ENCELADUS’ TIGER STRIPES AS FRICTIONAL FAULTS: IMPACT ON LOCAL AND GLOBAL TIDAL DEFORMATION. Marie Běhounková1,*, Kateřina Pleiner Sládková1 and Ondřej Souček2, 1Charles University, Faculty of Mathematics and Physics, Department of Geophysics, Prague, Czech Republic., 2Charles University, Faculty of Mathematics and Physics, Mathematical Institute, Prague, Czech Republic., *(Marie.Behounkova@mff.cuni.cz).

Introduction: Saturn’s icy moon Enceladus is one of the most active solar system bodies with a complex geological history [1], a unique cryovolcanic activity, and high heat flux [2]. The determination of the precise state of Enceladus’ shell rotation by Cassini proved that Enceladus has a global ocean beneath the icy shell and that the shell is thin [3]. Moreover, combined gravity [4], topography [5], and libration inversions models hint at large ice shell thickness variations with only a few kilometers thick shell under the southern polar region (SPR). The position of the observed jetting activity and increased heat flux correlate with the position of tiger stripes, the four most prominent features in the SPR. Thin ice shell and fast transport of material through the shell from the ocean [9] can indicate that the tiger stripes might be open fissures, possibly passing through the whole thickness of the shell. Such multiple disruptions of the ice shell in the south polar region would affect the stress field in the shell, enhance the tidal deformation, and possibly change the deformation both locally and globally.

Here, we will investigate the impact of tiger stripes described as frictional faults [10] on both local and global tidal deformation. We perform a parametric study depending on the friction coefficient. We compare our results with cases with no faults and idealized frictionless faults [11].

Numerical Model: We extend our previous model [11, 12] solving tidal deformation of a compressible Maxwell viscoelastic body in a hydrostatically prestressed state in a 3D domain and employing finite element method. Our model also allows for variable ice shell thickness and the tiger stripes included as finite-size zones that do not transmit stress. Here, we also included friction along the faults. We use visco-plastic rheology in the fault zones to mimic the stick-slip behavior. We employ Maxwell viscoelastic model with a stress-dependent effective viscosity:

\[ \eta_{\text{eff}} = \frac{\eta_0}{\left(1 + \left(\frac{2\eta_0 D_{\text{d, visc}}}{\sigma_Y} \right)^{\alpha} \right)^{\gamma}}, \]

where \( \eta_0 \) is the reference value of the viscosity, \( D_{\text{d, visc}} \) is the deviatoric part of the viscous strain rate tensor, \( \alpha \) denotes the second invariant of a tensor, \( \sigma_Y \) is the yield stress, and \( \alpha \geq 1 \) is a parameter controlling the onset of yielding. Therefore, the effective viscosity is designed to drop to ensure that the yield stress \( \sigma_Y \) is not exceeded.

In analogy with Coulomb-type friction, we assume that the mechanical properties of the fault depend on the friction coefficient \( \mu \) and normal stress:

\[ \sigma_Y = \begin{cases} \mu (p^{\text{eff}} - \sigma_{nn}) & \text{if } p^{\text{eff}} \geq \sigma_{nn} \\ 0 & \text{otherwise} \end{cases} \]

The yield stress is considered to be composed of two parts. First, the dynamic and time-dependent part \( \sigma_{nn} \) corresponds to the normal tidal stress acting on the faults. Second, the effective pressure \( p^{\text{eff}} \) represents the static part, and it is defined as ice overburden pressure minus liquid water pressure averaged over the depth.

In our model, we take into account variable ice shell thickness [7] and geometry of tiger stripes [13], which does not change with depth. Rheology outside the fault zone is effective elastic \( (\eta_0 = 10^{19}\text{Pa s}) \), and inside the fault zones, visco-plastic rheology is taken into account. The coefficient of friction depends on several factors, including slip velocity, temperature, and the presence of a liquid state. We treat it here, however, as a constant and a free parameter.

Results: The local impact of the faults on the deformation is significant, especially if combined with a thin ice shell in the SPR (local increase of displacement is up to factor 8). As expected, the frictionless and no-fault models are the two end-member models, and the amplitude of deformation and displacement jump across the faults decreases strongly with increasing friction coefficients (see Fig. 1).

The faults also impact the deformation from a global point of view. We represent the impact of the faults on the global deformation in terms of Love numbers representing the body’s response normalized with respect to the tidal potential; \( h_2 \) characterizing the radial component of periodic deformation and \( k_2 \) the tidally induced periodic gravitational potential. Due to the 3D nature of faults, large local impact of faults on the deformation, and spectral interaction (see Tab. 1), we observe i) a splitting of Love numbers according to the order and ii) an apparent phase lag even for the effectively elastic shell, and iii) deformation not only on spatial degree 2 as expected due to the degree-two nature of the tidal loading but also on other degrees, the power on degrees 3 and 4 reaching up to 10% of power on degree 2. Again, the values of Love numbers converge for low friction coefficients to the values obtained for the
frictionless model. A large apparent phase lag quickly disappears with the presence of friction.

We also observe a similar spectral coupling in the frequency domain due to the non-linear rheology. However, the spectral power of the radial displacement for high frequencies is more than one order of magnitude lower than for the forcing frequency. Interestingly, we observe a large contribution on zero frequency, i.e., a static deformation, with an amplitude of deformation comparable to the periodic diurnal amplitude. The static deformation and the corresponding stress must develop to compensate for the asymmetry in the frictional response and to ensure a periodic solution as forced by tidal loading.

Our model also allows us to predict the frictional heating along the faults. In our model, the dissipation is dominated by the Baghdad sulcus. The exact value is sensitive to numerical details of the implementation. Nevertheless, the global frictional dissipation is robustly bounded from above by 1GW.

Conclusion: The presented model provides a framework for understanding the role of friction in tidal deformation and for quantifying the mechanical dissipation along the fault zones. The presence of faults combined with a thin ice shell in the SPR increases the periodic deformation locally up to eight compared to the no-fault model. From a global point of view, the presence of faults also tends to increase Love numbers up to factor 1.5 compared to the model without faults. However, the friction along faults tends to lower the magnitude of deformation compared to the frictionless model. The friction also induces an asymmetry between the compressional and extensional phases along the faults. This asymmetry induces static deformation and static background stress characterized by a compression acting on the faults and possibly inducing a long-term flow in Enceladus’ shell. We estimate a maximum of 1GW to be produced along faults. This value is significantly smaller than the estimate of the heat losses observed or obtained by the modeling and cannot compensate for the heat losses.


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