FRICTIONAL SLIDING OF COLD ICE. E. M. Schulson, Thayer School of Engineering, Dartmouth College, 8000 Cummings Hall, Hanover, NH 03755, email: erland.schulson@dartmouth.edu.

Introduction: Frictional sliding is a fundamental process underlying tectonic activity within the icy crusts of Saturn's Enceladus and Jupiter's Europa. This is evident from a variety of features. For instance, active plumes emanating from localized "tiger stripe" rifts within the south polar region of Enceladus [1], [2] could be energized through frictional sliding and attendant heating that accompany diurnal-stress-driven cyclical shear deformation along the fractures/faults [3]. Similarly, lateral offsets along the long lineaments/fractures that lace through Europa [4]-[9] indicate that frictional sliding plays a role in their development, particularly should such features be formed under compressive stresses as suggested by the orientation of near-equatorial lineaments [10] and by the wing-like character of a wedge crack [11]. Thus, the coefficients of static friction μ_s and kinetic (or dynamic) friction μ_k become important factors in modeling, the former in determining whether the driving shear stress is great enough to effect sliding and the latter in both maintaining sliding and generating heat.

The purpose of this paper is to review current knowledge of the friction of ice on ice .

Coefficients for Sliding and Heating: The issue concerns the magnitude of the friction coefficients: if too high, then sliding and heating will not occur. For instance, in modeling the behavior of a vertically-oriented, brittle fault on Enceladus, assumed to be two km deep within a spherically symmetric icy shell 24 km thick, Smith-Konter and Pappalardo [12] found, upon invoking Coulomb's failure criterion and assuming both zero cohesion and a coefficient of static friction $\mu_s = 0.2$, that the fault exhibits *"slip windows"* when loaded by a combination of diurnal tidal shear stress of amplitude ~ 45 kPa, of diurnal normal stress of amplitude ~ 70 kPa and of an overburden pressure of ~ 200 kPa. That is, under the assumed conditions Enceladus' tiger stripe faults are expected to slide during two parts of the 360 ^{o} diurnal cycle, from ~ 55 ° to ~ 105 ° and again from ~ 195 ° to ~ 255 °. The windows are expected to open for lower values of the friction coefficient, but to close for $\mu_s > 0.3$. The closure limit would be lower should the fault possess cohesion, and it would be still lower for deeper faults. Similarly, for shear heating to account for the origin of plumes and heat flux on Enceladus, relatively low values of the kinetic friction coefficient (μ_k = 0.1-0.3) are necessary [3].

Measured Friction Coefficients: Actual values probably depend upon a number of factors, including the chemical composition and structure of the crust as well as temperature and sliding speed. There are no data for $MgSO_4.11H_2O$ or $Na_2SO_4.10H_2O$, two candidate materials. There are data for "pure" water ice Ih and so it is these data we review. Our focus is on behavior at temperatures between ~100 and 260 K and at speeds between ~10^{-8} -10^{-5} m s^{-1}, conditions relevant to modeling [13].

The literature offers insight, as well as contradictions. Specifically, Beeman *et al.* [14] obtained a (kinetic) coefficient of friction of either μ_k = 0.2 or μ_k = 0.55 for cold (77-115 K) fresh-water granular ice sliding slowly (3×10^{-7}-3×10^{-5} m s^{-1}) upon itself across 45° saw-cuts, loaded under a range of confining pressure (0.3-250 MPa). The lower value was obtained under higher pressures (> 10 MPa). Over the experimental ranges examined, neither temperature nor sliding speed appeared to affect the behavior. Through another set of high-pressure (10-50 MPa) tests on similar material, Rist *et al.* [15] and Rist [16] obtained the value μ_k = 0.4-0.8 upon sliding across a shear fault at a speed of ~10^{-3} m s^{-1} at temperatures of 233K and 253 K. Again, the behavior appeared to be independent of temperature.

Kennedy *et al.* [17], in an apparent contradiction, found that both temperature and sliding speed are important factors. Using a double-shear device, they slid at low speeds (5×10^{-7} to 5×10^{-2} m s^{-1}) warmer fresh-water granular ice (233-270 K) across smooth surfaces loaded under relatively low normal stresses (0.007 and 1.0 MPa). They obtained coefficients that varied between μ_k=0.05 and μ_k = 0.8. The higher values (μ_k > 0.5) generally correlated with lower temperatures and with lower sliding speeds (< 10^{-4} m s^{-1}), although at 233 K and at 243 K the coefficient exhibited a maximum at an intermediate speed of ~10^{-4} m s^{-1}. Maeno et al. [18] corroborated these findings. Through similar experiments, also on fresh-water granular ice sliding against itself across a smooth interface loaded under low normal stresses (0.001-.37 MPa), they found that the (kinetic) friction coefficient varied from μ_k ~ 0.02 to ~ 1.0. Again, it exhibited a complicated dependence on temperature and sliding speed over the ranges examined (243-273 K; 10^{-7}-10^{1} m s^{-1}).

Through a different kind of experiment, one that bears directly on sliding across natural shear faults, Fortt and Schulson [19] found that, again, temperature and sliding speed are important factors. They examined the resistance to sliding across natural Coulombic shear faults of roughness (~1 mm) loaded under low pressure (<2 MPa). Over the ranges of temperature (233-270 K) and sliding speed (8×10^{-7} to 4×10^{-3} m s^{-1}) examined, the friction coefficients varied between $\mu_s \sim \mu_k = 0.4$-1.6. The coefficients generally increased with decreasing temperature, independent of normal stress across the fault. Also, they depended upon sliding speed and reached a maximum at an intermediate speed around 10^{-5} m s^{-1}. At speeds below the maximum, sliding was quiet. At higher speeds, it was noisy.

To summarize, the coefficients of friction for "pure" water ice Ih vary from as low as 0.02 to as high as 1.6, depending upon the sliding conditions. Generally, values < 0.1 are measured at speeds > 10^{-3} m s^{-1}. At lower velocities ($\leq 10^{-5}$ m s^{-1}) and at higher temperatures (T $\geq$230 K), the (kinetic) friction coefficient varies between ~ 0.4 and 1.6, depending in a complex manner on these factors. For cold ice (T ~ 77-115 K) sliding upon itself at the higher end of the velocity range of interest to icy satellites, the coefficient appears to range between ~ 0.2 and 0.6, depending upon pressure, but apparently independent of temperature and sliding speed, as judged from the one study of record. Generally, ice exhibits stick-slip at higher sliding speeds (> 10^{-5} m s^{-1}).

Interpretation: The interpretation of this behavior is beyond the scope of this paper. Suffice it to say that both creep and fracture at points of contact across the sliding interface appear to operate [17]. Creep governs at higher temperatures and lower speeds, and can account pseudo-quantitatively for "velocity hardening" and for the quiet sliding. Fracture dominates at lower temperatures and higher speeds and accounts for the noise generated under those conditions.

The transition from velocity hardening to velocity softening can be viewed as a kind of ductile-to-brittle transition. It occurs at a velocity v_t that is consistent with that expected from the thickness of the shear zone that defines the sliding interface and from the transition strain rate that characterizes bulk ice [19]. The expectation, upon applying the model of the bulk transition strain rate described elsewhere [20], is that v_t decreases with decreasing temperature, possibly falling to a speed as low as 10^{-14} m s^{-1} at ~100 K. If that is true, then at the lower temperatures of interest to tectonic activity on Enceladus and Europa frictional sliding may fall well within the regime of brittle-like behavior. In that case, neither velocity strengthening nor thermal softening would not be expected at the relevant sliding speeds. This could account for the absence of such effects under the conditions explored by Beeman *et al.* [14] and could reconcile the contradiction noted above.

Questions Arising: In relation to the modeling of tectonic activity on Europa and Enceladus, several questions arise:

(i) Under exactly what conditions of temperature and sliding speed do those factors begin to affect frictional resistance to sliding of pure water ice Ih?

(ii) Do those conditions depend upon the character of the sliding surface (i.e., Coulombic fault, saw cut, smooth surface)?

(iii) What are the values of the friction coefficients of other candidate materials (e.g., $MgSO_4.11H_2O$, $Na_2SO_4.10H_2O$) that may comprise icy satellites?

(iv) Is the friction coefficient that is obtained from measurements on relatively small test specimens in the laboratory applicable to the larger scale of the field?

More work is needed to answer these points.

References:

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