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Porosity and particle shape changes leading to shear localization in small-displacement faults

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ABSTRACT

A microstructural study of shear localization in fault gouge was carried out in small-displacement faults so there would be minimum masking effects from a complex deformation history. We studied particle size, shape, and porosity changes in gouge adjacent to zones of shear localization in natural and synthetic gouges subjected to shear displacements δ, of up to 1.2 m. Scanning electron microscope images were used for estimating image porosity Φ_I, and measuring particle size of the deformed and undeformed gouges. The particle size data were used for calculating simulated porosity Φ_S from computer-generated simple fractal gouge model of each sample. Modeled microstructures contained round grains and a fractal distribution matched to that of the measured natural samples. Changes in Φ_I, Φ_S, and Φ_I/Φ_S with increasing δ were used for tracking changes in particle shape and porosity of the gouges precursory to shear localization. The Φ_I and Φ_S values for the natural and synthetic gouges converge at $\delta \sim 0.1$ m, suggesting that gouge particles adjacent to shear localization sites tend to become rounded. Porosity for such densified regions of the gouge adjacent to Y-shear zones was determined to be <1% at large displacements. In the same regions, the porosity reductions were also associated with decreased sorting coefficient and fractal dimensions $D > 2.6$. The study suggests that brittle shear localization may involve favorably-oriented micro porous pockets of gouge that result from competing changes in particle shape and particle size, which tend to affect gouge porosity in different ways.

1. Introduction

Brittle shear localization microstructures such as slip surfaces, shear bands, and cataclastic foliation are commonly found within the core of many natural fault zones. The localization process results in mechanical weakening of the fault and is often associated with the most comminuted and densified regions in fault gouge (e.g. Evans and Chester, 1995; Chester and Chester, 1998; Boullier et al., 2004; Hayman, 2006; Rawling and Goodwin, 2006; Rockwell and Ben-Zion, 2007; Tanaka et al., 2007; Brogi, 2008). Shear localization has been observed in relatively unaltered small-displacement faults with displacements typically <1 m as in most experimental faults as well as in mature natural fault zones involving a variety of alteration products. Experimental fault gouge studies have shown that ≤0.1 m of shear displacement results in shear localization, although microstructural changes leading to shear localization are not well understood. A number of studies of natural, experimental and computer simulated gouge deformation conclude that shear localization is primarily a particle size and particle-size distribution driven process (Dieterich, 1981; Marone and Scholz, 1989; Biegel et al., 1989; Logan et al., 1992; Gu and Wong, 1994; Billi, 2007; Keulen et al., 2007; Sammis and Ben-Zion, 2008). Experimental studies by Mandl et al. (1977), Vardoulakis (1980), Marone and Scholz (1989), Mair and Marone (1999), and Mair et al. (2002) indicate that gouge attains a critical strain or particle size distribution prior to shear localization. Mandl et al. (1977) based on experimental data, suggested that shear localizes in favorably-oriented bands of gouge that have achieved a critical PSD through confined comminution. This is possible because an increase in the proportion of fine particles in gouge, while not reducing cohesive forces, might reduce the friction. Subsequently, at a low threshold value of internal friction there will be a drastic reduction in boundary shear by development of a slip plane and growth of a shear zone. In the powder industry this

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phenomenon is attributed to rounding and size equalizing of particles which tend to reduce 'interlocking resistance' of a granular material (Lowrison, 1974). The microstructural aspects of the model described above draws support from a number of observations. Gouge deformation simulations by Morgan and Boettcher (1999) showed that a sharp drop in sliding contacts accompanied localized failure as fewer particles were involved in the zone of deformation. Mair and Marone (1999) studied the controlling effect of particle size on shear localization and noted that PSD evolution in fine and coarse gouge differed only by a shear strain γ of 3.4. They suggested that higher fracture toughness might have inhibited further comminution of fine gouge as its PSD became more uniform. Scarpelli and Wood (1982), Moore et al. (1989), Logan et al. (1992) reported the same sequence of microstructural development preceding shear localization in calcite and halite gouges. In a model presented by Shipton and Cowie (2001) a critical amount of comminution or strain was necessary for slip surface nucleation, but the slip surfaces accommodated further strain without appreciable amount of comminution. The experimental study of Marone and Scholz (1989) concluded that transition from pervasive to localized shear occurs at a critical strain or PSD in addition to the influence of gouge density.

This study attempts to provide a microstructural model for shear localization by investigating the combined effect of particle shape and particle size on porosity changes that precede shear localization in small-displacement natural and experimental faults. The effect of porosity changes on shear localization in granular material with varied particle size and PSD has been studied previously. The work of Mead (1925) and Frank (1965) shows that since in confined comminution dilatancy is suppressed, shear localization must occur in regions of gouge with least dilatancy rate. Marone and Scholz (1989) reported dilatant behavior at the onset of shear localization in their experimental quartz gouge. The actual shear localization occurred on R_1 Riedel shear bands, and the dilatancy was believed to be the result of unpacking of over consolidated gouge. Marone and Scholz (1989) noted that particles within their

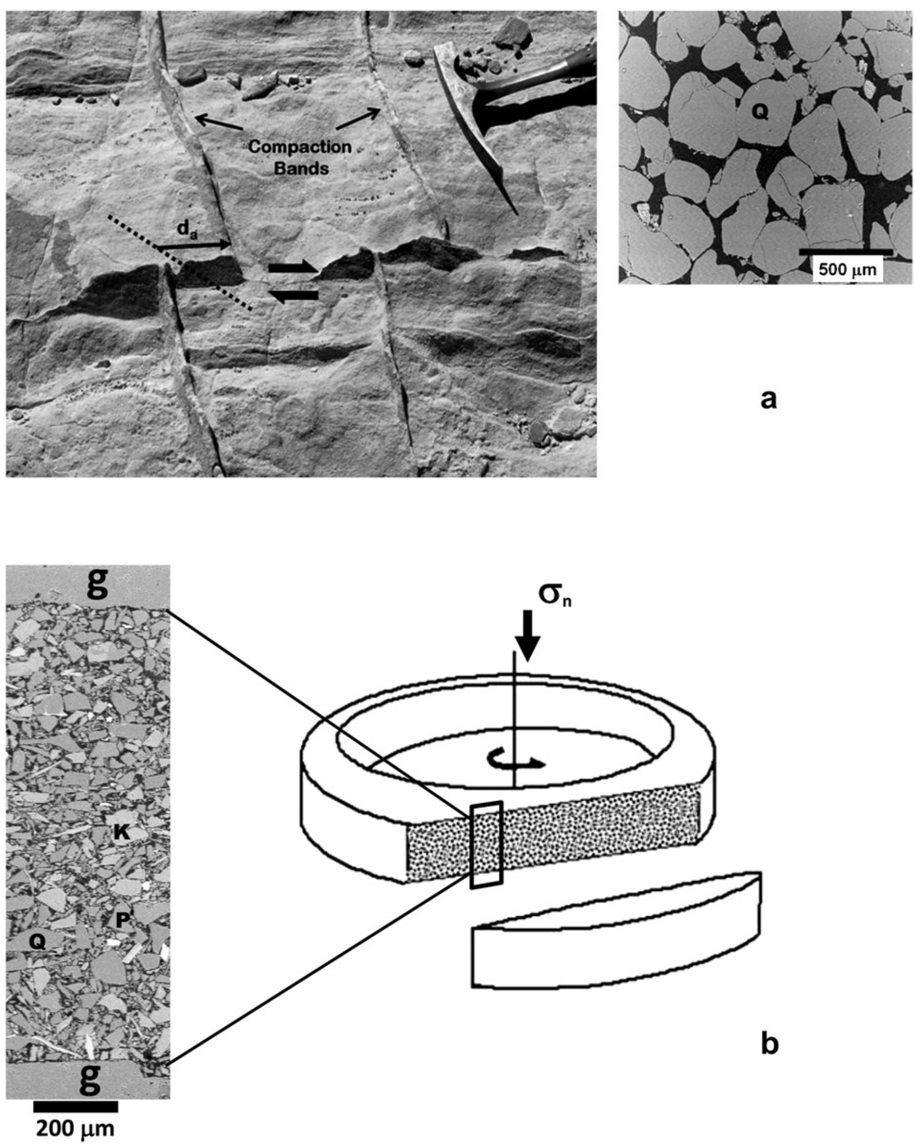

Fig. 1. Natural and synthetic gouges used in the study. (a) Typical small-displacement splay fault in the Aztec sandstone. Outcrop picture is labeled with the apparent displacement vector (d_a), and trend of the slickenside lineation on the fault plane (dotted line). Compaction bands serve as displacement markers. Typical undeformed texture of the sandstone is shown on the right. (b) Rotary shear sample ring consisting of a 2 mm gouge layer (not to scale). The close-up view of the gouge layer on the left is an actual section across undeformed simulated Westerly granite gouge compacted to 25 MPa pressure. The gouge is held between granite forcing blocks g, forming the shear zone boundaries; Q = quartz; K = potassium feldspar; P = plagioclase feldspar; lightest shade particles are phyllosilicates. Textures are back-scattered SEM images.