SECONDARY FRACTURING OF EUROPA’S CRUST IN RESPONSE TO COMBINED SLIP AND DILATION ALONG STRIKE-SLIP FAULTS. S. A. Kattenhorn, Department of Geological Sciences, University of Idaho, Moscow ID 83844-3022. (simkat@uidaho.edu)

Introduction: A commonly observed feature in faulted terrestrial rocks is the occurrence of secondary fractures alongside faults. Depending on exact morphology, such fractures have been termed tail cracks, wing cracks, kinks, or horsetail fractures [1, 2], and typically form at the tip of a slipping fault or around small jogs or steps along a fault surface. The location and orientation of secondary fracturing with respect to the fault plane or the fault tip (Fig. 1) can be used to determine if fault motion is left-lateral or right-lateral [1, 3].

Figure 1. Tail cracks at the tips of a slipping portion of a pre-existing lineament.

These secondary fractures, henceforth referred to as tail cracks, develop in response to concentrations of stress around the periphery of a slipping fault. The orientations of these perturbed stresses differ from the regional stress orientations responsible for fault slip. This causes secondary fracturing orientations to be rotated out of the plane of the primary fault. These orientations can be predicted analytically using principles of linear elastic fracture mechanics, assuming that the faulted material is behaving elastically.

Ice has been documented to behave elastically under conditions of low temperatures, low confining pressures and high strain rates [4]. These conditions typify deformation of Europa’s ice shell, which is subject to a constantly rotating diurnal stress field induced by the gravitational pull of Jupiter [5].

These tidal stresses on Europa are sufficient to drive strike-slip faulting [6]. Accordingly, strike-slip faults are well documented on Europa [6-10], with lengths of up to 810 km. My examination of many of these faults has revealed that tail cracks are also a common phenomenon along Europan strike-slip faults (Fig. 1) and reveal details about the nature of the stress field that existed at the time of fault motion.

Tail Crack Geometry: The geometry of the tail cracks in Fig. 1 is concave towards the region beyond the fault tips, as is commonly observed in terrestrial examples [1, 2]. However, the sense of curvature in the Euopan example in Fig. 2 is opposite to this. Furthermore, the “take-off angle” (θ) of the tail cracks away from the fault (i.e. relative orientations of fault and tail cracks) is relatively small in Fig. 2 compared to terrestrial tail cracks, which are commonly oriented at about 70° to the fault plane. Take-off angles have been calculated to vary theoretically [1, 3] based on the fracture mode, which describes the relative amounts of sliding and opening along a fracture or fault. I have extended such analyses to account for the sense of curvature of tail cracks, and thus describe the Europan crustal stress state at the time of fault motion, as well as the physical behavior of the fault during slip events.

Theoretical Treatment: The stress tensor can be calculated at any arbitrary point in an elastic body containing a slipping discontinuity using the modified Westergaard stress functions [11]. The generalized form of the crack stress function for any mode of crack motion is given by

\[ \sigma(z) = A_m \left( \left( z^2 - a^2 \right)^{1/2} - z \right) + B_m z, \]

where the crack length is 2a, m is the mode of failure (I, II, or III), and z is the complex variable z = x + iy. The constants A_m and B_m describe the nature of the loading of the crack (failure mode), and are given by:

\[ A_m = \left[ a_1, -i a_2, a_3 \right], \]

\[ B_m = \left[ (a_1^2 + a_2^2)/2, 0, i (a_1 a_2 - a_3) \right], \]

\[ a_1 = \left( a_1, -i (a_2 - a_3), -i (a_2 - a_3), -i (a_2 - a_3) \right), \]

\[ a_2 = \left( a_1 + a_2^2)/2, 0, i (a_1 - a_2) \right), \]

\[ a_3 = \left( a_1^2 + a_2^2)/2, 0, i (a_1 a_2 - a_3) \right), \]
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where the r and c superscripts refer to the remote and crack components of the stress tensor, respectively. The complex number i is equal to \((-1)^{1/2}\). For the two-dimensional case, the components of the stress tensor are directly related to the crack stress function through the relationships:

- \(\sigma_{11} = \text{Re}\{\sigma_{11}^0\} + x_1\text{Im}\{\sigma_{11}^0 + \sigma_{11}^c\} - C\)
- \(\sigma_{12} = -\text{Im}\{\sigma_{11}^0\} - x_1\text{Re}\{\sigma_{11}^0 + \sigma_{11}^c\} - D\)
- \(\sigma_{22} = \text{Re}\{\sigma_{11}^0 + 2\sigma_{11}^c\} - x_1\text{Im}\{\sigma_{11}^0 + \sigma_{11}^c\} + C\)

where \(\text{Re}\) and \(\text{Im}\) are real and imaginary parts, and the constants \(C\) and \(D\) are given by \(C = (\sigma_{22} - \sigma_{11}^0)/2\) and \(D = -\sigma_{12}^c\).

These stress tensor components can then be used to calculate the orientations of principal stresses at any coordinate point \((x_1, x_2)\) around a slipping crack [11].

**Effect of Fault Dilation on Tail Crack Geometry:**

Using the above equations, principal stress orientations were calculated in an elastic material around a slipping strike-slip fault, approximating fault slip in Europa’s ice shell. Several loading conditions were considered, ranging from the pure shear case (pure mode II – no fault dilation), to cases where increasing fault dilation accompanied strike-slip motion (increasing mode I/mode II ratio). The orientations of principal stresses and resultant tail crack shapes are shown in Fig. 3. As the amount of fault dilation increases, the tail crack curvature changes. The pure mode II case resembles many terrestrial examples, as idealized in Fig. 1, with a take-off angle of 70.5° [1]. It implies frictional contact of the fault surfaces during slip. However, with increasing fault dilation accompanying slip, tail crack curvatures begin to resemble those at the tip of Agenor Linea (Fig. 2), showing decreasing take-off angles and changing tail crack curvatures. The Agenor example resembles the result for a mode I/mode II ratio of 2, which is predicted to have a take-off angle of ~5° [1]. This result implies that Agenor Linea was dilating at the time that tail crack growth was occurring at its tip during fault slip.

**Discussion:** The current thinking on strike-slip fault kinematics on Europa is that fault slip is driven by a diurnal tidal process that induces tidal walking of the faults [6]. This process involves a repetitive cycle of fault motions that include dilation during slip, consistent with the model results presented here. This implies that a significant amount of fault-normal tension is needed during fault slip episodes. The mode I/mode II ratio of 2 suggested here for Agenor Linea is consistent with the ratio of normal to shear stresses suggested for the fault tidal walking model [6].

**References:**


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**Figure 3.** Analytical modeling results showing principal stress trajectories around right-lateral strike-slip faults (blue) in an elastic body for a range of boundary conditions. Locations and morphology of resultant tail cracks are shown in red. As the mode I/mode II ratio increases from left to right, the amount of fault dilation increases. For the pure mode II case on the left, there is no dilation of the fault. Tail crack morphology at the tip of Agenor Linea in Fig. 2 resembles the tail crack morphology for the mode I/mode II ratio = 2 modeling result. Long tic trajectories represent the maximum tensile stress direction.