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The spin zone: Transient mid-crust permeability caused by coseismic brecciation

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A B S T R A C T

Pore fluids migrating through the deep section of continental strike-slip fault zones have been invoked to explain such phenomena as tectonic tremor, stress transfer across the brittle-ductile transition, and short timescales of co-seismic healing. In this contribution, we describe a coseismic mechanism for forming transient vertical fluid conduits within dilational jogs in strike-slip faults.

We present field observations of breccias that formed coseismically at dilational stepovers in the dextral Pofadder Shear Zone, a ~ 1 *Ga* exhumed continental strike-slip fault in South Africa and Namibia. These breccias are interpreted to have formed when tensile fractures emanating from rupture tips intersected mylonitic foliation parallel to the rupture surface, which then failed, disaggregating the rock. We used quartz textures in the mylonites determined by electron backscatter diffraction to uniquely compare the orientation of each clast to the neighboring wall rock and constrain finite clast rotation within breccia bodies. Comparison of two- and three-dimensional rotation patterns show that clast trajectories are highly scattered when decoupled from wall rock, suggesting that Pofadder breccias were not formed by gradual plucking of clasts during slip. The dilational breccia bodies have sub-vertical geometries and high porosities relative to the host mylonites. We infer that the opening of these breccias may have created instantaneous, temporary vertical pathways for fluid draining through the brittle-plastic transition. These pathways healed post-seismically by cementation or ductile creep along the fault. The connection of many adjacent and overprinting breccia bodies through time provides a mechanism for fluid transport on a 10 s of km scale though the middle crust.

1. Introduction

Fault zones assert strong control on fluid flow in the continental crust, forming either fluid conduits or barriers (Sibson, 1992a; Caine et al., 1996, 2010; Caine and Forster, 1999; Faulkner et al., 2010). Transient fluid pressure gradients along faults affect fault strength and ultimately the mechanics of faulting (Hubbert and Rubey, 1959; Sibson et al., 1975; Sibson, 1981, 1992a; Chester et al., 1993; Byerlee, 1993; Evans and Chester, 1995; Evans et al., 1997; Bruhn et al., 1994; Scholz, 2002; Caine et al., 2010). Fluids along faults have been linked to the distribution and timing of aftershocks (e.g. Nur and Booker, 1972; Sleep and Blanpied, 1992; Micklethwaite and Cox, 2004; Cox and Ruming, 2004), the geometry of the base of the seismogenic zone (Sibson, 1984), the triggering of moderate earthquakes (Segall, 1989; Keranen et al., 2013) and tectonic tremor (Obara, 2002; Rogers and Dragert, 2003; Nadeau and Dolenc, 2005; Shelly and Hardebeck, 2010).

In many hydraulic fault models, maximum porosity and permeability may occur immediately following earthquake rupture, due to newly opened fractures (e.g. Sibson, 1992a; Micklethwaite and Cox, 2006; Peltzer et al., 1996), followed by a period of healing or infilling with hydrothermal precipitates (Sibson, 1987; Sibson et al., 1988). The study of fluid flow mechanisms on mid-crustal faults is limited to exhumed fault rock studies

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(e.g. Sibson, 1977; Etheridge et al., 1984; McCaig, 1988; Sibson, 1990a, 1992a; Carter and Dworkin, 1990, b; Wintsch et al., 1995; Fusseis et al., 2009; Faulkner et al., 2010; Menegon et al., 2015) or geophysical investigations (Connolly and Podladchikov, 2004; Fialko, 2004; Becken et al., 2011). Geophysical resistivity surveys suggest the transient activity of sub-vertical fluid pathways along the central San Andreas fault and can be linked to the occurrence of tremor and creep (Becken et al., 2011). Here we present direct observations of an inter-connected fluid pathway system in an ancient analogue for modern strike slip faults like the San Andreas, and explain the transience of structurally controlled changes in permeability across the seismic cycle.

The mid-crustal, brittle-plastic transition zone is especially important to most hydraulic fault models, as fluid flow at this depth likely plays an important role in earthquake-cycle stress transfers between different rheological crustal domains (e.g. McCaig, 1988; Sibson, 1992a; Bons, 2001; Fusseis et al., 2009; Menegon et al., 2015). At these depths fracture healing mechanisms are enhanced, due to elevated temperatures, and the ambient rock porosity is low (Etheridge et al., 1984; Smith and Evans, 1984), corresponding to a reduction in permeability at the base of the brittle zone (Ingebritsen and Manning, 2010). Thus, transient fracture porosity associated with fault slip has the potential to dramatically increase fault permeability as long as fractures remain open and connected. The strain rate dependence of brittle deformation in the mid-crust (e.g. Sibson, 1980; Scholz, 1988), implies a tie between fluid pathways and earthquakes must be especially important on mid-crustal structures.

The highest porosity fault rocks are fault breccias (Caine et al., 2010), which can have large, relatively uniform clast sizes precluding optimal packing (e.g. Zhang and Tullis, 1998), and creating interconnected pores which act as fluid pathways. Fault breccias can form by plucking clasts from wall rock during gradual slip along a fault interface (Caine et al., 2010), as well as by dynamic fracturing during earthquakes, on a fault irregularity or at dilational stepovers (Sibson, 1985, 1986; Melosh et al., 2014).

Can the attributes of these two different brecciation mechanisms be related to their deformation histories? “Attrition” breccias form during sliding and wear along a fault, and their clast size distribution evolves toward a fractal distribution with cataclasis and grain size reduction (e.g. Zhang and Tullis, 1998). This clast size distribution enables closer packing and lower porosity compared to other fault breccias. In contrast, coseismic breccias formed along slip surfaces or in dilational stepovers may have extremely high porosities, as a result of open fractures and the lack of fine wear material (Sibson, 1985; Melosh et al., 2014). Coseismic brecciation does not preclude a fractal distribution, although the fractal dimension tends toward lower values than comminution products (Sammis et al., 1987; Melosh et al., 2014).

In this contribution we describe breccias in dilational stepovers, which represent fluid conduits formed in mid-crustal conditions during earthquakes in the Pofadder Shear Zone (Melosh et al., 2014). To test whether geometric observations could distinguish dynamically-formed breccias from other breccias along faults, we developed a method using quartz textures in mylonite observed with electron backscatter diffraction (EBSD) as three-dimensional markers to measure the orientation of each clast in the breccias and determine the finite magnitude of rotation and orientation of rotation axes relative to local wall rock. We then compare these true rotations to the estimates acquired using two-dimensional markers (mylonite foliation) observed in thin sections (2D surfaces) to determine whether rotation patterns can be captured by simpler petrographic observations.

Below, we show the characteristic patterns of breccia clast rotations which uniquely identify dynamically formed breccias and present the methods for identifying them. We address the implications for the development of transient permeable pathways which would enable draining of pore fluids from the lower crust and influence effective fault strength throughout the seismic cycle.

2. Conceptual models of breccia clast rotation and fault porosity

We begin by presenting theoretical models for breccia formation and predicted clast rotation signatures. We predict the qualitative relationships between fracturing, clast rotation, porosity and permeability and present the possible trends in the permeability evolution on coseismic (seconds) to interseismic (years to centuries) timescales.

2.1. End member rotation models

We define two possible end-member breccia clast rotation models for fault breccia: 1) a “fault-confined” model where breccia forms at a fault interface that experienced continued slip (high shear strain, fluctuating strain rate), and 2) a “free-rotation” model where breccia forms instantaneously at a dilational stepover (low shear strain, high strain rate) opened spontaneously during an earthquake (Fig. 1). We recognize these are simplified end-member models and that cross-over and complications exist. However, these models can account for a large range of observed breccia textures and their applicability is meant to differentiate and categorize distinct breccia styles (see Section 6).

For the case of the “fault-confined” model (Fig. 1A), rotational axes are approximately perpendicular to the slip direction on the fault, within the plane of the fault, independent of strain rate. The sense of clast rotation will be directly related to the sense of motion across the fault (i.e. clockwise for a right lateral fault when looking down), and clasts will have rotated substantially. In this case, the maximum predicted clast rotation may be similar to the ratio of the clast circumference to fault displacement. The rotation of clasts may keep up with slip as long as the clast dimension is equal to or less than the width of the slipping layer, so this limit varies with fault roughness.

In the “free-rotation” model (Fig. 1B) the orientation of rotational axes are more variable as there is more room for clasts to rotate and inertial collisions between clast-clast and clast-wall rock are possible. Due to the increased void space, clasts are not always in contact with the wall rock, so there is minimal frictional force acting on the clasts to influence the orientation of the spin axes. Similarly, the direction of clast rotation (i.e. clockwise vs. counterclockwise) in the “free-rotation” model, is more variable than rotations in the “fault-confined” model. Lastly, unlike the “fault-confined” model, release from, and interaction with moving wall rock may impart initial momentum as clasts break away from the wall, possibly leaving a signature in the rotational axis patterns representative of this imparted directionality.

2.2. The link to fault porosity

Sibson (1986) originally recognized that dilational fault breccias generated during rapid slip can form by implosion due to high fluid pressure gradients, and that the resultant breccia bodies form ideal fluid conduits. We develop a conceptual model for the qualitative development of porosity on a fault which displays off-fault dynamic tensile cracks and dilational stepover breccias (Fig. 2A) (e.g. Sibson, 1986), consistent with paleoseismic slip (Sibson, 1985, 1986; Melosh et al., 2014; Rowe and Griffith, 2015). Prior to the