SLIP SLIDING AWAY: CALCULATING CYCLIC SLIP MAGNITUDES ON TIDALLY DRIVEN FAULTS ON EUROPA, N. P. Hammond[1] G. C. Collins[1] and J. C. Goodman[1], [1]Wheaton College of Massachusetts, Dept. of Physics and Astronomy, 26 E Main St, Norton MA, 02766 (hammond_noah@wheatoncollege.edu)

Summary: Faults on Europa likely slide back and forth 0.01 – 2 m per orbit in response to diurnal tidal stresses. Slip magnitudes depend strongly on the resolved stress shear magnitude, the coefficient of friction on the fault and the elastic properties of the fault zone. Cyclic slip causes substantial frictional heating, potentially enough to generate a zone of partial melting within 1 km of the surface. The rate of permanent fault slip dramatically increases once a warm, melt-rich layer is established at the base of the fault.

Introduction: Several studies have examined shear heating along strike-slip faults on Europa, which could potentially produce melting [1 – 3]. Near-surface melting from shear heating could strongly impact both the habitability and geologic resurfacing of Europa. Melts produced by shear heating could impact the formation of ridges [4,5], supply a water source for recently detected vapor plumes [6] and possibly enable the transport of oxidants from the surface to the subsurface ocean as near-surface melts migrate downward [2,3,7].

Do Europa's faults slide fast enough to generate melting? Previous investigations have modeled permanent sliding along strike-slip faults (as opposed to cyclic sliding where faults return to the same position each orbit), and found that permanent sliding rates of ~30 m/yr may be necessary to cause melting [1,2]. Previous work has also assumed sliding rates as a boundary condition, without showing how the sliding rate should be controlled by the resolved shear stress acting on the fault.

Model: Here we calculate the magnitude of cyclic-slip along strike-slip faults on Europa. A Mohr-Coulomb model is used to predict the depth of frictional failure from diurnal tidal stress of ~100 kPa in magnitude [8]. Sliding is possible at a particular depth z, when the shear stress magnitude exceeds the failure stress τ_f,

$$|\tau| > \tau_f = \mu(\sigma_n + \rho g z).$$

Here τ and σ_n are the resolved shear and normal stress on the fault from tidal deformation, ρ is the density of the ice shell, g =1.34 m/s^2 is Europa's surface gravity and μ is the coefficient of friction of ice on the fault. We test a range of coefficients of friction from μ = 0.1 – 0.7, consistent with experimental findings [9]. Faults experience alternating phases of tension and compression and left and right-lateral shear [10], causing the failure depth to vary over time.

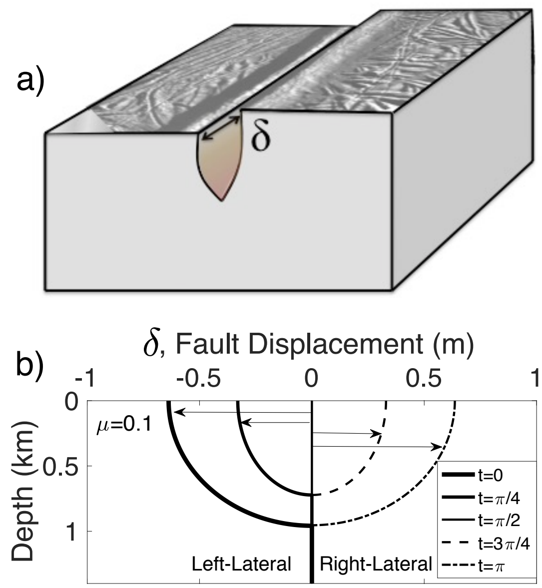

***Figure 1**: a) Schematic for cyclic-slip along faults on Europa. b) Calculations for cyclic-displacement with depth over the tidal cycle, assuming a tidal stress amplitude of 100 kPa, G=0.3 GPa and* $\mu = 0.1$.

An elastic half space model is used to calculate cyclic displacements between the fault walls, assuming the fault is locked below the maximum frictional failure depth, d_f. Shear stresses in excess of the failure stress cause elastic displacements between the fault walls [11].

$$\delta(z,t) = 2\frac{|\tau| - \tau_{fail}}{G}\sqrt{d_f^2 - z^2},\ \ z < d_f$$

Here G is the shear modulus of Europa's near-surface ice, which may be reduced due to intense fracturing in the upper few kilometers [12,13]. Diurnal stress amplitudes were calculated following [14], assuming a degree-two radial love number h_2=1.25 [15]. While obliquity and non-synchronous rotation could contribute to stress patterns on Europa [16-17], we first consider eccentricity tides only.

Results: Figure 1 shows an example calculation of cyclic-slip with depth, assuming a stress amplitude of 100 kPa, and a weak ice shell with G=0.3 GPa and $\mu = 0.1$. The maximum observed offset is ~0.65 m, but the total cyclic sliding after one full orbit is ~2.6 m. On most faults on Europa, the maximum shear stress is near 60 kPa, leading to cumulative cyclic slip amplitudes of up to 1 m (Fig 2).

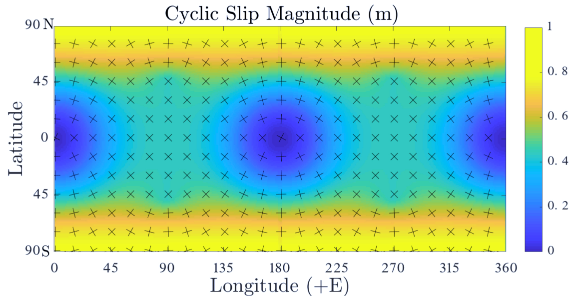

Figure 2: *Map of total cyclic slip per orbit along faults on Europa in response to diurnal tides. Black crosses indicate the orientation of faults aligned for maximum shear, on which cyclic slip was calculated.*

Shear Heating: We use our calculated cyclic-slip velocities to compute shear heating and melt generating rates along faults. A two-dimensional finite difference model is used to solve for the temperature increase on the fault. Our model includes a 10 km thick ice shell, ice thermal diffusivity of κ=10^{-6} m^2/s, an initially linear temperature profile and a fault depth ~1km determined from the frictional failure criterion.

While [1] found slip rates of 10^{-6} m/s could generate melt, their model included permanent fault slip which generates additional viscous heating from ductile deformation below the fault. We find that tidal stresses do cause cyclic-slip rates of 10^{-6} m/s, but these conditions can only cause melting if the thermal conductivity of the surface is significantly reduced [18].

Near-surface melting could also be generated if diurnal tides add with other stress sources, such as non-synchronous rotation (NSR). NSR could generate stresses of over 1 MPa, depending on the rotation period [8], but even an additional 100 kPa of resolved shear stress could strongly affect fault dynamics. This would deepen the frictional failure depth, which increases the sliding rate, in turn driving permanent fault motion and greater viscous heating below the fault.

Coupling Fault Motion and Heating: Figure 3 shows an example of our coupled fault-slip and thermal evolution model. A constant driving stress of 100 kPa (from NSR) is applied as a boundary condition, and the slip rate is obtained assuming free slip conditions on the fault down to the frictional failure depth. The viscosity of the shear zone limits the permanent slip rate, and viscosity is computed assuming a composite rheology [19]. Cyclic-slip from tides generates frictional heating, causing the fault to initially warm up. Once the fault is warm, the permanent slip rate increases leading to additional heating and then melting. If the fault remains cold, high viscosities below the fault prevent the fault from sliding.

These results suggest that warm, potentially melt-rich layers could exist at the base of active strike-slip faults on Europa. Upcoming missions could look for evidence of melt, and potentially detect cyclic offsets along strike-slip faults. Future work will explore feedbacks between melt-generation and frictional heating. Frictional heating could either be a self-limiting mechanism (as melt reducing the coefficient of friction limits its frictional heating) or could be a runaway process, as weakening the fault zone enables faster slip rates. We will also explore the interplay between driving stress mechanisms and stress relaxation due to permanent fault slip, another limiting mechanism that could shut down the activity of melt-producing faults.

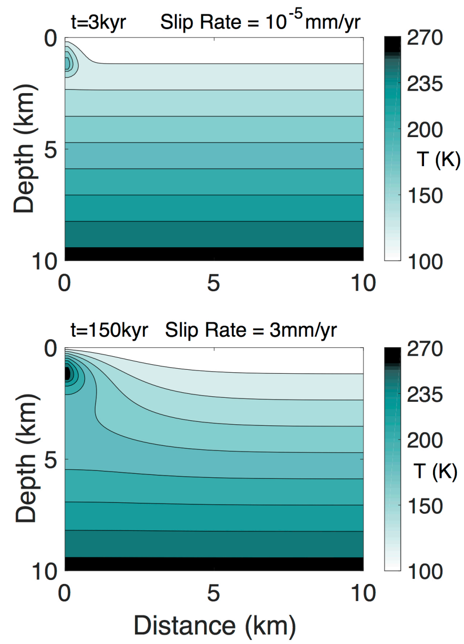

Figure 3: *Temperature and permanent slip rate on a ~1.5 km deep fault after 3kyr and 150 kyr. A constant driving stress of 100 kPa was applied as a boundary condition at the right. Shear heating from cyclic slip of 1 m/orbit was also applied along the fault (top left).*

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