FRICTION OF ICE PARTIAL MELT SYSTEMS: A POSSIBLE SOURCE OF SEISMICITY ON ICY SATELLITE FAULTS. C. McCarthy[1] , T. Caswell[1], A. Domingos[2], A. O. Katz[1], D. C. Newtown[1], D. Zhang[1], and H. M. Savage[1], [1]Lamont-Doherty Earth Observatory (Palisades, NY mccarthy@ldeo.columbia.edu), [2]U.C. Berkeley Environmental Sciences (Berkeley, CA).

Introduction: The material properties of ice and relevant ice mixtures directly control dynamics in the shells of icy satellites. Currently, the manner in which faults rupture and propagate on icy satellites is not well known, but probably controls the morphology of surface features like cycloids. Tidally loaded strike-slip faults are thought to be present on both Enceladus and Europa [e.g., 1, 2]. Knowledge about ice fault mechanics can assist in planning for future missions. In particular, identification of the source of seismicity in a tidally loaded fault system would benefit interpretation of seismic observations.

Although the surfaces of icy satellites are dominated by water ice, near-infrared spectrometry has identified non-ice phases on many satellites. Of particular interest are those phases that display a deep eutectic with ice, such as ammonia (Fig. 1). Hydrated ammonia has been suggested as a possible component on the surface of Enceladus [e.g., 3, 4]. The equilibrium phase diagram for ice+NH_3 suggests that, even at dilute concentrations, a melt phase would be stable at some depth in the shell (i.e. at the isotherm representing the solidus and all temperatures greater). That melt would be found at triple junctions between ice grains.

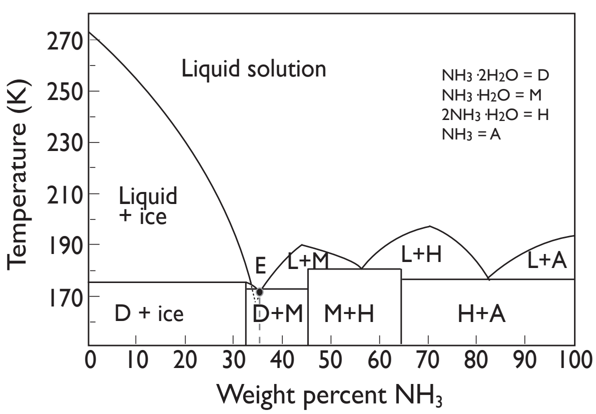

Figure 1: *schematic of the equilibrium phase diagram for the ice + ammonia system based on [5]. At 1 atm, the eutectic composition is 35.4wt%NH_3 and the eutectic temperature T_E is 174 K.*

The mechanical and transport properties of partially molten material are heavily dependent on the distribution of melt within the aggregate. The effect of partial melt on steady-state viscous rheology has been studied in many forms [e.g. 6, 7], including studies on ice + melt phases [e.g. 8 - 10]. In such studies, a significant reduction in viscosity is observed with a small amount of partial melt. The effect of partial melt on elastic properties is well known. However the effect of an equilibrium melt phase on the frictional behavior of ice has received less attention.

Rate- and state- dependent friction formulation has been widely used to describe earthquakes and fault mechanics [11 – 13]. Friction at steady-state velocity is described as:

$$\mu = \mu_0 + a\left(\frac{V}{V_0}\right) + b\left(\frac{\theta V_0}{D_C}\right) \qquad (1)$$

where μ is friction, μ_0 is the reference friction at the reference velocity V_0, V is sliding velocity, D_c is the critical slip distance required to renew asperity contacts, θ is the state variable that is equal to D_c/V at steady state, and *a* and *b* are empirically derived friction parameters. Faults behave in an inherently stable way when the friction rate parameter (a-b) is positive. This means that the fault strength increases when the fault is pushed at faster velocities and earthquakes cannot nucleate (referred to as velocity-strengthening behavior). On the other hand, if the friction rate parameter is negative, faults become weaker at faster velocities (velocity-weakening behavior) and earthquakes can nucleate. Faults will be conditionally stable if the shear stiffness of the wall rock is greater than the critical stiffness of the fault, which is determined by friction parameters and normal stress:

$$k_C = \frac{\sigma(b-a)}{D_C} \qquad (2)$$

where σ is normal stress [14]. Faults will fail in unstable, stick-slip motion (earthquakes) if the critical stiffness is greater than the wallrock stiffness. Using rate-state formulation, we report initial results from friction experiments on ammonia-ice mixtures that are designed to explore the effect of partial melt at planetary conditions.

Experimental method: Samples of polycrystalline ice were made using a modified standard ice method [15] of grinding and sieving bubble free seed ice that is packed into a rectangular die, pulling a vacuum and flooding with deionized water, all while at an equilibrium (273 K) temperature. The flooded die is then placed on a cold plate in an insulated box to finish freezing. Ammonia ice samples were made in the same way (using the same seed ice) but the floodwater was instead dilute (10wt%) NH_3 liquid solution. Such samples were placed on dry ice to freeze with a final drop into LN just before loading.

Friction experiments were conducted in double direct shear configuration using a servo-hydraulic biaxial apparatus described elsewhere [16]. A new cryogenic chamber was developed using circulating LN within a methanol+water reservoir to obtain conditions consistent with icy satellites (~120<T(K)<230). While normal stress was held constant, a sinusoidally-varying driving stress was applied to represent the tidal shear stress on pre-existing faults. The frictional response was measured as a function of frequency, amplitude, normal stress, and temperature.

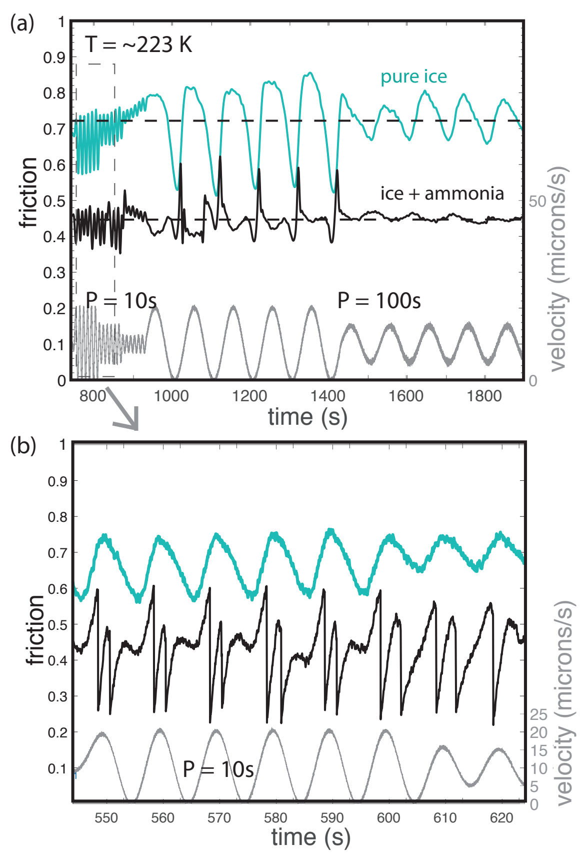

Figure 2: *Transient friction tests of pure ice and ice with ~3wt%NH_3 (a) Sample with melt has reduced average friction and demonstrates stick-slip behavior (velocity weakening) at both 10s and 100s forcing periods. (b) At 10s periods a double stick-slip occurs on every cycle.*

Preliminary Results: Figure 2 shows results from two frictional tests: one in which the sliding block was pure ice and one in which it contained ~3wt%NH_3, but otherwise all other conditions were the same (stationary blocks were made of ice in both tests). The median friction for the pure ice sample was approximately 0.72, which is consistent with previously reported steady-state friction values for ice at this temperature and median velocity [17]. The sample containing ammonia showed significant reduction in friction. At T = 223, the ammonia would be found as a melt phase. Strikingly, the sample containing melt exhibited distinct stick-slip events (velocity weakening) during every cycle when forced at the highest amplitudes.

This study is ongoing. We will map stability in terms of composition, frequency, amplitude, and normal stress so that results can be scaled and applied to icy satellite fault systems. Additionally, we intend to explore a wider temperature range, examining the efficiency of frictional heating at subsolidus conditions.

Discussion/Conclusions: Our results indicate a profound difference in fault stability, with a small quantity of partial melt demonstrating earthquake-like stick-slip events. Thus, we provide a possible source of seismicity on icy satellite faults systems at depth. This could provide valuable information for planning of missions, in particular ones with lander-based seismometers on board. Developing a rate-and-state formulation for ice and ice mixtures will allow an assessment of the likely style of rupture propagation on icy satellites. Studying the rheological response of ice under melt-bearing conditions is required to be able to model the origin of features in which melting is thought to play a role, such as double ridges and chaos terrains on Europa, and the "tiger stripes" on Enceladus.

References: [1] Nimmo, F. and E. Gaidos (2002) *JGR* 107 (E4), 5021. [2] Olgin et al. (2011) *GRL* 38, L02201 [3] Squyres et al. (1983) *Icarus 53,* 319. [4] Kargel, J. S. and S. Pozio (1996) *Icarus 119,* 385. [5] Kargel, J. S. (1992) *Icarus* 100, 556-574. [6] Faul U. H. and I. Jackson (2007) *JGR* 112, B04204 [7] McCarthy, C. and Y. Takei (2011) *GRL* 38, L18306. [8] de La Chapelle et al. (1995), *Scripta Metal. Et Mater.* 33, 3, 447-450. [9] Duval, P. (1977) *IAHS Publ.* 118, 29. [10] Li et al. (2009) *J. Glaciol.* 55, 191. [11] Dieterich, J. H. (1978) *Pure App. Geophys*. 116, 790. [12] Ruina, A. (1983) *JGR*, 88, 10,359. [13] Marone, C. (1998) *Ann. Rev. Earth Planet. Sci*. 26, 643. [14] Scholz, C. H. (2002) *The mechanics of earthquakes and faulting, 2nd*, NY, NY. [15] Cole, D. M. (1979) *Cold Reg. Sci. Tech*. 1, 153-159. [16] McCarthy et al. (2016) *RSI* 87, 055112. [17] Schulson, E. M. and A. L. Fortt (2012) *JGR* 117, B12204.