Limits of Enceladus’s ice shell thickness from tidally driven tiger stripe shear failure

John G. Olgin, Bridget R. Smith-Konter, and Robert T. Pappalardo

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[1] Enceladus’s south polar thermal anomaly and water-rich plumes suggest the existence of a subsurface ocean, which is overlain by an ice shell of uncertain thickness. Our objective is to constrain Enceladus’s ice shell thickness, through assessment of tidally driven Coulomb failure of Enceladus’s tiger stripe faults. We find that thin to moderate ice shell thicknesses (<40 km) support shear failure along the tiger stripes, assuming low ice coefficients of friction (0.1–0.3) and shallow fault depths (<3 km). These results are marginally consistent with the minimum ice shell thickness which can permit convection within Enceladus’s ice shell. A plausible scenario is one in which the heat loss and tectonic style of Enceladus has changed through time, with convection initiating in a thick ice shell, and tiger stripe activity commencing as the ice shell thinned. Citation: Olgin, J. G., B. R. Smith-Konter, and R. T. Pappalardo (2011), Limits of Enceladus’s ice shell thickness from tidally driven tiger stripe shear failure, Geophys. Res. Lett., 38, L02201, doi:10.1029/2010GL044950.

1. Introduction

[2] Cassini observations of the south polar region of Enceladus revealed four large linear faults, nicknamed the “tiger stripes,” associated with anomalously high geothermal gradients and active jets that supply a broader plume at Enceladus [Porco et al., 2006; Spencer et al., 2006]. The tiger stripes are thought to be sites of tectonic strike-slip and/or oblique open-close motions [Nimmo et al., 2007; Hurford et al., 2007; Smith-Konter and Pappalardo, 2008], which are likely a result of tidally induced stresses that are exerted on the satellite during its 1.37 day (diurnal) orbital path around Saturn. It has been suggested that a subsurface ocean may exist at Enceladus, based on the tidal amplitude necessary to permit significant tectonic displacements at the surface [Nimmo et al., 2007], detection of a 40Ar and ammonia within plume material [Waite et al., 2009] and salts within associated E-ring material [Postberg et al., 2009]. However, there are few constraints on the thickness of the ice shell or ocean. Convection models of Enceladus [Barr and McKinnon, 2007] suggest an ice shell >40 km thick is required for convection to initiate, but this is a loose constraint.

[3] Assuming that shear failure is a viable mechanism for tiger stripe activity, here we explore possible constraints for Enceladus’s ice shell thickness by assessing diurnal tidal stresses along the tiger stripes. In this study, contributions of both shear and normal stress are considered in a Coulomb failure model [Smith-Konter and Pappalardo, 2008] and we investigate the effects of ice shell thickness, coefficient of friction, and fault depth. Here we pose the question: What is the upper bound on the thickness of Enceladus’s ice shell, along with the range of ice frictional coefficients and fault depths, that permit Coulomb failure along the tiger stripe fault segments?

2. Tiger Stripe Fault Failure Models

[4] In this study, our fundamental objective is to develop a fault failure model that best represents shear failure along the tiger stripes. We focus on diurnal tidal stresses to determine if they are sufficient to provide driving forces for shear and normal fault motions to occur along the tiger stripes. To examine diurnal Love numbers (h1, l2) appropriate to Enceladus and to extract the tidal diurnal stress components, we utilize SatStress [Wahr et al., 2008], an available numerical modeling code that calculates the 2D tidal stress tensor at any point on the surface of an icy satellite for diurnal and/or nonsynchronous rotation stresses. SatStress is parameterized into four layers: upper ice shell (more rigid), lower ice shell (less rigid), global liquid ocean, and rocky core. In this study, we assume an upper ice shell thickness of 3 km2 a combined H2O layer thickness (i.e., upper and lower ice shell (H) + ocean layer) of 95 km [Nimmo et al., 2007], and a rocky core radius of 156 km (see auxiliary material). We also adopt the following SatStress parameters for all models: Poisson ratio ν = 0.33; gravity g = 0.11 m/s2; ice density ρ = 0.92 g/cm3; total planet radius r = 252 km; satellite mass = 1.08 × 1022 kg; orbital semi-major axis = 2.38 × 109 m; and orbital eccentricity e = 0.0047 (parameter values from Nimmo et al. [2007]). In this investigation, we assume a shear modulus μ = 3.5 GPa [Moore and Schubert, 2000], an upper ice shell viscosity ηu = 1012 Pa s and lower ice shell viscosity ηl = 1013 Pa s (see auxiliary material). We note that while alternative models have been suggested to explain the source of plume activity along the tiger stripes (i.e., dilatation along cracks [Hurford et al., 2007] or clathrate decomposition [Kieffer et al., 2006]), this study focuses solely on the effects of shear failure based on the assumption of a strike-slip faulting mechanism [Nimmo et al., 2007; Smith-Konter and Pappalardo 2008].

[5] We first calculate Love numbers h1 and l2, which are indicative of tidal radial displacements and latitudinal-longitudinal displacements, respectively, as appropriate for...
Enceladus ice shells of thickness $H_i = 6 − 90$ km (Table 1). We choose 6 km as a reasonable lower limit for ice shell thickness considering estimates of the brittle–ductile depth transition [Nimmo et al., 2007; Giese et al., 2008], while the 90 km model represents a reasonable upper bound for the ice shell thickness based on internal structure (density) models [Schubert et al., 2007]. The $H_i = 24$ km model represents our reference model, from Smith–Konter and Pappalardo [2008]. We calculate Love numbers for each model (Table 1, see auxiliary material), which range from $h_2 = 0.25 − 0.02$ and $l_2 = 0.067 − 0.002$ and decrease with increasing total ice shell thickness (Figure 1). Larger Love numbers imply a lower shear modulus, e.g. due to a thinner ice shell; smaller Love numbers imply a higher shear modulus, e.g. due to a thicker ice shell. We find that for Enceladus, Love number sensitivity to ice shell thickness diminishes substantially for $H_i > 40$ km (Table 1).

Using these Love numbers and the parameters listed above, we calculate diurnal tidal shear ($t_s$) and normal ($s_n$) stresses along the tiger stripe faults for various ice shell thicknesses. Shear and normal tensile stresses approach peak amplitudes of $\sim 130$ kPa and 153 kPa, respectively, for an ice shell thickness of 6 km (Table 1). To investigate the failure conditions along each fault segment as a function of orbital position, we used a modified version of the Coulomb failure criterion

$$\tau_c = \tau_s - \mu_f (\sigma_n + p g z),$$

which depends on the shear and normal stresses, the overburden pressure ($p g z$), and the effective coefficient of friction ($\mu_f$). According to this model, frictional sliding will occur on optimally oriented fault segments when the resolved shear stress exceeds the frictional resistance on the fault. Negative Coulomb stresses imply a locked fault, while positive stresses imply conditions supporting fault slip in a shearing sense. In our example models (Figure 2), we assume $\mu_f = 0.2$ [Smith–Konter and Pappalardo, 2008]. As Coulomb stresses can only accumulate on a closed fault interface where the overburden stress is larger than the normal tensile stress (otherwise a fault would dilate), we assume an overburden fault depth of $z = 2$ km for our initial evaluation of

![Figure 1. SatStress-derived diurnal Love numbers as a function of total ice layer thickness ($H_i$) for Enceladus. Ice shells ranging from $H_i = 6 − 90$ km are underlain by a global ocean, where we assume a total $H_2O$ (ice shell + ocean) depth of 96 km. The three model cross-sections represent the thickness of the upper and lower ice shell ($H_i$), liquid ocean ($H_o$), and rocky core ($r_c$). See text and auxiliary material for additional model parameters.](image)

<table>
<thead>
<tr>
<th>$H_i$ (km)</th>
<th>$h_2$</th>
<th>$k_2$</th>
<th>$l_2$</th>
<th>$\tau_c$ (kPa)</th>
<th>$\tau_s$ (kPa)</th>
<th>$\sigma_n$ (kPa)</th>
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<tr>
<td>6</td>
<td>0.256</td>
<td>0.086</td>
<td>0.067</td>
<td>94</td>
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<td>153</td>
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<td>0.087</td>
<td>0.060</td>
<td>91</td>
<td>121</td>
<td>153</td>
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<td>0.059</td>
<td>0.040</td>
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<td>0.014</td>
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<td>0.003</td>
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<td>65</td>
<td>90</td>
</tr>
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$a$ $H_i$ represents the ice shell thickness, $h_2$, $k_2$, and $l_2$, the calculated Love numbers, $\tau_c$, the Coulomb stress, $\tau_s$, the shear stress and $\sigma_n$, normal tensile stress. The $\tau_c$, $\tau_s$, and $\sigma_n$ here are peak stress along all fault segments during one orbital period. Negative $\tau_c$ means that shear failure is not permitted and a fault segment is in a locked state.
We compute Coulomb stresses for each ice shell thickness model (Table 1) to identify regions of the fault system that are more or less likely to fail throughout the tidal cycle for a given set of applied conditions.

3. Results and Discussion

We first discuss the variable Coulomb stresses generated by representative models of varying ice shell thickness (6–60 km), maintaining a constant $\mu_f = 0.2$ and $z = 2$ km (Figure 2). These models display a declining trend in fault failure with increasing ice shell thickness. Very thin to moderate ice shells (6–24 km) exhibit Coulomb failure conditions implying an active fault failure model (Figures 2a and 2b). Both 40 and 60 km ice shells (Figures 2c and 2d) demonstrate complete quiescence. These results suggest that ice shells thicker than 40 km do not permit failure on any fault segments for an assumed $\mu_f = 0.2$ and $z = 2$ km.

Assuming that shear failure is a good proxy for fault activity, we also calculate the total amount of time that each tiger stripe fault segment would experience shear failure over the course of one orbital period (Figures 2e–2h). The 6 and 24 km ice shell models are dominated by shear failure throughout the orbit and exhibit relative variations in fault activity. In contrast, the 40 and 60 km ice shell models demonstrate complete fault quiescence throughout the orbit for all fault segments. For the 6 and 24 km ice shell models, fault activity is most prominent along the southern extents of the Cairo and Damascus tiger stripes.

To evaluate the sensitivity of our models to the friction and fault depth parameters, we also vary both the ice coefficient of friction ($\mu_f = 0.1 – 0.3$) and the fault overburden depth ($z = 0.5 – 3$ km) for each model (Figure 3). For simplicity, we present only the results of the 24 km and 40 km ice shell models. These calculations demonstrate that both an increase in the coefficient of friction and fault depth result in a decrease in fault failure, which is limited to the upper few kilometers of the ice shell. The 6 km ice shell model (see auxiliary material) demonstrates fault failure tendencies for all $\mu_f$ and $z$ values. Fault failure is permitted for the 24 km model for ice friction and maximum depth combinations of $\mu_f = 0.1$ ($z > 3$ km), $\mu_f = 0.2$ ($z = 3$ km), and $\mu_f = 0.3$ ($z = 2.5$ km). In contrast, the 40 km model suggests fault failure conditions are feasible for $\mu_f = 0.1$ ($z = 3$ km), $\mu_f = 0.2$ ($z = 1.5$ km), and $\mu_f = 0.3$ ($z = 1$ km). For ice shells thicker than 40 km, opportunities for shear failure on any of the tiger stripe segments are scarce.

Laboratory experiments of ice-motion validate ranges of $\mu_f = 0.1 – 0.7$ depending on sliding velocity, pressure, and temperature [Beeman et al., 1988; Fortt and Schulson, 1990].

Figure 2. (a–d) Coulomb stress models at orbital position $m = 200^\circ$ past periapse, representing peak fault activity for the entire orbital sequence (see auxiliary material) for 6 km, 24 km, 40 km and 60 km ice shell models, assuming $\mu_f = 0.2$ and $z = 2$ km. Note that the color scheme represented here is optimized to reveal stress variations for the 24 km ice shell model. (e–h) Normalized relative fault activity for each model. Colors represent the summed amount of time that each fault segment experiences conditions that meet the Coulomb failure criterion throughout an entire orbit, normalized by the relative maximum value. For Figures (g) and (h), no fault segments exhibit stresses required for failure throughout the entire orbit.
Calculated fault activity along the tiger stripes based on two ice shell models (24 km and 40 km) for variable $\mu_f$ and $z$. Here we define “fault activity” along digitized 159 points of the tiger stripes as those points having positive Coulomb stress values throughout one complete orbit, which we evaluate at every 10 degrees. We sum all points for each model and normalize to the ideal case where all segments along the tiger stripes are active through an entire orbit (e.g. 159 segment points $\times$ 36 orbital position observations $= 5724$ occurrences). Here the explored range of coefficients of friction ($\mu_f = 0.1$ – 0.3) and fault depths ($z = 0.5$ – 3 km) are plotted for the 24 km (solid line) and the 40 km (dashed line) ice shell models.

Figure 3. Calculated fault activity along the tiger stripes based on two ice shell models (24 km and 40 km) for variable $\mu_f$ and $z$. Here we define “fault activity” along digitized 159 points of the tiger stripes as those points having positive Coulomb stress values throughout one complete orbit, which we evaluate at every 10 degrees. We sum all points for each model and normalize to the ideal case where all segments along the tiger stripes are active through an entire orbit (e.g. 159 segment points $\times$ 36 orbital position observations $= 5724$ occurrences). Here the explored range of coefficients of friction ($\mu_f = 0.1$ – 0.3) and fault depths ($z = 0.5$ – 3 km) are plotted for the 24 km (solid line) and the 40 km (dashed line) ice shell models.

[11] We assume a global subsurface liquid ocean for our Enceladus model, consistent with geophysical and geochemical evidence. Waite et al. [2009] propose a global subsurface ocean based on the presence of $^{40}$Ar and ammonia in Enceladus’s plume, suggesting that an ocean layer provides an efficient means for these to reach the surface of a differentiated interior. Sodium detected in Saturn’s E-ring [Postberg et al., 2009] and analysis of the curvilinear fractures near the tiger stripes and apparent rotation about the southern pole [Patthof and Kattenhorn, 2009] also hint at a global ocean. Furthermore, shear motion along Enceladus’s tiger stripes requires sufficient generation of tidal stresses from models based on a global ocean [Nimmo et al., 2007; Smith-Konter and Pappalardo, 2008]. Other studies have suggested a localized south polar sea beneath the tiger stripes [Nimmo and Gaidos, 2002; Nimmo et al., 2007]. Furthermore, failure at depths $\ll 1$ km is speculative. Faults may lack sufficient contact due to small overburden pressures overcome by larger diurnal tensile stresses at such shallow depths [Smith-Konter and Pappalardo, 2008], faults subject to Coulomb failure are limited to an upper depth (representing the top of the locked fault) of, for example, 0.7 km for a 24 km thick ice shell. We note that thicker ice shells will have smaller tensile stresses at depth relative to thinner ice shells; thus shallower upper fault depths ($\sim 0.3$ km) are possible. In this study we determine that tiger stripe failure conditions may extend down to lesser depths (representing the bottom of the locked fault) of $\sim 2$–3 km for a 24 km thick ice shell and even shallower depths ($\sim 1$ km) for thicker ice shells.

[12] The thickness of Enceladus’s ice shell is relevant to thermal convection models [e.g., R&B, 2008a, 2008b]. Barr and McKinnon [2007] find that convection could initiate for an ice shell thickness $>40$ km, depending on the rheology and ice grain size. Mitri and Showman [2008] place a lower limit on the ice shell thickness at 50 km based on their analysis of thermal convective and conductive models, assuming grain sizes of 0.1 mm. Barr [2008] suggests that mobile–lid convection can occur in a much thinner ice shell ($\sim 10$ km given specific viscosity assumptions), but a thick ice shell ($>40$ km) would be necessary to initiate convection. Our analysis of Coulomb failure suggests that 40 km is an upper limit to ice shell thickness that can permit tiger stripe fault activity, given reasonable assumptions for the coefficient of friction and shallow fault depth. However, our work also suggests that slightly thicker ice shells are plausible if...
very low friction and shallow fault depths exist. Analysis of NaCl concentration models by Glein and Shock [2010] argue that an ice shell cannot exceed 50 km in thickness. It might also be that Enceladus is conductive rather than convective [R&B, 2008a; Zhang and Nimmo, 2009]. Alternatively, if the ice shell of Enceladus is convecting, then plausibly the ice shell has evolved in thickness and convective-tectonic style. Perhaps convection initiated in a thick (>40–50 km) ice shell, then the ice shell thinned (to <40 km) such that tiger stripe fault activity initiated. Such an idea seems consistent with a temporal transition from stagnant-lid to mobile-lid convection [Barr, 2008].

4. Conclusions

[13] Assuming a tidal stress model of Coulomb failure at Enceladus’s tiger stripes, we estimate that the thickness of Enceladus’s ice shell is limited to <40 km, assuming normal parameters for ice coefficient of friction (μf ≈ 0.2) and fault depths (z = 2 km). For thicker ice shells (60 km), failure is limited to a few isolated segments of the tiger stripe system, but only for extreme values of μf (<0.1) and very shallow fault depths (z ~ 1 km). These models offer conditions suitable for fault failure of the tiger stripes but are marginally consistent with the lower limits of ice shell thickness derived from convection models of Enceladus. With convection initiating in a thick ice shell, and tiger stripe activity commencing as the ice shell thinned, a plausible scenario is one in which the convective and tectonic style of Enceladus has changed through time.

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References


J. G. Olgin and B. R. Smith-Konter, Department of Geological Sciences, University of Texas at El Paso, 500 West University Ave., El Paso, TX 79968, USA.
R. T. Pappalardo, Jet Propulsion Laboratory, California Institute of Technology, M/S 321-560, Pasadena, CA 91109, USA.