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Lithological controls on the deformation mechanisms operating within carbonate-hosted faults during the seismic cycle☆

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ABSTRACT

A significant proportion of moderate-large earthquakes, plus aftershocks, nucleate within and propagate through upper-crustal carbonate-dominated sequences, where the effects of lithological variations on fault behaviour are poorly understood. The Gubbio fault is an active (1984, Ms = 5.2) normal fault in Italy, hosted in Mesozoic–Cenozoic limestones and interbedded marls. Fault core domains derived from limestone at the studied outcrop are characterised by fractures/hydrofractures and breccias and host a number of localised (<1.5 mm wide) principal slip zones (PSZs). The majority of displacement of up to 230 m is concentrated in these PSZs, which comprise cataclasites, gouges, and calcite veins. Degassing bubbles, 'quenched' calcite, and the transformation of smectite to illite, are also observed within PSZs, implying frictional heating and seismic slip. In contrast, marl-rich domains exhibit distributed shear planes bounding a continuous and pervasive foliation, defined by phyllosilicate-rich pressure-solution seams. Microstructures in the seams include folds/kinks of phyllosilicates and pressure shadows around clasts, consistent with aseismic fault creep. A model is proposed for the behaviour of lithologically complex carbonate-hosted faults during the seismic cycle, whereby limestone-dominated fault core domains behave in a predominantly seismic manner, whereas phyllosilicate-rich domains behave in a predominantly aseismic manner.

1. Introduction

The large-scale architecture of upper-crustal faults at <5 km depth comprises either a single high-strain fault core surrounded by a damage zone (e.g. Chester et al., 1993), or multiple high-strain cores, which bound lenses of damaged material (e.g. Faulkner et al., 2003). The differentiation between fault core and damage zone is generally based on the presence and spatial distribution of deformation products (Chester and Logan, 1986; Chester et al., 1993; Shipton et al., 2006). The fault core, which ranges from a few metres up to a few tens of metres wide, consists of cataclastically deformed fault rocks and typically contains one or more principal slip surfaces (PSSs) (Shipton et al., 2006; Faulkner et al., 2010). Damage zones, which are up to a few hundred metres in width, consist of fractured protolith rocks and smaller displacement subsidiary slip surfaces (Faulkner et al., 2010). The fault core is where most of the displacement is accommodated, and the deformation processes occurring here are the focus of the present paper.

Fault core architectures vary widely between faults and appear to be controlled, in part, by the composition of the protolith. Upper-crustal faults derived from carbonates (e.g. Agosta and Aydin, 2006; Micarelli et al., 2006; De Paola et al., 2008; Bastesen and Braathen, 2010; Molli et al., 2010; Smith et al., 2011a; Fondriest et al., 2012) and crystalline rocks (e.g. Chester and Chester, 1998; Wibberley and Shimamoto, 2003; Walker et al., 2013) tend to exhibit narrow fault cores that are less than a few metres in width, comprising cohesive and incohesive random-fabric fault rocks such as breccias, cataclasites and gouges (Sibson, 1977). The majority of the displacement within these fault cores is localised along discrete PSSs and within their associated principal slip zones (PSZs).

Numerous field studies of major seismogenic faults suggest that slip during individual earthquake events is localised along these PSZs, which are typically no more than a few cm thick (see Sibson, 2003, for a review). Notable examples include: the PSZ associated with the 1999 Mw 7.6 Chi Chi thrust earthquake in Taiwan, which has been estimated to be just 1 mm thick (Kuo et al., 2013); the Nojima fault, responsible for the 1995 M 7.2 Kobe earthquake in Japan, which contains several gouge and pseudotachylyte layers,

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each less than a few mm thick (Otsuki et al., 2003); and the PSZ responsible for the 2008 Ms 8.0 Wenchuan earthquake in China, which comprises a ~1 cm thick layer of fault gouge (Li et al., 2013). At the microscale, PSZs are often observed to contain sub-zones, which range from a few hundred microns to a few millimetres in width, composed of variably developed cataclasites and gouges and frequently displaying Riedel shear geometries (e.g. Power and Tullis, 1989; Otsuki et al., 2003; De Paola et al., 2008; Smith et al., 2011a; Fondriest et al., 2012).

In contrast, upper-crustal fault zones rich in phyllosilicates typically display much wider fault cores, often adhering to the multiple fault cores model. For example, the exhumed Carboneras fault in SE Spain has a fault core up to 1 km wide (Faulkner et al., 2003), which comprises numerous high-strain gouge zones of a few metres in thickness (Faulkner et al., 2003). Similarly, the SAFOD (San Andreas Fault Observatory at Depth) borehole core and field studies of the Median Tectonic Line in Japan have revealed several phyllosilicate-rich fault core strands, each >1 m wide (Zoback et al., 2010; Holdsworth et al., 2011; Jefferies et al., 2006). Rather than displacement being localised within PSZs, it is uniformly distributed within each gouge band; and rather than random-fabric fault rocks being the dominant deformation products, phyllosilicate-rich fault cores typically display a continuous, highly foliated fabric, though Riedel shear geometries are still conspicuous features (e.g. Rutter et al., 1986, 2012; Faulkner et al., 2003).

Consequently, in lithologically heterogeneous, upper-crustal fault zones, where crystalline/carbonate and phyllosilicate-rich protoliths are interlayered, we might expect to see a complex fault zone architecture with separate domains of localised and distributed deformation. This geometry has been documented along ancient, exhumed examples of presently inactive major strike-slip faults (e.g. the Carboneras fault zone, Faulkner et al., 2003), low-angle normal faults (e.g. the Zuccale fault in Central Italy, Collettini and Holdsworth, 2004; Smith et al., 2011b) and in accretionary complexes (e.g. the Chrystalls Beach Complex mélange, New Zealand, Fagereng and Sibson, 2010). Attention now is turning to active fault zones, in an attempt to understand how lithological heterogeneities within multi-layered sequences cut by a fault may affect not only the fault zone architecture, but also the seismic behaviour of the fault (e.g. Nemser and Cowan, 2009; Chiaraluce, 2012; Gratier et al., 2013; Tesei et al., 2013).

Quartzo-feldspathic and carbonate rocks typically have sliding friction coefficients in the Byerlee range of 0.6–0.85 (Byerlee, 1978) and experimentally exhibit slip-weakening and velocity-weakening behaviour (Logan et al., 1992; Beeler et al., 1996; Marone et al., 1990; Gu and Wong, 1994; Verberne et al., 2010; Collettini et al., 2011), which is necessary for earthquake nucleation and unstable stick-slip behaviour (Dieterich and Kilgore, 1994; Marone, 1998; Scholz, 1998). These lithologies also display dynamic-weakening behaviour during high-velocity rotary shear experiments (see Di Toro et al., 2011, for a review), with the coefficient of friction reducing to sub-Byerlee values (<0.2) at seismic slip velocities, facilitating earthquake propagation.

In contrast, many phyllosilicates (e.g. talc, smectites) are weak, particularly when wet, (sliding friction ≪0.3, e.g. Behnsen and Faulkner, 2012) and most types exhibit velocity-strengthening behaviour (e.g. Saffer et al., 2001; Saffer and Marone, 2003; Moore and Lockner, 2004, 2011; Ikari et al., 2007, 2009, 2011; Morrow et al., 2007; Tembe et al., 2010; Behnsen and Faulkner, 2012; Sone et al., 2012; Tesei et al., 2012). Velocity-strengthening behaviour does not favour earthquake nucleation and rock units displaying this behaviour are expected to act as barriers to earthquake propagation due to a positive stress drop (Scholz, 1998). Thus, upper-crustal fault rocks rich in weak phyllosilicate minerals are thought to deform predominantly aseismically by fault creep. For example, the creeping behaviour of faults such as the San Andreas is attributed to the presence of smectitic phyllosilicates in fault gouges (e.g. Carpenter et al., 2011; Lockner et al., 2011; Holdsworth et al., 2011).

Over the course of the seismic cycle, a fault may experience a broad spectrum of slip rates. These range from mm/yr, during the interseismic period, to mm/day-week during the pre-seismic (earthquake nucleation) and post-seismic (afterslip) periods and, then, to slip rates of m/s during earthquake propagation. It seems reasonable to hypothesise that lithological heterogeneities within the fault core will strongly influence which parts of a fault zone deform seismically or aseismically during the different seismic intervals. To further investigate this proposal, we document here the deformational and microstructural characteristics of the Gubbio normal fault (1984, Ms = 5.2) in the northern Apennines of Italy (Fig. 1a). This upper-crustal, seismically active fault deforms a succession of alternating limestone and cm-scale marl beds. Outcrop to microscale deformation features within the Gubbio fault zone have previously been studied by Bussolotto et al. (2007), who characterised the spatial and temporal relationships of structures in the fault zone, together with a determination of the P/T conditions and fluid behaviour during deformation. Here, we use a combination of microstructural (optical microscopy and field emission scanning electron microscopy, SEM) and mineralogical analyses (energy-dispersive X-ray spectroscopy, EDX, and X-ray diffraction, XRD) to study the dominant deformation mechanisms active within the fault core, and to assess the likely influence of lithology on deformation style. We use these findings to propose a conceptual model for the long- (inter- and post-seismic period) and short-term (coseismic) frictional behaviour of the fault zone, which can then be tested by future experimental work.

2. Geological setting

The northern Apennines of Italy have undergone NE–SW shortening since the middle Miocene, resulting in the development of a NE-verging fold and thrust belt (Barchi et al., 1998b). In the Gubbio area, this deformation is represented by the NW–SE striking Gubbio anticline (De Paola et al., 2006 and references therein). An upper Pliocene–Quaternary late-orogenic extensional regime is superimposed upon the folds and thrusts, forming a series of extensional basins bounded by NNW–SSE trending normal faults (Barchi et al., 1998a; Boncio and Lavecchia, 2000) (Fig. 1a). This extensional regime currently dominates the tectonics of the northern Apennines, although it has a relatively slow separation rate of 2–3 mm/yr (D'Agostino et al., 2009).

The Gubbio fault is an active segment of a 150 km long fault system known as the Umbria Fault System (Collettini et al., 2003). The surface trace is 22 km long, striking NW–SE (~N130°) (Figs. 1a and 2a). Seismic reflection data suggest that it has a listric profile at depth, with average dips of ~60–70° to the SW at the surface, decreasing to 10–15° at ~6 km, where it reactivates a pre-existing thrust fault (Mirabella et al., 2004) (Fig. 1a). At the surface, the fault juxtaposes Jurassic-Oligocene carbonates, belonging to the Umbria–Marche succession, in the footwall against Quaternary fluvio-lacustrine deposits, of the Gubbio Basin, in the hangingwall (Collettini et al., 2003; Bussolotto et al., 2007) (Fig. 1b).

A maximum displacement of 3.2 km at the centre of the Gubbio Basin was estimated by Collettini et al. (2003), which accumulated during multiple tectonic phases. Historical and instrumental records of moderate-large earthquakes occurring on the Gubbio fault are limited, since no permanent station coverage exists (Collettini et al., 2003; Pucci et al., 2003). However in 1984, the Gubbio area experienced an Ms 5.2 (Haessler et al., 1988) earthquake, located ~10 km south of the town of Gubbio at 7 km depth (ISC, 2001), and