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Friction and scale-dependent deformation processes of large experimental carbonate faults

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ABSTRACT

We studied the frictional behaviour and deformation products of large (20 cm × 20 cm bare surfaces) experimental limestone faults. We sheared samples in a direct shear configuration, with an imposed normal force of 40–200 kN and shear velocity of 10 μm/s. The steady-state shearing of these surfaces yielded a coefficient of friction $0.7<\mu<1$ (average $\mu\sim0.9$), significantly higher than gouge friction of the same material, $\mu\sim0.6$. Frictional healing, studied via slide-hold-slide tests, is null ($\Delta\mu\leq0$ upon re-shear). Moreover, sliding of these surfaces is accompanied by dilatation and production of grooves, gouge striations and fault mirrors. These products are entirely analogous to slip surface phenomena found on natural limestone-bearing faults at both the macroscale and at the microscale. We infer that high friction, accompanied by dilatant deformation, and null frictional healing are the macroscopic effect of brittle damage on the sliding surface, constrained by the strength of the rock and by fast healing processes in the gouge. Simultaneously to brittle failure, plastic deformation occurs on the sliding surface and inside the intact rock via nanoparticle formation (mirrors) and twinning at the micron scale. Because of the similarity between experimental and natural structures, we suggest that sliding of carbonate-bearing faults in the uppermost crust could be characterized by high friction, fast healing and strongly dilatant deformation, which would help to explain shallow seismicity frequently documented in carbonatic terrains such as the Northern Apennines of Italy.

1. Introduction

In the uppermost crust, most of the displacement between rock masses is accommodated by brittle faults. The inner structure of fault zones can be complex as it is the result of complex geological histories and processes (e.g. Faulkner et al., 2010; Niemeijer et al., 2012 for recent reviews and references therein). However, a common characteristic of brittle fault zones is that they can be seen as a hierarchy of slip localization features, from large-scale fault systems to microscale fractures (Tchalenko, 1970; Ben Zion and Sammis, 2003). Individual fault zones are commonly characterized by damage zones and associated subsidiary faults, which host a "fault core" of more intensely deformed rocks (typically a few meters thick). In turn, the fault core hosts one or multiple throughgoing, "knife-edge" slip zones, commonly known as Principal Slip Zones (PSZ e.g. Sibson, 1986 and references therein) that accommodate most of the fault's displacement.

It is commonly assumed that the PSZ accommodate coseismic sliding (Sibson, 2003), which is corroborated by field and microstructural evidence, both in silicatic and carbonatic PSZ (e.g. Heesakkers et al., 2011; Rowe et al., 2012; Collettini et al., 2013). However, localized slip zones can also accommodate aseismic slip (e.g. Burford and Harsh, 1980; Scotti and Cornet, 1994). It is therefore crucial to study the deformation products and assess the mechanical properties of the PSZ, in order to understand fault motion and correlate field observations with slip dynamics.

In the field, PSZ are characterized by various slip surface phenomena (e.g. Stewart and Hancock, 1991). In particular, grooves and wear material are common products associated with fault slip (e.g. Engelder, 1974) and suggest directional and scale-dependent

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heterogeneity that may mirror equivalent heterogeneities in stress and slip behaviour along the PSZ (e.g. Dunham et al., 2011; Kirkpatrick and Brodsky, 2014).

The small thickness of typical PSZ, typically ranging from a few cm to a few microns (e.g. Sibson, 2003), enables the possibility to reproduce them during mm-size laboratory experiments (e.g. Brace and Byerlee, 1966; Barton, 1976; Sammis et al., 1987; Reches and Lockner, 2010 and many others). However, a number of outcrop-scale phenomena, and in particular those involving PSZ surrounded by cohesive fault materials or intact rocks (e.g. grooves and wear production), are not commonly captured in standard (mm-size) high-pressure rock friction experiments (but see e.g. McLaskey and Kilgore, 2013; Delle Piane et al., 2016). These features most likely depend on local stress heterogeneities imposed by the topography of the slip surfaces and/or competence contrasts between the hangingwall and footwall and remain poorly understood (e.g. Bistacchi et al., 2011; Brodsky et al., 2016).

To study the deformation of PSZ at different laboratory scales and to better understand the slip behaviour of carbonate-bearing faults, we performed biaxial experiments on limestone PSZ. We link the frictional properties with deformation mechanisms during slip and compare them with field observations. We performed direct shear experiments on large (20 cm × 20 cm) limestone bare surfaces simulating smooth carbonate PSZ surrounded by cemented fault rocks. With this experimental design, we are able to reproduce typical phenomena that affect PSZ such as grooves (toolmarks), fault mirrors and localized gouge formation. For comparison with previous experimental work and to test the reliability of our setup, we also performed experiments on standard synthetic fault gouge of the same limestone.

2. Characteristics of Principal Slip Zones in carbonatic faults

Carbonates frequently host intense seismicity (e.g. Ben-Menahem, 1991; Valoroso et al., 2014) and large carbonate-bearing fault zones are typically characterized by a complex interaction of brittle and ductile (mostly pressure-solution) processes (e.g. Koopman, 1983; Gratier et al., 2013; Tesei et al., 2013 and references therein). These processes may result in heterogeneous slip behaviour (i.e. seismic/aseismic) along these faults (e.g. Tesei et al., 2014). Still, fault displacement is generally localized along thin slip surfaces, albeit sometimes partitioned between several PSZ (e.g. Bussolotto et al., 2007; Collettini et al., 2014a).

Field observations in competent limestone formations show that PSZ of large faults (e.g. Fig. 1) are characterized by very fine-grained cataclastic rocks (e.g. Agosta and Aydin, 2006; Smith et al., 2011). These rocks are typically cohesive due to the lithification ("healing" s.l.) of the slip zone via compaction and cementation of the fault gouge after slip events (Fig. 1a–d). The slip zones are almost invariably decorated by slickenlines, slickenfibres and grooves (Fig. 1b and c), frequently filled with cemented cataclasites (Fig. 1d), or covered by unconsolidated gouge ("attrition gouge" *sensu* Sibson, 1986, Fig. 1e), depending on the fault's exhumation. Fig. 1 summarizes structures commonly found along PSZ in carbonates observable along the M. Maggio and Assergi fault system (Northern and Central Apennines, Italy), and in particular highlights deformation structures occurring at the outcrop scale that are rarely reproduced in the laboratory.

Moreover, unaltered carbonatic PSZ are frequently highly reflective ("fault mirrors", e.g. Fig. 1b) and are characterized, at the microscale, by smooth layers of nanoparticles and/or polygonal grains along the slip zone (Siman-Tov et al., 2013; Collettini et al., 2014a). Such nanoparticles still have unclear origin, and have been sometimes attributed to coseismic slip, in particular, when mirrors cover extensive fault portions and are associated with truncated clasts and shattered rocks. These features exhibit a striking similarity between natural and experimental faults (Boneh et al., 2013; Fondriest et al., 2015). Indeed, carbonate slip surfaces produced during high velocity friction experiments truncate gouge clasts and are characterized by nanoparticle formation and/or polygonal grains, showing evidence of crystal growth indicative of a thermal anomaly (Smith et al., 2012). However, nanoparticles can also form at sub-seismic slip rates in localized shear bands (e.g. Verberne et al., 2013, 2014; Tesei et al., 2014) and may not be indicative alone of co-seismic slip, even though they may be a prerequisite for efficient dynamic weakening (e.g. De Paola et al., 2015).

3. Methods

To study the friction of limestone surfaces at different laboratory scales, we designed sliding friction experiments in a "single direct" configuration (Fig. 2). Samples were cut into limestone blocks using a diamond saw. We cut slabs with dimensions of 20 cm × 20 cm x 3.5 cm and 25 cm × 20 cm x 3.5 cm to simulate slip zones embedded in a cemented (healed) fault rock (e.g. Fig. 1a–d). We simulated strongly cemented cataclastic fault rocks using a bioclastic limestone (Maljat$^{®}$ biomicrite/biosparite). The Maljat limestone is constituted by bioclasts, with heterogeneous size and shape and surrounded by sparite or a fine-grained matrix, similar to a cataclasite (Fig. S1). All of the experimental limestone blocks were cut from a single slab and show a mostly isotropic texture without stylolites. Block faces were ground flat with a precision grinder, better than 0.1 mm, and then ground along the edges to perfectly fit the sample holders (Fig. 2b). The sliding surfaces were then roughened with sandpaper to attain a similar starting roughness before the tests and to simulate the smoothness of natural PSZ. "Rough" surfaces, polished with #60 or #40 grit sandpaper (265 and 425 μm average abrasive grain size, respectively), and "smooth" surfaces, polished up to #3000 grit sandpaper (6 μm grain size), were used to study the effect of different initial roughness on the frictional properties of the experimental fault.

Experiments were performed using the BRAVA biaxial apparatus (INGV Rome, Collettini et al., 2014b) under conditions of room humidity (35–50% relative humidity) and ambient temperature (T 18–26 °C). In the single-direct configuration, two sliding blocks are sheared against each other (Fig. 2b). Alternatively a layer of rock powder can be built between the sample holders to study fault gouge-like materials. The sliding blocks, with area 20 cm × 20 cm and 20 cm × 25 cm respectively, are contained within two steel sample holders that act as a shear box (Fig. 2b). The side block is in contact with the horizontal ram, which applies the normal force to the samples, whereas the central block is pushed by the vertical piston to provide the shear force along the experimental surface. The central block in contact with a mirror-finished steel surface is lubricated with a MoS_2-based lubricant that ensures a very low friction contact ($\mu \ll 0.01$). The walls of the chamber act as the load frame. Forces are measured with stainless steel load cells (±0.03 kN precision) and displacements are measured with Linear Variable Displacement Transducers (LVDT, ±0.1 μm precision) attached to each piston (Fig. 2a). During data analysis, displacement measurements from LVDTs have been corrected for the elastic stretch of the steel chamber that acts as the load frame (1283 kN/mm and 928.5 kN/mm in the horizontal and vertical direction, respectively).

During each test on bare surfaces, normal force was kept constant during sliding, in the range 40–200 kN. These values are equivalent to ~1–5 MPa nominal normal stress on the surfaces, but are considered only as a reference value for the experiment given the uneven distribution of stress on the block surfaces. This uneven stress distribution is likely due to roughness and the progressive