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Fracturing, fluid-rock interaction and mineralisation during the seismic cycle along the Alpine Fault

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ABSTRACT

The Alpine Fault has a <50 m wide geochemically distinct hanging-wall alteration zone. Using a combination of petrological and cathodoluminescence (CL) microscopy, Energy Dispersive Spectroscopy and X-ray diffraction, we document the habitat and mineralising phases of macro- and micro-fractures within the alteration zone using samples derived from outcrop and the Deep Fault Drilling Project. Veins predominantly contain calcite, chlorite, K-feldspar or muscovite. Gouge-filled fractures are also observed and reflect filling from mechanical wear and chlorite mineralisation. CL imaging suggests that each calcite vein was opened and sealed in one episode, possibly corresponding to a single seismic cycle. The thermal stability of mineralising phases and their mutually cross-cutting relationships indicates a cyclic history of fracture opening and mineralisation that extends throughout the seismogenic zone. Cataclasites contain intragranular veins that are hosted within quartzofeldspathic clasts, as well as veins that cross-cut clasts and the surrounding matrix. Intragranular calcite veins formed prior to or during cataclasis. Cross-cutting veins are interpreted to have formed by fracturing of relatively indurated cataclasites after near-surface slip localisation within the Alpine Fault's principal slip zone gouges (PSZs). These observations clearly demonstrate that shear strain is most localised in the shallowest part of the seismogenic zone.

1. Introduction

Fracturing and brecciation during earthquake rupture leads to an increase of permeability in the surrounding rock mass (e.g. Muir-Wood and King, 1993; Sibson, 1994; Wibberley and Shimamoto, 2003; Woodcock et al., 2007; Xue et al., 2013; Wästeby et al., 2014; Gomila et al., 2016). This permeability is transient and is reduced by mineralisation and the closing of fluid pathways during the interseismic period. Fluid-rock interactions that occur over the seismic cycle are important for understanding fault mechanics (Evans and Chester, 1995; Clemenzi et al., 2015), the priming of future ruptures along faults (Sibson, 1973; Chester et al., 1993; Tenthorey et al., 2003; Woodcock et al., 2007; Menzies et al., 2016) and the formation of some types of ore deposits (Sibson, 1990; Micklethwaite and Cox, 2004).

Fluid-rock interaction often results in structural and geochemical changes that culminate in the development of distinct fault alteration zones (Evans and Chester, 1995; Schulz and Evans, 2000; Sutherland et al., 2012; Smith et al., 2013; Arancibia et al., 2014; Kristensen et al., 2016). Microstructural and geochemical analysis of such alteration zones can be used to constrain the composition of the mineralising phases and the source fluids, the permeability architecture of fault zones, and the relative sequence of fluid flow events. Faults are complex three-dimensional structures, and fluid flow and related alteration will inevitably vary with depth and along-strike, depending on factors such as host rock lithology and permeability (Laubach et al., 2014), hydrological regimes (Evans and Chester, 1995), and the distribution and scale of fault geometrical irregularities (Sibson, 1994; Micklethwaite and Cox, 2004).

Cross-cutting relationships between veins and fault rocks show that faults experience a multitude of fluid-flow episodes during their lifetimes (Sibson, 1990; Potts and Reddy, 1999; Gudmundsson et al., 2001; Petrie et al., 2014). However, the internal texture of

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individual veins demonstrates that their growth history may reflect single or multiple episodes of opening and sealing (Bons, 2001; Tarasewicz et al., 2005; Borg et al., 2014). The former can suggest complete sealing within the recurrence interval of earthquakes (Sibson, 1986; Woodcock et al., 2007; Melosh et al., 2014), while the latter indicates growth via crack-seal mechanisms possibly over multiple earthquake cycles (Ramsay, 1980; Chester and Logan, 1986; Gudmundsson et al., 2001; Renard et al., 2005).

This study investigates the spatial and temporal evolution of the Alpine Fault alteration zone by assessing the composition, texture, and cross-cutting relationships among veins, fractures and fault-rock fabrics sampled in outcrop and in drill-core recovered during the first phase of the Deep Fault Drilling Project (DFDP-1). The Alpine Fault is an active transpressive plate boundary fault (Fig. 1a) that rapidly exhumes (<10 mm/yr) its hanging-wall from depths of ~35 km (Little et al., 2005; Norris and Cooper, 2007; Sutherland et al., 2007). Fracture networks, veins and fault rocks in the hanging-wall therefore provide an important opportunity to investigate processes of fluid-rock interaction, mineralisation and strain localisation within a plate-boundary scale fault zone throughout the full thickness of the seismogenic zone.

2. Fault rocks and fluid-rock interaction around the Alpine Fault

DFDP-1 yielded ~130 m of 85 mm diameter drill-core from two <150 m deep vertical boreholes that intersected the Alpine Fault (Fig. 1a–b, Sutherland et al., 2011, 2012), adjacent to a well-exposed surface outcrop at Gaunt Creek (Cooper and Norris, 1994). Below, we summarise the structure and fault rock sequence encountered within the Alpine Fault's hanging-wall with reference to the lithological classification scheme for DFDP-1 drill-core (Toy et al., 2015). We then relate this to the width and distribution of the Alpine Fault alteration zone, as well as to previous work on crustal-scale fluid sources and fluid-rock interactions.

2.1. Alpine Fault rocks and structure

Units 1 and 2 of Toy et al. (2015) are ultramylonites. With respect to the active trace of the Alpine Fault, these units represent the most distal interval of core recovered during DFDP-1 (Fig. 1b). The ultramylonites are defined by a foliation of alternating quartzofeldspathic and mica/amphibole segregations (Unit 1) or by dark hairline seams of opaque minerals (Unit 2). They are derived from the Alpine Schist and have a mineralogy dominated by quartz, plagioclase, biotite and muscovite (Warr and Cox, 2001; Toy, 2008; Toy et al., 2015). Hanging-wall cataclasites (Units 3 and 4 of Toy et al., 2015) that are sourced from the ultramylonites comprise quartzofeldspathic clasts surrounded by a fine-grained matrix that is dark brown in plane-polarised light (PPL). A smectite-rich principal slip zone (PSZ) gouge (Unit 5) separates the hanging-wall cataclasites from the footwall cataclasites (Unit 6) or Quaternary gravels (Fig. 1b).

Foliation in Unit 4 cataclasites is defined by anastomosing seams of opaque minerals, which are inferred to form by pressure-solution processes during aseismic creep (Gratier et al., 2011; Toy et al., 2015; Boulton et al., 2017a). All lithologies sampled in DFDP-1 core contain pseudotachylytes (Sibson et al., 1981; Warr et al., 2003, 2007; Toy et al., 2011, 2015). The pseudotachylytes are likely to have formed at seismic slip rates (Sibson, 1975; Cowan, 1999; Kirkpatrick and Rowe, 2013) and so indicate fluctuating strain rates around the Alpine Fault (Toy et al., 2015). Using the model of fault zone structure developed by Chester and Logan (1986), Chester et al. (1993) and Caine et al. (1996), Units 3–6 represent the "core" of the Alpine Fault (Toy et al., 2015). A ~70–160 m wide zone with a relatively high density of gouge-filled fractures >1 mm thick is interpreted to constitute the hanging-wall fracture damage zone (Norris and Cooper, 2007; Williams et al., 2016; Williams, 2017). Such fractures are also pervasive in the fault core (Fig. 1b).

2.2. The Alpine Fault alteration zone

The alteration zone is the clearest expression of fluid-rock interactions within the Alpine Fault. It is defined by enhanced levels of phyllosilicate and calcite mineralisation compared to the surrounding rocks (Sutherland et al., 2012; Boulton et al., 2017a). In field exposures, the alteration zone is expressed as an interval of minty green rock that is 2–50 m thick in the fault hanging-wall (Norris and Cooper, 1997, 2007; Toy et al., 2012). It was also detected by wireline logging of the DFDP-1 boreholes within c. 50 m of the PSZs by an increase in spontaneous potential and neutron porosity and a decrease in resistivity (Sutherland et al., 2012; Townend et al., 2013). Geochemical analyses of DFDP-1 drill-core indicate that the alteration is most pervasive within c. 20 m of the PSZs (Boulton et al., 2017a). Therefore, in relation to the DFDP-1 lithologies discussed above, the alteration zone is most prevalent within the fault core cataclasites (Units 3 and 4), but also extends into the inner portion of the ultramylonite sequence (Units 1 and 2, Fig. 1b). Extensive mineralisation within the alteration zone has contributed to its relatively low permeability (10^{-16}–10^{-21} m^2) compared to the surrounding less altered ultramylonite sequence (10^{-14} m^2) (Boulton et al., 2012; Sutherland et al., 2012; Carpenter et al., 2014; Allen et al., 2017).

Hydrothermal mineralisation and veining in the Alpine Fault has occurred along a relatively well-constrained retrograde reaction path as fault rocks in the hanging-wall were rapidly exhumed from depths of ~35 km (Warr and Cox, 2001; Little et al., 2005). Geochemical and isotopic analyses of the main fluid-rock interactions suggest that fluids circulating within the hanging-wall are dominantly meteoric in origin (Upton et al., 1995; Templeton et al., 1998; Menzies et al., 2014, 2016). Fluids are capable of penetrating to depths below the brittle-ductile transition zone due to a combination of abundant rainfall, steep hanging-wall topography, an elevated geothermal gradient, and deformation-related dilatancy (Upton et al., 1995; Menzies et al., 2014). The low permeability PSZ gouges act as a barrier to cross-fault fluid flow (Boulton et al., 2012; Sutherland et al., 2012). Consequently, when meteoric fluids reach the PSZ they do not cross into the footwall but are instead focused back up the fault (Fig. 1c), emanating in warm springs distributed along the length of the Southern Alps (Barnes et al., 1978; Allis and Shi, 1995; Menzies et al., 2016). This hydrogeologic system, combined with the rapid advection of hanging-wall rocks (Koons, 1987), generates an elevated geothermal gradient within the seismogenic zone of the Alpine Fault of 40–60 °C/km (Toy et al., 2010; Sutherland et al., 2012), which can locally exceed 125 °C/km (Sutherland et al., 2017).

3. Methodology

3.1. Optical, cathodoluminescence and electron microscopy

Twenty-four polished thin sections cut from DFDP-1 core were examined. Sections were cut parallel to the core-axis, but since DFDP-1 core was not oriented, the geographic orientation of the sections is not known. Standard petrological techniques were used to characterise vein composition, microfracture damage and fault rock fabric. Cathodoluminescence images (CL) were collected on calcite veins with a 8200 Mark II cold CL stage operating at 20 kv with a gun current ranging between 500 and 600 μa.