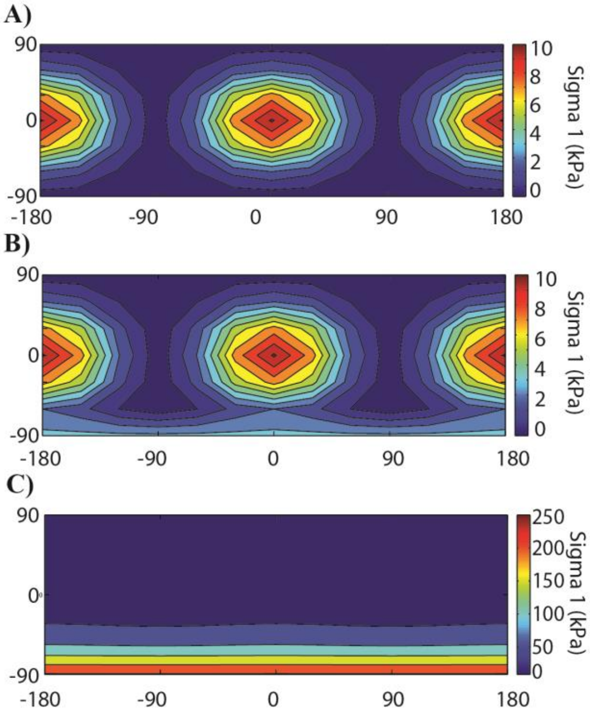

Figure 2. The maximum principal stress (σ_1) on Enceladus calculated to result from A) diurnal tidal stresses only, B) diurnal tidal stresses and stresses resulting from a small, pressurized ocean, and C) diurnal tidal stresses and stresses resulting from a large pressurized ocean. Tidal stresses are at periapsis.

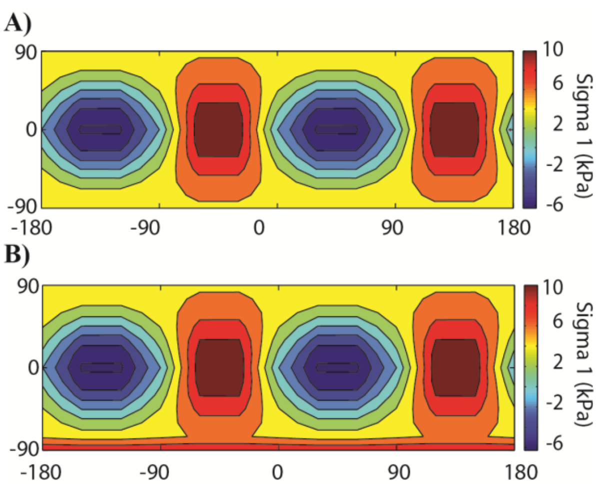

Figure 3. The maximum principal stress (σ_1) on Enceladus calculated to result from A) diurnal tidal stresses only and B) diurnal tidal stresses and stresses resulting from a pressurized ocean. Tidal stresses are at 90˚ past periapsis with a small ocean.

Figure 3 shows the maximum principal stress 90˚ past periapsis considering the diurnal tides only (A) and the combined diurnal tides and pressurized ocean (B) for a small regional sea beneath the South Pole.

Discussion: The relative magnitude of stress from the diurnal tides and ocean pressurization varies significantly depending on the size of the ocean and the thickness of the ice shell (Figure 2). If a pressurized south polar ocean does exist on Enceladus, it may contribute significantly to the stress field in the ice shell.

The combination of stresses in the manner shown here are only a first order result. The assumptions and construction of the two models are not entirely consistent with each other. SatStressGUI assumes uniform layers, while the pressurized ocean model assumes a thinned ice shell at the South Pole. A non-uniform ice shell is likely to have a significant impact on the orientation and magnitude of stresses in the ice shell [5] and tidal stresses. Additionally, the pressurized ocean model assumes a uniform rheology for the ice shell rather than the upper and lower ice shell rheology used in SatStress. A more rigorous treatment and integration of these two sources of stress would be needed, but is unfortunately not trivial. Modeling the stresses from a pressurized ocean in three dimensions proved to be problematic, and tidal stresses cannot be calculated in an axisymmetric model.

It is possible that because of the differing time scales (hours for diurnal tides rather than hundreds of years for a pressurized ocean) that the background stress state from a regional ocean can be imposed on a tidal stresses model and assumed constant. However, a more complete simulation requires the development of a model that can calculate the tidal stresses on an ice shell with a complex geometry.

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