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Shear zones in clay-rich fault gouge: A laboratory study of fabric development and evolution

Samuel H. Haines [a], [*], Bryan Kaproth [a], Chris Marone [a], Demian Saffer [a], Ben van der Pluijm [b]

[a] The Pennsylvania State University, Department of Geosciences and Center for Geomechanics, Geofluids, and Geohazards, Deike Building, University Park, PA 16802, USA
[b] University of Michigan, Department of Earth & Environmental Sciences, 1100 N. University Ave, Ann Arbor, MI 48109, USA

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ABSTRACT

Clay-rich fault rocks have long been recognized to host distinctive fabric elements, and fault rock fabric is increasingly thought to play a fundamental role in fault mechanical behaviour in the brittle regime. Although the geometries of fabric elements in fault gouges have been described for almost a century, the genesis and evolution of these elements during shear, and their links to bulk mechanical properties, remain poorly understood. We characterize the development and evolution of fabric elements with increasing shear in a variety of clay-rich experimental gouges over shear strains of <1 to >20 and at normal stresses of 2–150 MPa in the double-direct shear configuration. In addition to SEM observations of experiment products at a variety of shear strains, we quantified clay fabric intensity and the degree of grain size reduction using X-ray Texture Goniometry (XTG) and particle size distribution (PSD) measurements. We also measured P- and S-wave velocities during shear to further probe the evolution of shear fabric and gouge properties. We find that clay fabric elements develop in a systematic manner regardless of the gouge material. Riedel shears in the R_1 orientation and boundary-parallel shears are the dominant fabric elements. Riedel shears nucleate at layer margins and propagate into the layer shortly after reaching yield stress. Clay particles rotate into the P-orientation shortly after Riedels propagate through the layer. The Riedel shears are through-going, but are $>10\times$ thinner than similar zones observed in coarser granular materials. Our results suggest that the weakness of clay-rich fault gouge may be less a function of anisotropic crystal structure, as has been suggested previously, and more a consequence of very thin shear surfaces permitting deformation in clay-rich materials with minimal dilation or cataclasis. The very thin shear surfaces are a function of the fine grain size of the materials and possibly polymodal PSD's.

1. Introduction and aims

The mechanical behaviour of geologic materials deforming in the brittle regime has been the subject of considerable interest for over a hundred years, owing to its role both in interpreting deformed rocks and in understanding seismic phenomena (e.g., Gilbert, 1884; Cloos, 1928; Riedel, 1929; Morgenstern and Tchalenko, 1967; Sibson, 1977; Byerlee, 1978; Crawford et al., 2008; Collettini et al., 2009, 2011). Experimental deformation of simulated gouge materials under controlled laboratory conditions has been one fruitful approach to investigate the frictional strength and stability of brittle faults, and the geometry of fabric elements with respect to shear (e.g., Dieterich, 1981; Anthony and Marone, 2005; Niemeijer and Spiers, 2007; Collettini et al., 2009; Haines et al., 2009; Niemeijer et al., 2010a,b; Ikari et al., 2011). Clay-rich gouges have garnered considerable recent interest, because they may explain the weakness of some natural faults (e.g., Wu et al., 1975; Wu, 1978; Wang et al., 1980; Shimamoto and Logan, 1981; Carpenter et al., 2011).

Outcrop and drilling studies document clay-rich gouge in many fault zones, and these outcrops commonly include consistent patterns of fabric elements. These faults are often dominated by a crude 'scaly' foliation (*sensu* Vannucchi et al., 2003) and phyllosilicate preferred orientation parallel to the 'P' orientation of Logan et al. (1979) (hereafter "P-foliation" – see Fig. 1) and through-going narrow shear surfaces parallel to the R_1 orientation of Logan et al. (1979) (e.g., Rutter et al., 1986; Chester and Logan, 1987; Erickson and Wiltschko, 1991; Cowan et al., 2003). These patterns of fabric elements are pervasive, fundamental features, and occur across

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[*] Corresponding author. Present address: Chevron Energy Technology Corporation, 1500 Louisiana St., Houston, TX 77002, USA.
E-mail addresses: shhaines@umich.edu, faultgougeguy@gmail.com (S.H. Haines).

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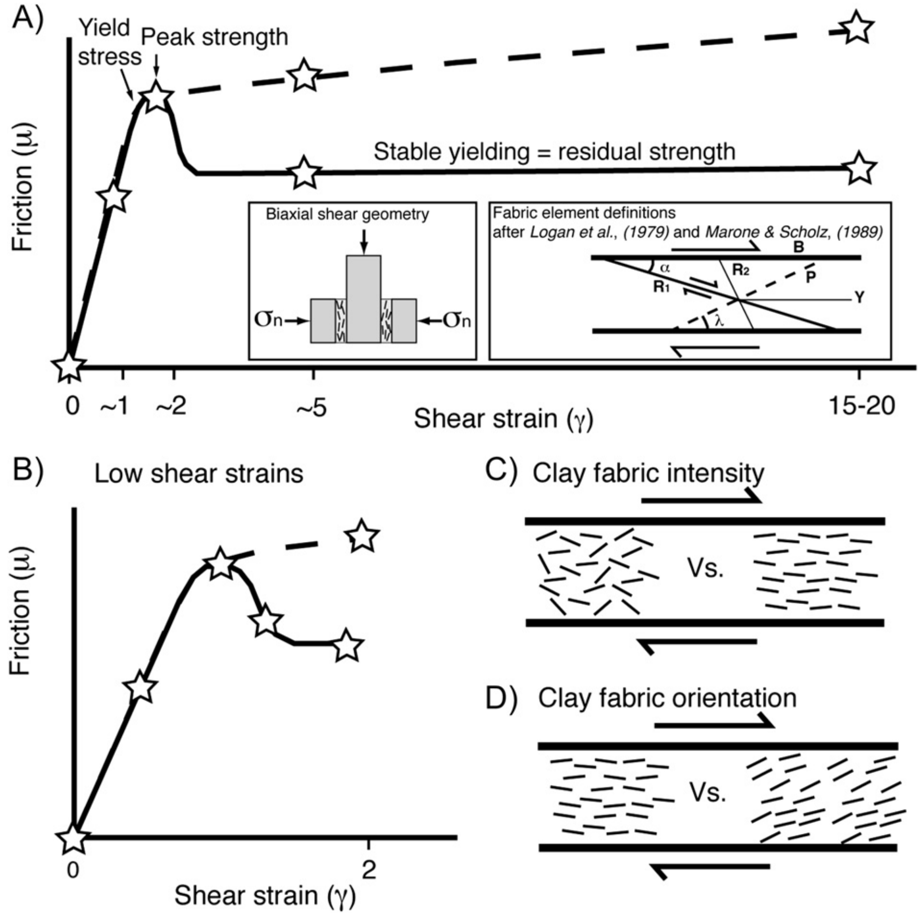

Fig. 1. Illustration of experiment plan used to understand fabric element evolution in this study. A) Stars are individual experiments stopped at particular points on stress-strain curves. Inset boxes show experimental configuration and terminology used for geometry of shear fabric elements of Logan et al. (1979) and Marone and Scholz (1989). B. Close-up of A) indicating region of multiple experiments at a given normal stress to understand the onset of Riedel shears. C) and D) Schematic depictions of phyllosilicate fabric intensity and fabric orientation as determined by XTG (X-Ray Texture Goniometry).

a wide range of conditions in both experimental and natural gouges (Fig. 1). Although studies of coarse-grained granular materials such as quartz, feldspars and carbonates (e.g., Logan et al., 1979; Marone and Scholz, 1989; Marone et al., 1990; Beeler et al., 1996) and experimental work specifically focused on phyllosilicate-rich materials have documented the evolution of similar fabric elements (e.g., Morgenstern and Tchalenko, 1967; Wijeyesekera and de Freitas, 1976; Maltman, 1977; Weber et al., 1978; Logan and Rauenzahn, 1987; Rutter et al., 1986; Arch et al., 1988; Logan et al., 1992; Saffer and Marone, 2003; Haines et al., 2009), the manner in which these elements evolve as a function of shear displacement, gouge mineralogy, particle morphology, and applied normal stress, as well as the associated changes in elastic properties, remains incompletely understood. The development and evolution of specific fabric elements, such as Riedel shears, and P-foliation, are also not well characterized.

Classic studies on fabric evolution in clay-rich materials date to the 1920's, but were conducted at significantly different conditions than those of modern friction experiments. These classic and systematic fabric evolution experiments were all conducted in the shear-box geometry common to soil mechanics (Morgenstern and Tchalenko, 1967; Tchalenko, 1968, 1970; Maltman, 1977, 1987; Naylor et al., 1986), which shears a relatively thick layer to low displacements and low shear strains at very low effective normal stresses <1 MPa. This approach also produces large gradients in the displacement magnitude across the layer.

Modern rock friction experiments, in contrast, employ one of three experimental configurations, the tri-axial 'saw-cut' configuration (e.g., Summers and Byerlee, 1977; Faulkner et al., 2010), the biaxial 'double-direct' configuration (e.g., Dieterich, 1981; Mair and Marone, 1999; Ikari and Saffer, 2011), or the ring-shear configuration (e.g., Beeler et al., 1996; Shimamoto and Tsutsumi, 1994; Niemeijer et al., 2010c). These configurations use much thinner layers and are sheared at higher normal stresses than the early shear-box experiments. Although shear-box experiments have compellingly reproduced the geometries of fault networks in the near surface and in the upper few km of the crust (e.g., Tchalenko, 1970; Naylor et al., 1986), their application to deeper tectonic faults, and comparison to modern experimental friction results, is problematic, owing to the different boundary conditions. The manner in which fabric elements develop in modern experimental configurations, which are more relevant to fault zone processes at higher stress and larger shear strains, remains surprisingly unclear.

Elastic wave velocities in granular materials are a function of the area and strength of grain contacts, stress across and between grains, and damage within grains (Sayers and Kachanov, 1995; Fortin et al., 2005), and therefore their measurement provides key insight into the evolution of these quantities during shear. Recent advances in experimental design have allowed quantification of elastic properties during shearing, by measuring ultrasonic wave speed across gouge layers (Knuth, 2011). Measurements of elastic wave velocities have been used to infer changes in microstructure