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Can grain size sensitive flow lubricate faults during the initial stages of earthquake propagation?

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ABSTRACT

Recent friction experiments carried out under upper crustal P–T conditions have shown that microstructures typical of high temperature creep develop in the slip zone of experimental faults. These mechanisms are more commonly thought to control aseismic viscous flow and shear zone strength in the lower crust/upper mantle. In this study, displacement-controlled experiments have been performed on carbonate gouges at seismic slip rates (1 $m\,s^{-1}$), to investigate whether they may also control the frictional strength of seismic faults at the higher strain rates attained in the brittle crust. At relatively low displacements (<1 cm) and temperatures (≤100 °C), brittle fracturing and cataclasis produce shear localisation and grain size reduction in a thin slip zone (150 μm). With increasing displacement (up to 15 cm) and temperatures (T up to 600 °C), due to frictional heating, intracrystalline plasticity mechanisms start to accommodate intragranular strain in the slip zone, and play a key role in producing nanoscale subgrains (≤100 nm). With further displacement and temperature rise, the onset of weakening coincides with the formation in the slip zone of equiaxial, nanograin aggregates exhibiting polygonal grain boundaries, no shape or crystal preferred orientation and low dislocation densities, possibly due to high temperature (>900 °C) grain boundary sliding (GBS) deformation mechanisms. The observed micro-textures are strikingly similar to those predicted by theoretical studies, and those observed during experiments on metals and fine-grained carbonates, where superplastic behaviour has been inferred. To a first approximation, the measured drop in strength is in agreement with our flow stress calculations, suggesting that strain could be accommodated more efficiently by these mechanisms within the weaker bulk slip zone, rather than by frictional sliding along the main slip surfaces in the slip zone. Frictionally induced, grainsize-sensitive GBS deformation mechanisms can thus account for the self-lubrication and dynamic weakening of carbonate faults during earthquake propagation in nature.

1. Introduction

Earthquakes are typically hosted in the shallower portion of crustal fault zones (≤15 km depth and ambient $T \leq 300\,°C$), where fracturing and cataclasis are traditionally thought to be the dominant processes during frictional sliding (Kohlstedt et al., 1995; Scholz, 1998; Sibson, 1977). At greater depths and temperatures, in the lower crust/upper mantle, viscous flow, potentially associated with superplastic behaviour (Ashby and Verrall, 1973; Boullier and Gueguen, 1975; Hiraga et al., 2010; Rutter et al., 1994; Schmid et al., 1977; Walker et al., 1990), is inferred to facilitate aseismic creep along shear zones, based on experimental data and microstructural observations (Ashby and Verrall, 1977; Kohlstedt et al., 1995; Passchier and Trouw, 2005; Poirier, 1985; Rutter, 1995, 1999). Grain boundary sliding (GBS) diffusion creep, associated with superplastic behaviour, i.e., the ability of materials to achieve unusually high elongations (>100%) before failure, has been observed at high strain rates (>$10^2\ s^{-1}$) for a range of nano-phase alloys (Chandra, 2002) and ceramics (Lankford, 1996). These mechanisms could potentially occur in ultrafine-grained (nano-scale) geological materials deformed at higher strain rates and temperatures appropriate for seismic slip or slow earthquakes (Green et al., 2015; Rutter and Brodie, 1988; Schubnel et al., 2013; Verberne et al., 2014).

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Recent laboratory experiments, performed using rotary shear apparatuses, show that when sliding at seismic velocities ($\geq$0.5 m s^{-1}) the frictional strength of faults, μ, is significantly lower ($\mu = 0.1$–0.3) (Di Toro et al., 2011; Goldsby and Tullis, 2011; Hirose and Shimamoto, 2005; Reches and Lockner, 2010) than when sliding at low (<1 mm s^{-1}), sub-seismic speeds ($\mu = 0.6$–0.85) (Byerlee, 1978). Understanding the processes controlling the evolution of fault strength as seismic slip rates are approached is of paramount importance. Strength cannot be measured directly using seismological data, yet it affects the magnitude of the stress drop, the heat flow signature of seismogenic faults, and the relative partitioning of the earthquake energy budget (i.e., the proportion of energy dissipated as seismic waves that can travel to the Earth's surface and cause damaging earthquakes). It has been proposed that slip weakening of experimental and natural seismic faults is caused by thermally-activated processes triggered by localised frictional heating and high temperatures attained in the slip zone (Rice, 2006). Furthermore, recent studies show that cohesive slip zones (SZs), in natural (Siman-Tov et al., 2013) and experimental carbonate seismic faults (De Paola et al., 2011a, 2011b; Fondriest et al., 2013; Green et al., 2015; Ree et al., 2014; Smith et al., 2013; Verberne et al., 2014), are composed of striated and mirrored slip surfaces (SSs). Microstructural analyses show that the SSs and the adjacent SZ material are made of calcite nanograin ($D < 1$ μm) aggregates with a polygonal texture, a microstructure consistent with deformation by creep deformation mechanisms. The use of mirror SSs and nano-granular SZ textures as indicators of seismic slip on faults in carbonates (e.g. Ree et al., 2014; Smith et al., 2013) has been questioned by Verberne et al. (2013, 2014) who have shown that similar features can develop during low velocity (1 μm s^{-1}) friction experiments performed on simulated calcite gouge at upper crustal P–T conditions. However, the grain-scale processes suggested to account for the observed weakening of rocks deformed in the laboratory at seismic velocities are still debated (De Paola et al., 2011a, 2011b; De Paola, 2013; Han et al., 2010; Tisato et al., 2012), as is their occurrence along natural faults during earthquake propagation. Verberne et al. (2014) performed microstructural analyses on experimentally deformed samples at sub-seismic slip rates (1 μm s^{-1}) and low temperatures (<140 °C). They show that nanofibre formation during nanogranular flow with diffusive mass transfer can promote velocity-weakening behaviour and earthquake nucleation in carbonate rocks. Green et al. (2015) integrated microstructural observations and experimental work to show that mineral phase transformation in carbonate rocks, occurring at the high temperatures produced by frictional heating, can generate nanometric materials which are weak at seismic slip rates ($\approx$1 m s^{-1}) and flow by grain-boundary sliding mechanisms.

Here we study the evolution of deformation mechanisms, and their control on the frictional strength of slip zones developed in simulated, carbonate gouges during accelerating sliding to seismic slip rates ($v = 1$ m s^{-1}). To do so we combine results from new laboratory friction experiments with microstructural observations on samples sheared up to the attainment of dynamic weakening, but *prior* to the onset of phase transformation. Flow stress calculations are performed to investigate whether grainsize-sensitive creep deformation mechanisms, potentially associated with superplastic behaviour, can effectively weaken faults and facilitate earthquake propagation in the shallow crust. To illustrate the relevance of our findings to natural faults, we also carried out microstructural observations on the principal slip zone material extracted from natural, seismically active faults in carbonates.

2. Experimental settings

Friction experiments were performed in the Rock Mechanics Laboratory, at Durham University (UK), using a low to high velocity rotary shear apparatus (details in Supplementary Information 1 – Fig. SI1) built by the Marui and Co., Ltd Company (Osaka, Japan). We performed a set of eight displacement-controlled experiments at room temperature and humidity conditions on fine-grained ($63 < D < 93$ μm), carbonate gouges at target slip rates $v = 1$ m s^{-1} and normal stresses $\sigma_n = 12$–18 MPa (Supplementary Information Table 1). During displacement-controlled experiments, arrested at pre-determined displacements, the electric servomotor of the apparatus was controlled in the digital mode, using a signal generator DF1906 (NF corporation) (Supplementary Information 1).

A synthetic fault zone was created by sandwiching 2 g of simulated fault gouge between two stainless steel cylinders (25 mm in diameter), whose ends were machined with radial grooves 500 μm high to grip the sample surface (Supplementary Information 1 – Fig. SI2). The experiments were run under drained conditions, and to limit gouge loss during the experiments, the sample assembly was confined using a Teflon ring. Teflon rings were cut and tightened onto the stainless steel cylinder using a hose clamp. The inner edges of the rings were machined to reduce their sharpness, and thus avoid ring damage and sample contamination by Teflon during the insertion of the stainless steel cylinders (Supplementary Information 1 – Fig. SI2).

Samples were recovered after each experiment to study the slip zone microstructures. Thin sections for optical microscope observations were taken from slices of the slip zone cut at 2/3 of the radius, to make observations consistent with calculated values of the velocity, v, and the displacement d (Supplementary Information 2).

3. Mechanical data

To identify the mechanisms controlling the evolution of friction, we performed a set of displacement-controlled experiments, with a target speed $v = 1$ m s^{-1}, normal stresses $\sigma_n = 12$–18 MPa, and arrested at displacements d from 0.007 to 1.46 m (Supplementary Information Table 1). Experiments arrested at different displacements show similar acceleration paths (Fig. 1a–b), showing that the conditions during our experiments are reproducible (Fig. 1c–d). It also means that microstructures developed at different stages/displacements can be used to study the evolution of deformation mechanisms in the slip zone, and how these may affect frictional strength evolution.

During experiments run up to 1.44–1.46 m total slip, the imposed target speed of 1 m s^{-1} was attained after 0.12 m of slip (Fig. 1a–b). The measured strength consistently showed a four stage evolution (e.g. Exp. Du304–307 in Fig. 1c–d, Supplementary Information Table 1): Stage I) attainment of initial friction values, $\mu_i = 0.67$, upon instantaneous acceleration toward target speed; Stage II) increase in friction up to peak values $\mu_p = 0.80$–0.88, attained just before acceleration to target speed was complete; Stage III) sudden decrease in friction to low steady-state values, $\mu_{ss} = 0.17$–0.21, attained during sliding at constant velocity $v = 1$ m s^{-1}; and Stage IV) sudden increase of friction to $\mu_f = 0.44$–0.45, observed upon deceleration of the motor.

The temperature rise produced during the laboratory experiments has been estimated, to a first approximation, using (Rice, 2006)

$$\Delta T = \frac{\mu \sigma_n \sqrt{vd}}{\rho c_{p\sqrt{\pi\kappa}}} \qquad (1)$$

where μ represents the friction coefficient, σ_n is the normal stress, d is the displacement, ρ is the rock density, c_p is the specific heat