TIDALLY DRIVEN COULOMB FAILURE ALONG EUROPA'S AGENOR LINEA. M. E. Cameron[1], A. L. Nahm[1], B. R. Smith-Konter[1], and R. T. Pappalardo[2], [1]University of Texas at El Paso, Department of Geological Sciences, 500 W. University, El Paso, TX 79968, mecameron@miners.utep.edu, [2]Jet Propulsion Laboratory, California Institute of Technology, M/S 321-560, Pasadena, CA 91109.

Introduction: Much of Europa's surface is cross-cut by a dense network of fractures; thus, there are many candidate faults for studying past tectonic activity. To better understand the role of tidal stress sources and implications for faulting on Europa, we investigate the relationship between shear and normal stresses at Agenor Linea, a ~1000 km generally E-W oriented bright band spanning Europa's southern mid-latitudes. *Voyager* analyses of Agenor Linea suggested a compressional origin [1] supported by a Galileo-based analysis [2], while detailed structural relationships within the fault band suggest a component of right-lateral strike-slip motion [3]. Previous studies have also suggested that diurnal tidal stresses: (1) are responsible for the formation of Europa's ridges [4,5,6], and (2) may trigger geological activity at the tiger stripes of Europa's cousin moon Enceladus [7,8,9]. Our analysis builds upon this cumulative body of work to assess the roles of both tidal diurnal stresses and non-synchronous rotation (NSR) stresses, the latter potentially providing a critical stress contribution for shear failure to be achieved along Agenor Linea.

As a tidally locked satellite orbits its parent planet, variations in gravitational tidal forces, due in part to the satellite's eccentric orbit, act to deform the moon's surface [4]. These stresses vary over a period equal to that of the satellite's orbital (diurnal) period (3.55 days for Europa). NSR tidal stresses may arise if a satellite has an outer icy shell that is decoupled from its interior [10]. As the outer shell rotates, the surface migrates eastward relative to the tidal bulge and will result in an additional source of stress within the rigid icy shell. It has been suggested that the period of NSR stress may be $10^4 – 10^7$ yr for Europa [5,10].

Tidal Stress Modeling: To calculate tidal stresses on Europa, we utilize SatStress, a numerical code that calculates tidal stresses at any point on the surface of a satellite for both diurnal and NSR stresses [11]. We adopt SatStress model parameters appropriate to a spherically symmetric ice shell of thickness 20 km, underlain by a global subsurface ocean: shear modulus μ = 3.5 GPa, Poisson ratio ν = 0.33, gravity g = 1.32 m/s^2, ice density r = 920 kg/m^3, satellite radius R = 1.56 x 10^3 km, satellite mass M = 4.8 x 10^{22} kg, semi-major axis a = 6.71 x 10^5 km, and eccentricity e = 0.0094. To investigate stresses arising from a diurnal stress model alone (assuming a NSR period of 10^7 yr), we adopt elastic Love numbers h_2 = 1.2 and l_2 = 0.32 [11]. Alternatively, to simulate the diurnal + NSR tidal stress field, we assume an NSR period of 5.7 x 10^4 yr, using Love numbers of h_2 = 1.8 (real) and -4.2 x 10^{-3} (imaginary), and l_2 = 0.47 (real) and -2.8 x 10^{-3} (imaginary) [11]. We resolve stress tensor components onto discrete fault segments of length ~4 km and of varying orientation into both normal and shear stress components.

To assess shear failure at Agenor Linea, we adopt a model based on the Coulomb failure criterion [12]. This model balances stresses that encourage and resist the motion of a fault, simultaneously accounting for both normal and shear tidal stresses, the coefficient of friction of ice, and additional stress at depth due to the overburden pressure. In this model, tidal shear stresses drive strike-slip motions, while normal stresses control a fault's frictional resistance to failure. To model this behavior, we calculate Coulomb stress, $\tau_c = |\tau_s| - \mu_f(\sigma_n + \rho g z)$, where τ_s and σ_n are the shear and normal stresses, $\rho g z$ is the overburden pressure (z is the vertical depth of the fault plane), and μ_f is the effective coefficient of friction. The sign of the overburden stress quantity is taken to be positive, while the normal tidal stress is assumed positive when in compression and negative when in tension. The sign of the shear stress (positive for right-lateral, negative for left-lateral) becomes important when inferring the direction of slip when the failure conditions are met. According to this model, shear failure will occur on optimally oriented fault segments when the shear stress exceeds the frictional resistance of the fault. Negative Coulomb stresses imply a locked fault, while positive stresses imply conditions supporting fault slip in a shearing sense. In this study we assume μ_f = 0.6 [13] and consider a range of fault depths z to 6 km.

Results: We first evaluate the opportunity for shear failure resulting from diurnal tidal stresses alone. For even the shallowest depths along Agenor Linea, shear failure from diurnal tidal stress mechanisms is difficult to achieve because the relatively large overburden stress (1.2 MPa at z = 1 km) dominates the stress field and cannot be overcome by the peak shear (~35 kPa) and normal (~70 kPa) diurnal stress amplitudes. Because the occurrence of strike-slip fault motion would be expected on Europa given the satellite's many observed strike-slip offset features, we consider the role of NSR stresses as a secular stress source for strike-slip faulting at Agenor Linea. NSR can provide stresses on the order of one to several MPa for ~1° of NSR as traditionally parameterized [4,14], or by steady-state rotation of a viscoelastic ice shell of viscosity ~10^{22} Pa s and rotation period ~ $10^4 – 10^5$ yr in the parameterization of [11].

Assuming a smaller NSR period of 5.7 x 10^4 yr and other parameters fixed as above, we next investigate the conditions for shear failure resulting from a diurnal + NSR tidal stress model (Figure 1). In this case, the NSR stress amplitudes are a factor of 10 – 60 times larger than diurnal stress amplitudes. Along Agenor Linea, total shear stresses are primarily right-lateral (~1.8 MPa), while normal stresses are predominantly compressive along the west side of the structure (~0.7 MPa) and tensile along the east side (~2.9 MPa). Because the Coulomb criterion only applies for a closed fault interface, we evaluate the role of fault depth for both normal tensile and compression regimes separately: (1) Tensile zones: where the normal stress is tensile, the overburden stress must be larger than the tensile stress (otherwise a fault would dilate); this requirement limits Coulomb failure to depths greater than 3 km for tensile stress regimes, as tensile stress from diurnal + NSR contributions is ~ 3 MPa. (2) Compressive zones: where the normal stress is compressive, no minimum fault depth limitation applies. Applying the Coulomb criterion for appropriate depths ranging from 0.1 – 5 km (Figure 1), we find that all segments of Agenor Linea achieve shear failure over a limited depth range. From 0.1 – 2 km depth, only compressive zones are subject to shear failure, with patches of slip manifested along the west side of the fault. At 3 km depth, both compressive and tensile zones are subject to shear failure; however, Coulomb stresses suggest that the west side of the fault transitions to a locked state, while large sections of the east side can achieve shear failure. At 4 km depth, a limited region along the east side of the fault achieves minimal shear failure conditions; however, a majority of the fault is in a locked state. For depths greater than 5 km, Coulomb stresses suggest a completely locked fault from end to end.

Conclusions: These results indicate that for shear failure to occur at Agenor Linea, tidal shear stress magnitudes must be on the order of the overburden pressure, which even at shallow depths (~ 1 km) is at least 1 MPa. Diurnal tidal deformation cannot provide this large stress, while NSR tidal deformation provides stresses ~1 to several MPa, depending on the assumed NSR rotation period. Using a NSR stress model, shear failure along Agenor Linea is possible although very sensitive to fault depth, with the west side of the fault failing at shallow depths (< 3 km) and the east side of the fault failing at 3 – 4 km depths. Future work will be directed toward investigating both the role of stress triggering among fault segments as a function of depth and the role of the NSR period to best fit the observations of strike-slip structures on Europa.

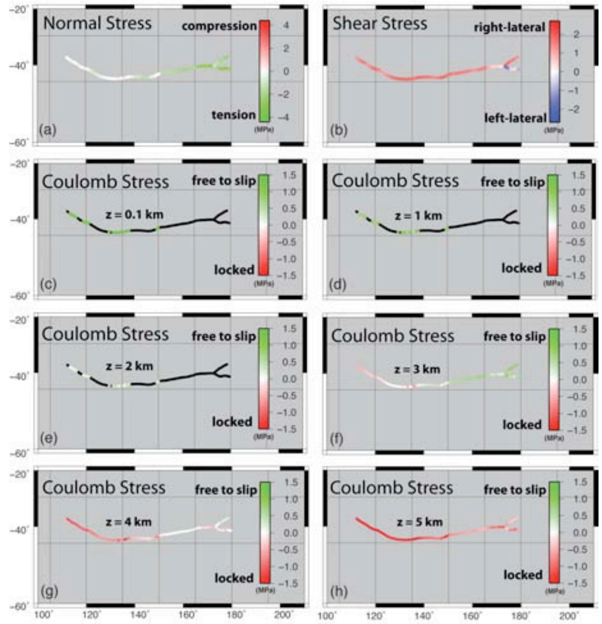

Figure 1. Tidal (diurnal + NSR) stress and Coulomb stress in MPa. (a) Resolved normal stress. (b) Resolved shear stress. (c-h) Coulomb stress as a function of depth *z*. Each plot represents instantaneous stress conditions at periapse (mean anomaly position 0°); these stresses are also representative of the entire orbital sequence, as diurnal stress variations are on the order of 50 kPa. Segments colored black in (c-e) represent regions of high tensile stress that are not subject to Coulomb failure at the indicated depth.

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