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Fault-induced perturbed stress fields and associated tensile and compressive deformation at fault tips in the ice shell of Europa: implications for fault mechanics

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Abstract

Secondary fractures at the tips of strike-slip faults are common in the ice shell of Europa. Large magnitude perturbed stress fields must therefore be considered to be a viable driving mechanism for the development of part of the fracture sequence. Fault motions produce extensional and compressional quadrants around the fault tips. Theoretically, these quadrants can be associated with tensile and compressive deformational features (i.e. cracks and anti-cracks), respectively. Accordingly, we describe examples of both types of deformation at fault tips on Europa in the form of extensional tailcracks and compressional anti-cracks. The characteristics of these features with respect to the plane of the fault create a fingerprint for the mechanics of fault slip accumulation when compared with linear elastic fracture mechanics (LEFM) models of perturbed stress fields around fault tips. Tailcrack kink angles and curving geometry can be used to determine whether opening accompanies sliding motion. Kink angles in the 50–70° range are common along strike-slip faults that resemble ridges, and indicate that little to no opening accompanied sliding. In contrast, tailcrack kink angles are closer to 30° for strike-slip faults that resemble bands, with tailcrack curvatures opposite to ridge-like fault examples, indicating that these faults undergo significant dilation and infill during fault slip episodes. Anti-cracks, which may result from compression and volume reduction of porous near-surface ice, have geometries that further constrain fault motion history, corroborating the results of tailcrack analysis. The angular separation between anti-cracks and tailcracks are similar to LEFM predictions, indicating the absence of cohesive end-zones near the tips of Europan faults, hence suggesting homogeneous frictional properties along the fault length. Tailcrack analysis can be applied to the interpretation of cycloidal ridges: chains of arcuate cracks on Europa that are separated by sharp kinks called cusps. Cusp angles are reminiscent of tailcrack kink angles along ridge-like strike-slip faults. Cycloid growth in a temporally variable tidal stress field ultimately resolves shear stresses onto the near-tip region of a growing cycloid segment. Thus, resultant slip and associated tailcrack development may be the driving force behind the initiation of the succeeding arcuate segment, hence facilitating the ongoing propagation of the cycloid chain.

Keywords: Europa; Faults; Strike-slip; Tailcracks; Anti-cracks; Compression; Stress

1. Introduction

It has long been recognized that fractures of various types develop alongside terrestrial faults and intrusive dikes in response to motion along the fault or magma pressure within the dike (e.g. Delaney et al., 1986; Pollard, 1987; Rubin, 1993; Kattenhorn and Watkeys, 1995; Petit and Mattauer, 1995; Willemse et al., 1997; Vermilye and Scholz, 1998). Because these fractures are a direct result of the faulting or dike injection, they are referred to as secondary fractures, implying they would not have developed in the absence of the structure with which they are affiliated. The exact type of secondary fracture that develops will depend on the available stresses, fluid pressures, and rock properties, but may include joints,

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veins, pressure solution surfaces, minor shear fractures, or even fully-developed faults or fault systems. In all cases, the secondary fractures form in response to the growth of the primary feature and may even facilitate further growth by providing a zone of weakness through which the primary feature can propagate.

Secondary fractures may develop in the form of macroscale tailcracks (or wing cracks) that emanate away from the tips of faults or slipping interfaces such as joints or bedding planes (Rispoli, 1981; Cruikshank et al., 1991; Cruikshank and Aydin, 1994; Petit and Mattauer, 1995; Willemse et al., 1997; Martel and Boger, 1998; Younes and Engelder, 1999; Cooke et al., 2000; Kattenhorn et al., 2000). All such slipping interfaces are hereafter referred to simply as faults. Tailcracks are extremely common tension fractures that form on opposite sides of opposite tips of a fault (where present at both tips), defining a pattern that is a direct indicator of the shear sense along the fault (Fig. 1a). Tailcracks may also develop at points along a fault where it deviates from planarity (such as at jogs, steps, and relay zones), or at points of variable frictional properties along the fault surface (Cooke, 1997). Tailcracks have very different orientations to the fault with which they are associated and are typically curved (Fig. 1b and c). Although tailcracks are usually smaller than the fault along which they formed, it is possible for them to reach lengths in excess of the primary feature when a large crack-parallel compression exists (Brace and Bombolakis, 1963; Erdogan and Sih, 1963; Hoek and Bieniawski, 1965; Nemat-Nasser and Horii, 1982).

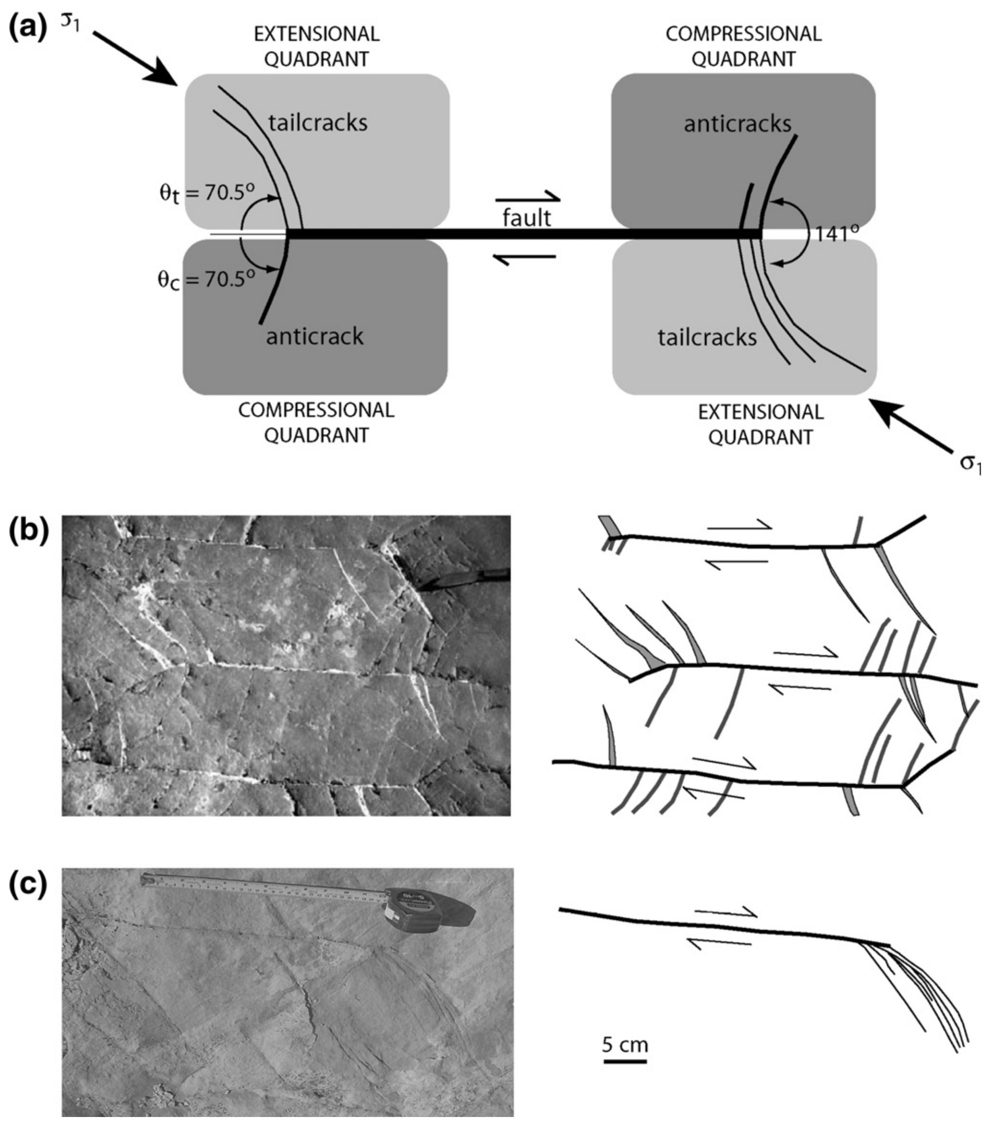

Fig. 1. (a) Schematic diagram showing the locations and orientations of tailcracks and anti-cracks that would form at the tips of a right-lateral strike-slip fault. The left-lateral case is the mirror image of this illustration. Extensional and compressional quadrants are antisymmetrically distributed about opposite fault tips. Tailcracks form in extensional quadrants with a kink angle, θ_t=70.5°. Anti-cracks form in compressional quadrants with a kink angle, θ_c=70.5°. The far-field maximum compressive stress direction is shown as σ_1. (b) Example of vein-filled tailcracks (light gray) and anti-cracks (dark gray) along right-lateral slipped fractures (black) in limestone at Languedoc, France. Knife blade for scale. (c) Example of tailcracks with an opposite sense of curvature to (b) at the tip of a right-lateral slipped joint in sandstone in Nevada, U.S.A. The total slip was a few millimeters.