Tidally Driven Frictional Heating and the Seismogenic Zone on Enceladus' Tiger Stripes

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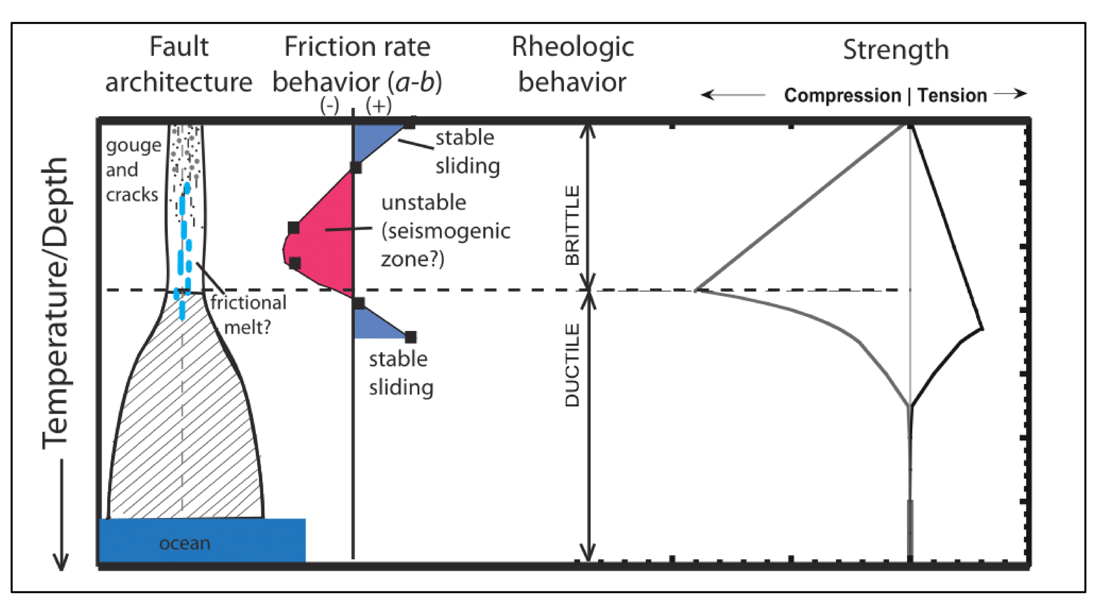
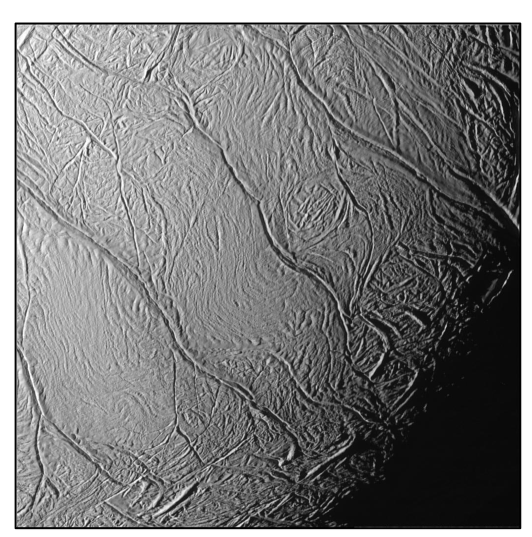
Motivation

Frictional strength of polycrystalline ice and ice-ammonia mixtures have been measured in the laboratory in order to constrain fault behavior on the south polar region of Enceladus and the depth of partial melt within the icy shell. These faults, known as the tiger stripes, are associated with anomalous temperature gradients and active jets, which have been linked to tidally induced stresses on the faults. The temperature dependence of fault stability is used to map a seismogenic zone within the brittle layer of Enceladus' icy shell. The results from our experimental study and models of frictional heating are used to infer fault strength and heat generation within the brittle layer. The frictional response was measured in steady-state as well as at dynamic conditions, as a function of frequency, amplitude, normal stress, and temperature. For the modelling, a simple 1-D numerical frictional heating model was constructed showing the change in temperature on a fault during sliding. Using estimated fault depth and slip distance from previous studies, as well as our experimentally determined friction coefficient, frictional heating with depth was determined with varying values for fault width and slip velocity.

Depth of Partial Melt



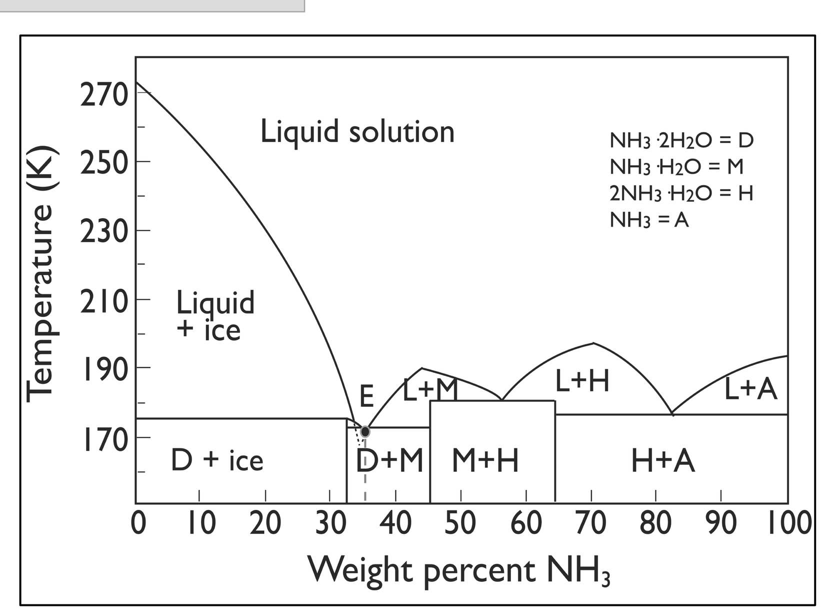


Dombard and McKinnon, 2006

Depth Profile

Depth profile showing change in frictional behavior, strength, and rheological behavior in the icy shell as a result of temperature.

Friction experiments can determine stable (creeping and unstable (stick-slipping) behavior with depth. Our goal is to constrain if and where frictional melt is created in the icy shell considering two compositions: pure ice and ice + ammonia.



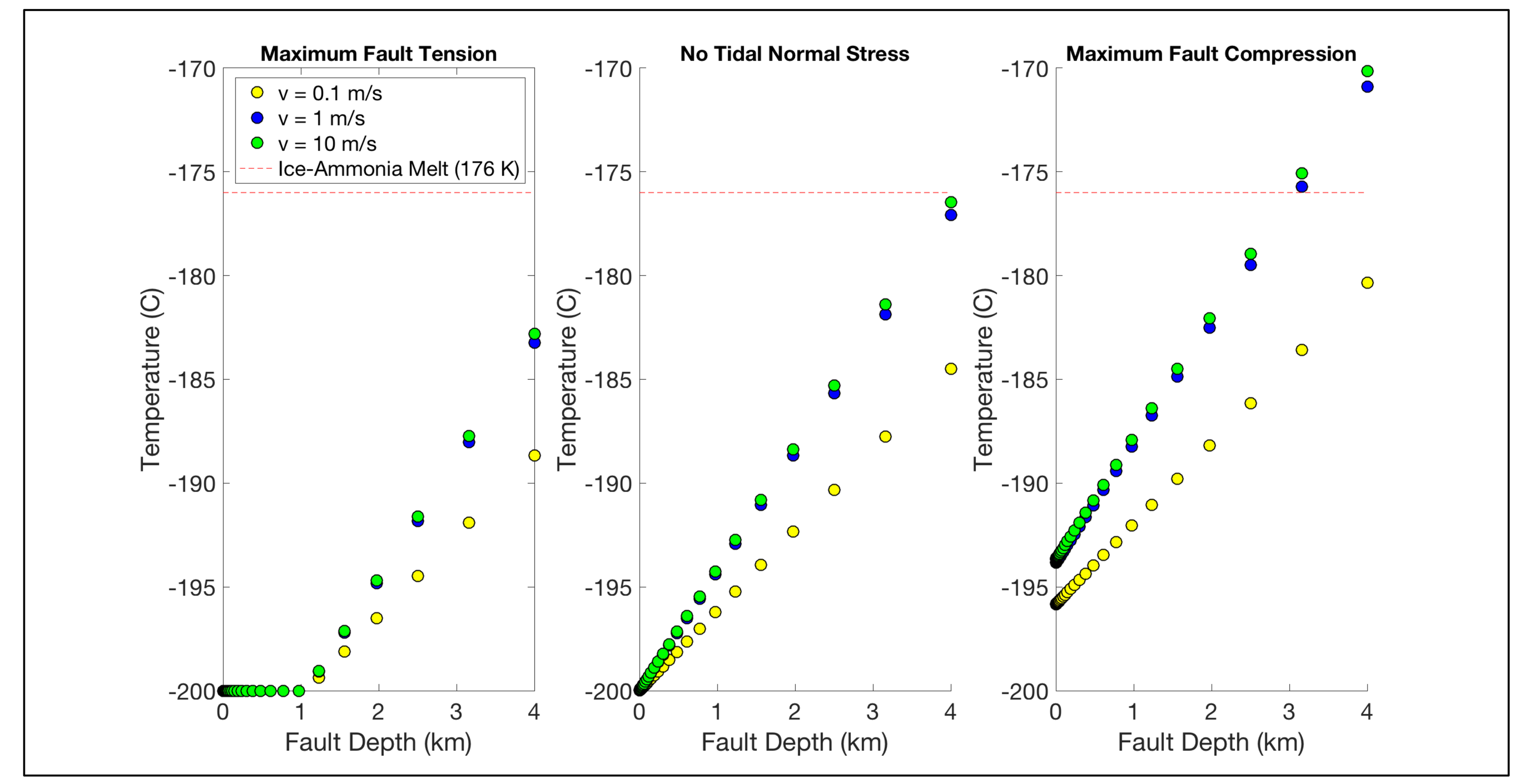
NH_3 Phase Diagram

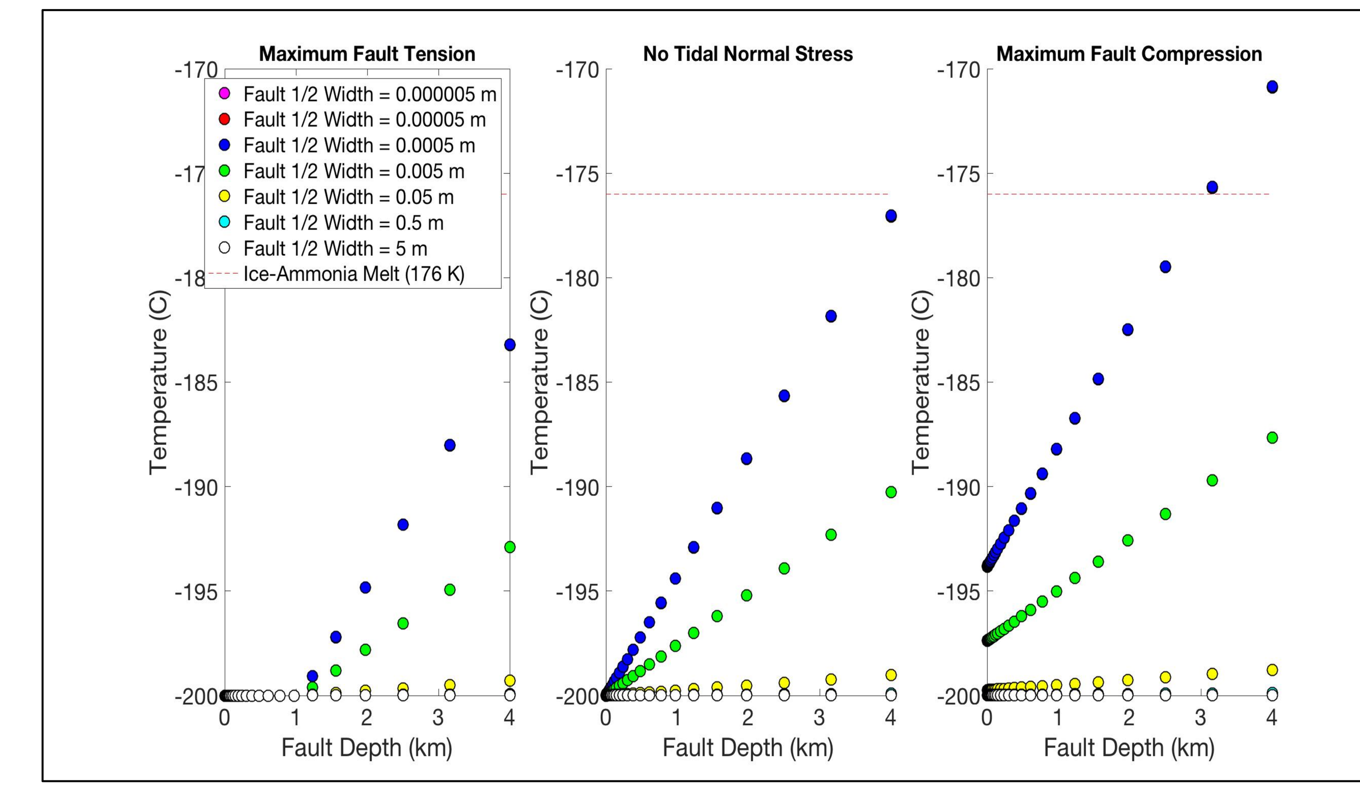
Phase diagram showing the eutectic melting temperature for ice + ammonia (at 1 atm) is 176 K. This means that partial melt could be found relatively near the surface.

References and Acknowledgements

[1] Nimmo et al. 2007 [2] McCarthy, et. al, 2016 [3] Smith-Konter and Pappalardo 2007. I would like to thank Dr. Christine McCarthy for supporting and advising this project and Dr. Heather Savage for providing the base for the numerical model.

Frictional Heating Model





Model Set-Up and Varying Parameters

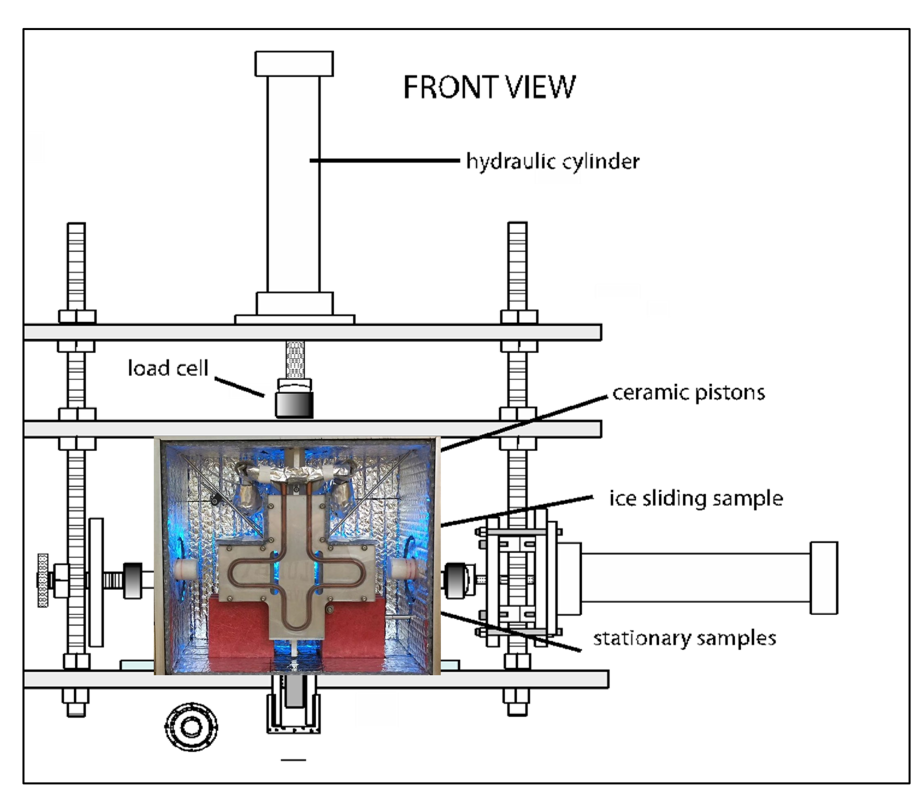
Frictional heating estimations were based on the solution for heat diffusion during sliding on a fault of finite thickness by Lachenbruch [1986] using the Carslaw and Jaeger [1959] equation based on the solution for heat diffusion through a fault of finite thickness. Temperatures were calculated for different time/space combinations as functions of time during/after slip and inside/outside the slipping zone.

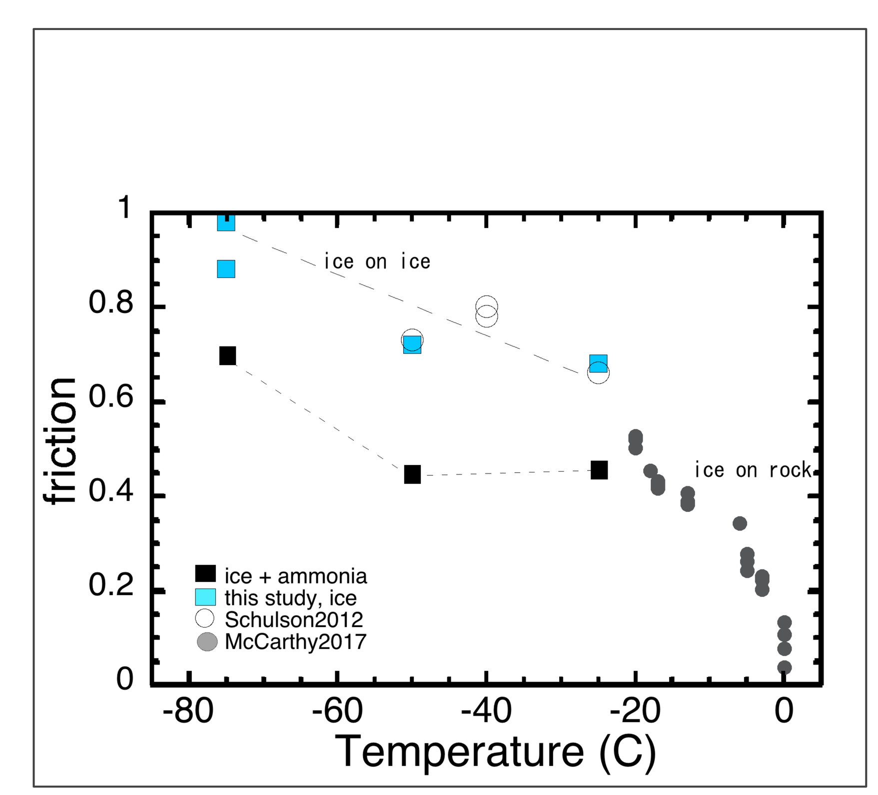
Varying slip velocities and fault-width magnitudes were used at different points of the tidal cycle.

Preliminary Observations

- Current model predicts partial melt temperatures in brittle layer could be reached in one slip event during fault compression.
- Magnitude of fault width during slip seems to strongly control heat generation.
- Heat generation will vary along faults based on fault geometry and Coulomb criteria of stresses.

Friction Experiments





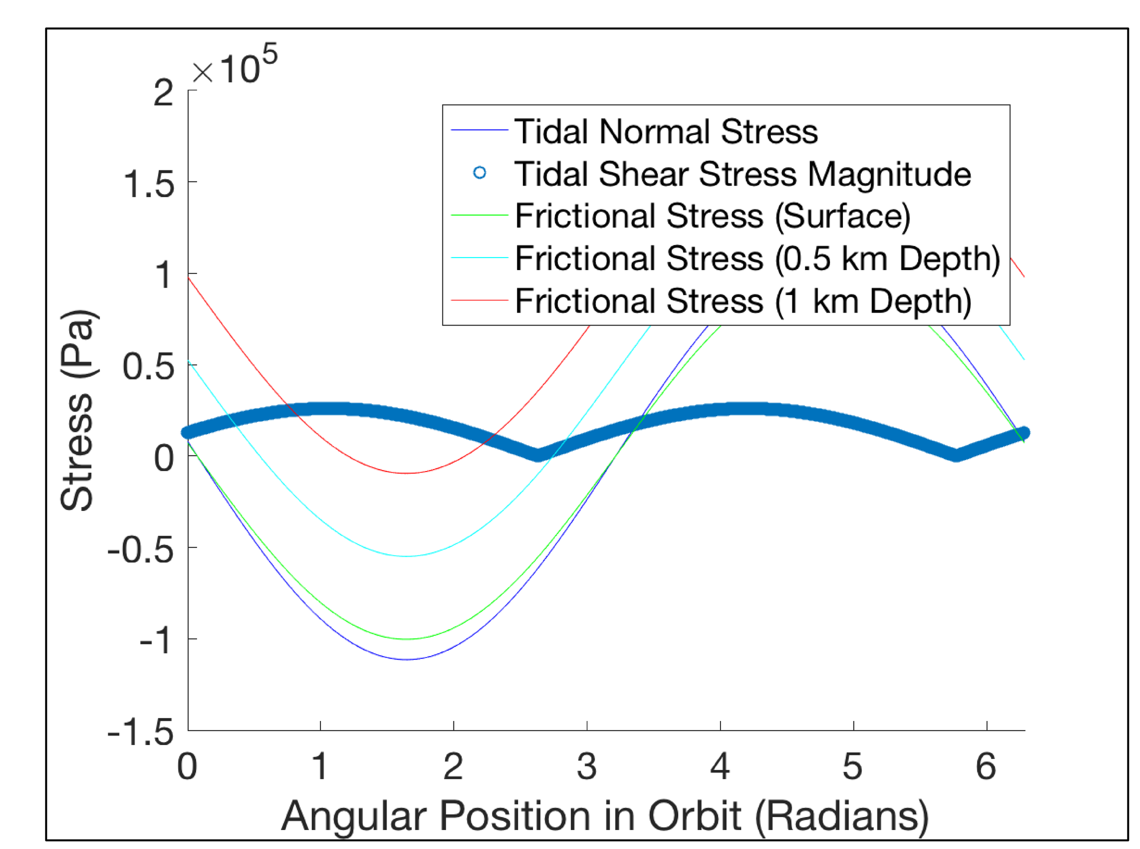
Apparatus Schematic

The friction experiments were conducted using polycrystalline ice and ice-ammonia mixtures in a custom servo-hydraulic biaxial deformation apparatus with a liquid nitrogen-cooled cryostat at icy satellite conditions.

Experimental Results

Friction coefficient increases with decreasing temperature and levels off at around 0.9 as icy satellite temperatures are approached. Samples with partial melt (~3wt% ammonia) have lower frictional strength.

Tidal and Frictional Stresses



Stresses During Orbit

Stresses during a tidal cycle for a particular point on a the Damascus tiger stripe (315 W, 80 S).

$$\tau_s = \frac{1}{2}(\sigma_{\phi\phi} - \sigma_{\theta\theta})\sin 2\beta + \sigma_{\theta\phi}\cos 2\beta,$$

$$\sigma_n = \sigma_{\theta\theta}\cos^2\beta + \sigma_{\phi\phi}\sin^2\beta + \sigma_{\theta\phi}\sin 2\beta.$$

Tidal stress equations

$$|\bar{\tau}_s| > \mu_f(\rho g z + \bar{\sigma}_n),$$

Coulomb criteria