SHEARING-INDUCED TECTONIC DEFORMATION ON ICY SATELLITES: EUROPA AS A CASE STUDY. S. A. Kattenhorn, J. M. Groenleer, S. T. Marshall, and J. C. Vetter. University of Idaho, Dept. of Geological Sciences, PO Box 443022, Moscow, ID 83844-3022, U.S.A. (simkat@uidaho.edu).

Introduction: Brittle deformation on the icy satellites can be the result of numerous processes. On Earth, many of these processes are related in some way to plate tectonics; however, plate-like motions are rare on Europa [1]. A dominant driving force may be tidal deformation, which caused the majority of the fracturing on Europa [2-7] and possibly in the south polar region of Enceladus [8-9]. Such deformation is prevalent where the ice shell responds to the oscillations of tidal bulges above a liquid layer on any icy satellite having an orbital eccentricity [4]. Surface fracturing can also be driven by endogenic processes such as diapiric uplift [10], spreading due to gravitational collapse, folding and warping of the ice shell [11], flexure alongside a surface load [12], and impact events [13].

Regardless of the source of stress in a deforming ice shell, another type of tectonic deformation that may plate a significant contributor to the strain history and surface morphology is that due to shearing effects. Shearing of a pre-existing structure (whether it be a discrete crack or a weak zone of finite width) loaded by any source of differential stress, may induce locally perturbed, high magnitude stress fields that cause localized deformation [14]. We outline the mechanics of secondary tectonic deformation due to shearing and provide examples of its significance in the tectonic history of Europa. Similar deformation could potentially be found on other icy satellites, particularly if there is a significant source of stress to drive shearing, such as from tidal forcing.

Secondary Tectonic Deformation: When a pre-existing discontinuity is reactivated by horizontal shear stresses, resultant lateral motions turn the discontinuity into a strike-slip fault. For the case of a constant maximum compressive principal stress direction acting at some oblique angle to a fault, motion occurs when the Coulomb failure criterion is met: $\tau \geq \mu\sigma_n$, where τ is shear stress, σ_n is normal stress, and μ is the coefficient of static friction. Tidal stresses on a satellite with orbital eccentricity rotate during the course of the orbit, so the mechanics of motion along the fault may vary during the day [15]. Tensile stresses may cause a discontinuity to open during the orbit, in which case there is no frictional resistance to shear motion. Evidence for both dilational shear motion and frictional shear motion has been described on Europa [14].

Because sheared lineaments on icy satellites must have a finite length, linear elastic fracture mechanics predicts that concentrations of stress occur at the tips of the shearing discontinuities. In fact, the entire region adjacent to a strike-slip fault experiences a perturbation to the regional stress field, resulting in localized zones of extension and compression arranged antisymmetrically about each fault tip (Fig. 1a). Localized deformation in these zones of increased stress is referred to as secondary tectonic deformation and may include fracturing and crustal thinning in extensional quadrants, and folding, pressure solution, or crustal thickening in compressional quadrants.

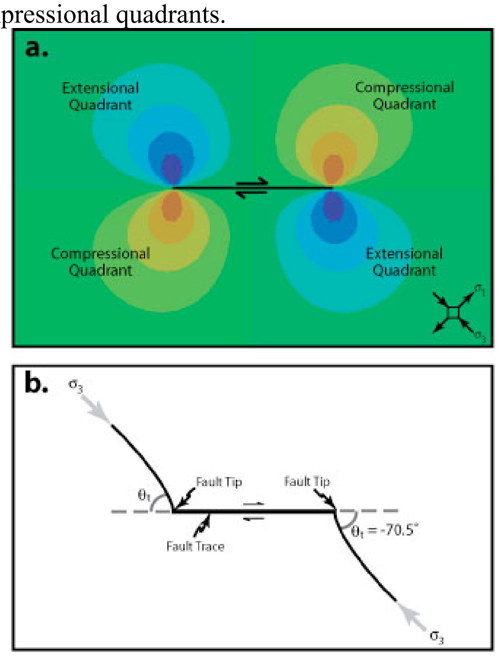

Fig. 1. (a) Quadrants of locally increased extension (blue colors) and compression (orange colors) adjacent to a right-lateral fault. (b) Tailcracks form at fault tips and propagate into the extensional quadrants. The maximum compressive stress is σ_3. Tailcrack angles are shown as θ_t. Both (a) and (b) are for a right-lateral fault. The left-lateral case is the mirror image.

Application to Europa: Shearing of lineaments and secondary tectonic deformation have played an important role in Europan tectonics.

Tailcracks. Stress concentrations at fault tips may induce secondary cracks called tailcracks that propagate into the extensional quadrants (Fig. 1b). The angle of the tailcrack (θ_t) is commonly around 70° but may be less if there is a component of opening along the fault during shearing [14]. Tailcracks have been identified on Europa [14, 16-17] and should be relatively easy to identify on any icy satellite (Fig. 2).

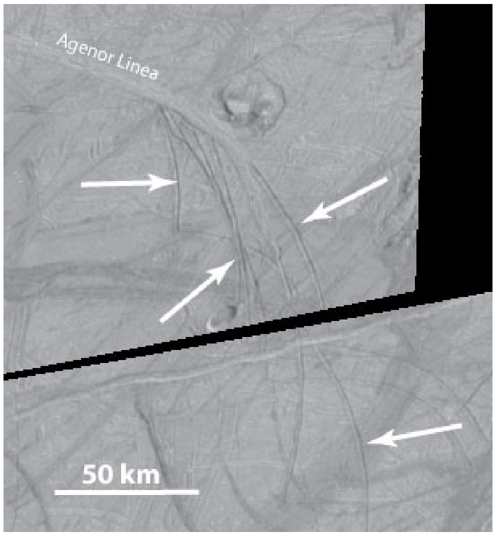

Fig. 2. Tailcracks at the SE tip of Agenor Linea, which experienced concomitant dilation and shear [14].

Anti-cracks. These are very subtle contractional features that form in the compressional quadrants at the tips of a shearing lineament. They have been described at Argadnel Regio [18] but are uncommon.

Cycloidal cracks. Although cycloids on Europa have been shown to trace out the changing direction of the maximum tensile diurnal tidal stress during the orbit [5], there is a period of time during which crack growth ceases while stresses continue to rotate. During this time, shear stresses are resolved onto the tip region of the arrested cycloid segment. Cycloid cusp angles and geometries are compatible with having formed by a tailcrack process, thus initiating a new cycloid segment that then propagates into the extensional quadrant driven onwards by the tidal stresses [19].

Cusp angles are thus analogous to tailcrack angles and must similarly be dictated by the exact ratio of shear-to-normal stress (τ/σ_n) resolved onto the cycloid tip at the instant of cusp growth. Our analysis of Europan cycloids in the northern trailing hemisphere reveals that it is always possible to find a point in the orbit at which the required τ/σ_n ratio occurs needed to account for measured cusp angles (Fig. 3) [20]. This point in the orbit occurs later than when the maximum tension is achieved, implying that new cycloid segments are only able to form due to the effects of shearing and tailcrack development at the tip of a previously formed segment. Hence, initial cycloid growth is likely triggered by shearing along, and cracking away from, an older lineament.

Crustal contraction. Shearing of a pre-existing lineament produces shear heating that may be responsible for thermal upwelling and the construction of ridge ramparts to either side of a central crack [21].

Our analysis of ridges showing strike-slip offsets reveals that they could not have formed purely due to lateral motions. Instead, apparent offsets were also produced than can only be reconciled with crustal convergence at ridges during shearing and heating [22].

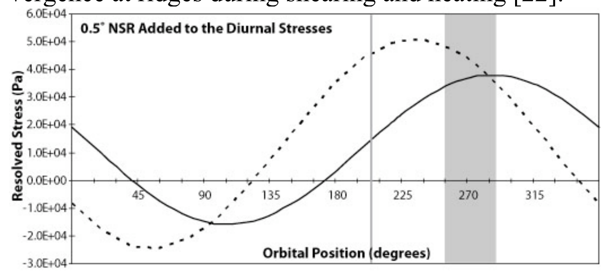

Fig. 3. Shear stress (dashed curve) and normal stress (solid curve) resolved onto a cycloid tip where a cusp developed. The gray area represents the point in the orbit where the ratio of the stresses was exactly right for the cusp to form. The vertical gray line is the point at which the the tensile principal stress is maximized.

Conclusions: Shearing of lineaments on Europa has contributed to the tectonic deformation through the creation of strike-slip faults and associated development of secondary tailcracks and anti-cracks, the initiation of cycloid segments, and the accommodation of crustral contraction along ridges. Similar deformation could conceivably occur on other icy satellites.

References: [1] Patterson, G. W. et al. (2006) *JSG, 28,* 2237–2258. [2] Helfenstein, P., Parmentier, E. M. (1985) *Icarus, 61,* 175-184. [3] McEwen, A. S. (1986) *Nature, 321,* 49-51. [4] Greenberg, R. et al. (1998) *Icarus, 135,* 64-78. [5] Hoppa, G. V. et al. (1999) *Science, 285,* 1899-1902. [6] Figueredo, P. H., Greeley, R. (2000) *JGR, 105,* 22,629-22,646. [7] Kattenhorn, S. A. (2002) *Icarus, 157,* 490-506. [8] Porco, C. C. et al. (2006) *Science, 311,* 1393-1401. [9] Hurford, T. A. et al. (2007) *Nature,* in press. [10] Collins, G. C. et al. (2000) *JGR, 105,* 1709–1716. [11] Prockter, L. M., Pappalardo, R. T. (2000) *Science, 289,* 941-943. [12] Billings, S. E., Kattenhorn, S. A. (2005) *Icarus, 177,* 397-412. [13] Melosh. H. J. (1989) Impact Cratering: A Geologic Process. [14] Kattenhorn, S. A. (2004) *Icarus, 172,* 582-602. [15] Hoppa, G. V. et al. (1999) *Icarus, 141,* 287-298. [16] Prockter, L. M. et al. (2000) *JGR*, *105*, 9483-9488. [17] Schulson, E. M. (2002) *JGR*, *107*, doi:10.1029/2001JE001586. [18] Kattenhorn, S. A., Marshall, S. T. (2006) *JSG*, *28*, 2204-2221. [19] Marshall, S. T., Kattenhorn, S. A. (2005) *Icarus*, *177*, 341-366. [20] Groenleer, J. M., Kattenhorn, S. A. (2006) *Eos, Trans. AGU*, *87*, P31D-08. [21] Nimmo, F., Gaidos, E. (2002) *JGR*, *107*, 1-8. [22] Vetter, J. C., Kattenhorn, S.A. (2005), *LPSC*, *XXXVI*, abstract #1053.