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Snap, Crackle, Pop: Dilational fault breccias record seismic slip below the brittle–plastic transition

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A B S T R A C T

Off-fault dynamic tensile cracks form behind an earthquake rupture front with distinct orientation and spacing. These cracks explode the wall rock and create breccias, which we hypothesize will preserve a unique fingerprint of dynamic rupture. Identification of these characteristic breccias may enable a new tool for identifying paleoseismic slip surfaces in the rock record. Using previous experimental and theoretical predictions, we develop a field-based model of dynamic dilational breccia formation. Experimental studies find that secondary tensile fracture networks comprise closely spaced fractures at angles of 70–90° from a slip surface, as well as fractures that branch at angles of ∼30° from a primary mode I fracture. The Pofadder Shear Zone, in Namibia and South Africa, preserves breccias formed in the brittle–ductile transition zone displaying fracture patterns consistent with those described above. Fracture spacing is approximately two orders of magnitude less than predicted by quasi-static models. Breccias are clast-supported, monomict and can display an abrupt transition from fracture network crackle breccia to mosaic breccia textures. Brecciation occurs by the intersection of off-fault dynamic fractures and wall rock fabric; this is in contrast to previous models of fluid pressure gradient-driven failure "implosion breccias". This mechanism tends to form many similar sized clasts with particle size distributions that may not display self-similarity; where self-similarity is observed the distributions have relatively low *D*-values of 1.47 ± 0.37, similar to other studies of dynamic processes. We measure slip distances at dilational breccia stepovers, estimating earthquake magnitudes between M_w 2.8–5.8 and associated rupture lengths of 0.023–3.3 km. The small calculated rupture dimensions, in combination with our geologic observations, suggest that some earthquakes nucleated within the quartz-plastic transitional zone and potentially record deep seismic slip.

1. Introduction

Continental scale, strike-slip fault systems define the boundaries of continental plates or micro-plates, accommodate large amounts of displacement (Sylvester, 1988), and host large earthquakes that can reach up to ∼M 8 (Lin et al., 2002; Stirling et al., 2007). The nucleation and cessation of fault ruptures are in part controlled by deformation mechanisms operating during the seismic cycle (Tse and Rice, 1986; Scholz, 1998, 2002; Rice, 2006). Within the seismogenic zone where velocity weakening mechanisms dominate, an increase in slip rate causes a strength reduction on the fault plane allowing for large earthquakes to occur (Sibson, 1977; Scholz, 1988, 1998, 2002). This is manifested by the concentration of earthquakes between approximately 5–15 km depth (Sibson, 1984). However, earthquake rupture is not limited to the seismogenic zone and can propagate into velocity strengthening regimes due to the strain rate sensitivity of deformation mechanisms (Sibson, 1983; Scholz, 1988). The lower boundary of the seismogenic zone in granitic crust is defined by the onset of quartz plasticity marking the top of a quasi-plastic transitional zone (Sibson, 1980; Scholz, 1988).

The study of ancient exhumed faults (e.g. Sibson, 1977) or actively exhuming faults (e.g. Toy et al., 2008) presents an opportunity to study deformation mechanisms operating at seismogenic or sub-seismogenic depths. The most widely accepted evidence of earthquakes in exhumed faults is tectonically generated

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