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High-velocity frictional properties of Alpine Fault rocks: Mechanical data, microstructural analysis, and implications for rupture propagation

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ABSTRACT

The Alpine Fault in New Zealand is a major plate-bounding structure that typically slips in ~M8 earthquakes every c. 330 years. To investigate the near-surface, high-velocity frictional behavior of surface- and borehole-derived Alpine Fault gouges and cataclasites, twenty-one rotary shear experiments were conducted at 1 MPa normal stress and 1 m/s equivalent slip velocity under both room-dry and water-saturated (wet) conditions. In the room-dry experiments, the peak friction coefficient ($\mu_p = \tau_p/\sigma_n$) of Alpine Fault cataclasites and fault gouges was consistently high (mean $\mu_p = 0.67 \pm 0.07$). In the wet experiments, the fault gouge peak friction coefficients were lower (mean $\mu_p = 0.20 \pm 0.12$) than the cataclasite peak friction coefficients (mean $\mu_p = 0.64 \pm 0.04$). All fault rocks exhibited very low steady-state friction coefficients (μ_{ss}) (room-dry experiments mean $\mu_{ss} = 0.16 \pm 0.05$; wet experiments mean $\mu_{ss} = 0.09 \pm 0.04$). Of all the experiments performed, six experiments conducted on wet smectite-bearing principal slip zone (PSZ) fault gouges yielded the lowest peak friction coefficients ($\mu_p = 0.10$–0.20), the lowest steady-state friction coefficients ($\mu_{ss} = 0.03$–0.09), and, commonly, the lowest specific fracture energy values ($E_G = 0.01$–0.69 MJ/m^2). Microstructures produced during room-dry and wet experiments on a smectite-bearing PSZ fault gouge were compared with microstructures in the same material recovered from the Deep Fault Drilling Project (DFDP-1) drill cores. The near-absence of localized shear bands with a strong crystallographic preferred orientation in the natural samples most resembles microstructures formed during wet experiments. Mechanical data and microstructural observations suggest that Alpine Fault ruptures propagate preferentially through water-saturated smectite-bearing fault gouges that exhibit low peak and steady-state friction coefficients.

1. Introduction

The Alpine Fault, South Island, New Zealand is a long-lived crustal-scale continental transform fault that has accommodated at least 460 km of cumulative displacement in the past c. 45 Myr (Wellman, 1953; Sutherland et al., 2000). Paleoseismological records indicate that the Alpine Fault produces quasi-periodic large-magnitude (M~8) earthquakes that propagate along-strike for 300–600 km (Wells and Goff, 2007; Sutherland et al., 2007; Berryman et al., 2012). Single-event strike-slip and dip-slip surface displacements on the Alpine Fault are 7.5–9 m and c. 1 m, respectively (Barth et al., 2013). Boulton et al. (2012) and Barth et al. (2013) measured the frictional strength and stability of smectitic principal slip zone (PSZ) gouges from well-studied localities spanning c. 220 km along strike of the central and southern Alpine Fault. They concluded that the velocity-strengthening frictional properties of surface-outcrop PSZ gouges tested while fluid-saturated at

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room temperature and low sliding velocities (v < 100–300 μm/s) were incompatible with paleoseismological and geomorphological evidence for surface-rupturing earthquakes. Subsequent hydrothermal experiments at close to in situ conditions comparable to 2–8 km depth showed that central Alpine Fault gouges do have the velocity-weakening properties required for earthquake nucleation (Boulton et al., 2014; Niemeijer et al., 2016).

Dynamically, a large (≥3-fold) reduction in the coefficient of friction of both intact and granular rocks during high-velocity sliding (v > 0.1 m/s) has been observed repeatedly since the first rotary shear experiments by Tsutsumi and Shimamoto (1997) (for reviews, see Wibberley et al., 2008; Di Toro et al., 2011; Niemeijer et al., 2012). A wide range of dynamic weakening mechanisms has been proposed to explain this effect, including: melt lubrication (e.g., Hirose and Shimamoto, 2005; Nielsen et al., 2008), silica gel lubrication (Goldsby and Tullis, 2002; Di Toro et al., 2004), flash heating (Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011), powder lubrication (e.g., Han et al., 2010; Reches and Lockner, 2010; Chang et al., 2012), fluid film lubrication (Brodsky and Kanamori, 2001; Ferri et al., 2011), and thermal pressurization (e.g., Sibson, 1973; Lachenbruch, 1980; Wibberley and Shimamoto, 2005; Rice, 2006; Sulem et al., 2007; Tanikawa and Shimamoto, 2009; Faulkner et al., 2011) or thermochemical pressurization (Brantut et al., 2008, 2011; Chen et al., 2013; Platt et al., 2015). To what extent hanging wall, principal slip zone (PSZ), and footwall Alpine Fault rocks undergo high-velocity weakening remains untested.

The present study documents the results of room-dry and water-saturated high-velocity, low-normal stress (v = 1 m/s, $\sigma_n = 1$ MPa) friction experiments conducted on Alpine Fault gouge and cataclasite samples collected from the surface at Gaunt Creek and Hokuri Creek, and from shallow depths during the Deep Fault Drilling Project (DFDP-1) at Gaunt Creek (Fig. 1). A focus of these experiments is to quantify the peak coefficient of friction (μ_p), as this value represents the yield strength and thus a barrier to rupture propagation. An additional aim is to quantify the steady-state coefficient of friction (μ_{ss}) at high velocity as well as the slip-weakening distance (d_w) over which μ_{ss} is reached. Finally, microstructures produced during six experiments with varying velocity histories and pore-fluid conditions are compared with microstructures formed in naturally occurring smectitic PSZ fault gouges. By doing so, we test: (1) the effect pore fluids have on microstructural evolution during high-velocity sliding; (2) the effect decelerating slip and simulated afterslip have on recovered experimental microstructures, and (3) the degree to which natural microstructures resemble those produced during experimental deformation. Our results allow us to conclude that small variations in sliding velocity following a high-velocity slip event have little effect on microstructures recovered and that natural microstructures resemble those formed during wet high-velocity friction experiments.

2. Fault rock descriptions

2.1. Analytical methods

Samples were collected from unoriented drill core retrieved during the first phase of the Deep Fault Drilling Project (DFDP-1) at Gaunt Creek (hereafter GC) (Fig. 1). An additional sample of PSZ gouge was collected from a nearby outcrop (the GC scarp outcrop of Boulton et al., 2012). All sample depths reported from DFDP-1B are adjusted by +0.20 m from borehole lithological logs following Townend et al. (2013). Saponite-rich gouge collected from a 12 m-wide PSZ at Hokuri Creek (HkC PSZ) on the southern Alpine Fault was also tested. The gouge mineralogy, microstructure, and low-velocity frictional and hydrological properties of the HkC PSZ gouge were described in detail by Barth et al. (2013). With the exception of the DFDP-1B 144.04 m gouge, all samples were gently disaggregated using mortar and pestle, and the powdered material was passed through a 100# sieve to obtain a <150 μm separate. Quantitative X-ray diffraction (XRD) analyses were undertaken to determine the mineralogy of each sieved DFDP separate and the bulk rock mineralogy of the DFDP-1B 144.04 m gouge, which was tested without sieving due to the limited quantity of material available.

2.2. Fault rock occurrence, nomenclature, and mineralogy

Brief descriptions of the eight fault rock samples used in high-velocity friction experiments are presented here following the lithologic units described by Toy et al. (2015a). Core-scale images of the DFDP-1 samples are illustrated in Fig. 1. High-velocity friction experiments were performed on two Unit 4 foliated cataclasites (DFDP-1A 86.41 m and DFDP-1A 90.32 m), one Unit 6 cataclasite (DFDP-1B 128.80 m), and four Unit 5 gouges (DFDP-1A 90.62 m, DFDP-1B 128.44 m, DFDP-1B 144.04 m, and GC Scarp PSZ) (cf. Fig. 5b,d and f in Toy et al., 2015). Hokuri Creek fault gouge (HkC PSZ) was also deformed (cf. Fig. 6c,f,i and l in Barth et al., 2013). Henceforth, DFDP-1 samples are referred to by hole (1A or 1B), depth below top of the hole (m), and fault rock lithology (foliated cataclasite, gouge, or cataclasite).

In the DFDP-1 boreholes, hanging wall lithologic units 2, 3, and 4 occur within the fault core; these units have formed due to alteration (Unit 2, 3, and 4) and brittle fragmentation, translation, and rotation (Units 3 and 4) of Unit 1 quartzofeldspathic and metabasic ultramylonites (Sutherland et al., 2012; Toy et al., 2015a; Boulton et al., 2017). The Unit 4 foliated cataclasite samples tested contain irregularly spaced planar to locally anastomosing seams of aligned phyllosilicates (Fig. 1d and e). The Unit 6 cataclasite comprises comminuted quartz-plagioclase-potassium feldspar granitoid aggregates and rare gneiss clasts (Fig. 1f). The Unit 5 gouges are incohesive fault rocks with >90% matrix grains <0.1 mm in size. Unit 5 gouges can be differentiated by phyllosilicate mineralogy (described below) and the nature and abundance of protolith clasts. 1A 90.62 m gouge contains ultramylonite and cataclasite clasts, calcite vein fragments, and rare clasts, lenses, or veins of underlying smectitic gouge (Fig. 1e) (see also Boulton et al., 2014).

Compared to the 1A 90.62 m gouge, 1B 128.44 m (PSZ-1) gouge has a higher proportion of gouge clasts relative to cataclasite and ultramylonites clasts and fewer calcite vein fragments (Fig. 1f). In drill core, the 1B 128.44 m gouge is c. 20 cm-thick, and its contact with the hanging wall was not recovered. In two thin sections, one unoriented and one cut subparallel to a slickenside lineation, the PSZ-1 gouge exhibits reverse grading with distance from its contact with the underlying footwall cataclasite. Near the footwall contact, microstructures include a random-fabric matrix (Fig. 2a) with a single fault-parallel (Y-shear) shear band <50 μm-thick (Fig. 2c and d). The 1B 144.04 m (PSZ-2) gouge contains clasts of gneiss, ultramylonite, gouge and quartz-feldspar-plagioclase aggregate (Figs. 1g and 2b). In drill core, the 1B 144.04 m gouge is c. 10-cm thick and both its hanging wall and footwall contacts were recovered. In an unoriented thin section, the PSZ-2 gouge comprises a random fabric with anastomosing but discontinuous shear bands developed locally adjacent to competent hanging wall and footwall cataclasites (Fig. 2e and f). There is no evidence of continuous shear band(s) with a crystallographic preferred orientation. GC Scarp PSZ gouge clasts include reworked fault gouge, cataclasite, calcite vein fragments, metamorphic quartz, and vein quartz; the outcrop was described by Boulton et al. (2012).

Table 1 lists the mineralogy of each fault rock <150 μm separate; note the 1B 144.04 m gouge was not sieved. All fault rocks analyzed