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Relationships between kinematic indicators and strain during syn-deformational exhumation of an oblique slip, transpressive, plate boundary shear zone: The Alpine Fault, New Zealand

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In order to assess how different elements of plate boundary-scale shear zone tectonite fabrics reflect the boundary kinematics and strain history, we have examined a range of such structures within the active Alpine Fault mylonite zone, New Zealand. In this oblique slip zone we find that quartz CPO fabric symmetry and individual mica grain lineations reflect incremental stretches but develop stable orientations parallel to the finite stretching direction (S_1). This S_1 trends oblique to the plate motion vector because the shear zone experiences some extrusion toward the free surface. Conversely, asymmetric structures (such as shear bands and mica fish) reflect simple shear-dominated deformation late in the shear zone history, parallel to the imposed relative plate motion vector. Finally, linear fabrics are a poor record of the mylonitic deformation in this zone, because (1) they are dominantly inherited and have been only partially re-oriented during mylonitisation, and (2) macroscopically they become less visible at higher strains due to fabric homogenisation. Generally, these results indicate that, particularly in heterogeneous, polyphase shear zones, a full understanding of the movement history can only be obtained by considering kinematic information from as many different sources as possible.

1. Introduction

1.1. Tectonite fabrics in shear zones

Various tectonite fabric components, such as foliations, lineations, shear sense indicators, and crystallographic fabrics, develop in response to strain in crustal shear zones (Ramsay, 1980). These fabrics impart physical anisotropy that can influence permeability and therefore fluid transport directions (e.g. Fusseis et al., 2009) and elastic wave travel paths (e.g. Scherwath et al., 2003; Stern et al., 2007), and can result in geometric weakening (e.g. Schmid et al., 1987) or hardening (e.g. Toy et al., 2008) that influences localisation. In ideal simple shear zones, simple relationships between fabrics and shear zone boundary (s.z.b.) kinematics allow fabrics to be used to understand the geometry of offset features. However, many large crustal shear zones did or do not accommodate ideal simple shear (e.g. Czeck and Hudleston, 2003; Díaz Azpiroz and Fernández, 2005). Furthermore, in many of these other examples there is little control on the true relationship of tectonite fabrics to s.z.b. kinematics, since they are inactive, and subsequent deformation has commonly affected fabric orientations. Consequently, predicting the fabrics that are present at depth in active shear zones and deciphering the movement histories of exhumed ancient shear zones based on their internal fabrics is challenging. In this contribution we address the relationship between fabrics and s.z.b. kinematics in one of the few crustal shear zones worldwide that was formed in a still active tectonic regime.

1.2. The Alpine Fault and its mylonite zone; exhumed equivalent of an actively deforming plate boundary shear zone

The Alpine Fault strikes NE–SW through the western South Island of New Zealand, forming the western boundary of the locally >3500 m high Southern Alps mountain range (Fig. 1(a)). The mountains are uplifted in the hangingwall of the SE-dipping fault due to dextral reverse fault slip at rates that account for ~70% of the total Pacific-Australian plate motion across this boundary (Bull and Cooper, 1986; Tippett and Kamp, 1993; Norris and Cooper, 2001; Batt et al., 2004; Little et al., 2005; Sutherland et al., 2006). Consequently, the structure exhumes the hangingwall portion of a mylonitic shear zone, formed by ductile creep down dip of the brittle fault, at depths up to 35 km based on geophysical (Van Avendonk et al., 2004) and thermobarometric datasets (Vry et al., 2004, 2007; Toy et al., 2010). Maximum hangingwall rock uplift rates of the order of 9–10 mm yr^{-1} in the focus area for this study (Little et al., 2005) mean rocks exposed at

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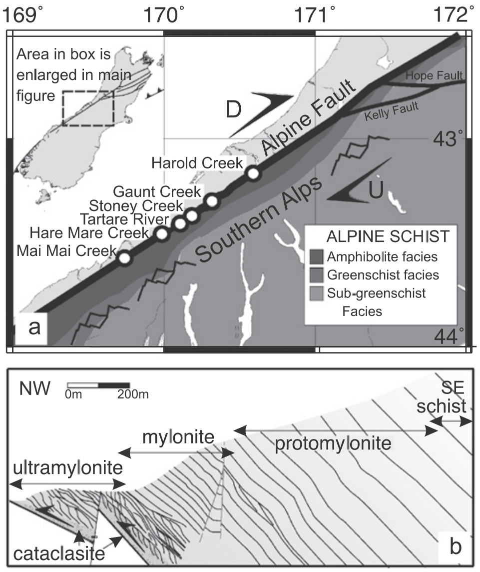

Fig. 1. (a) Tectonic map of the South Island of New Zealand. Metamorphic grades in the hangingwall Alpine Schist are indicated. (b) Cross section through a typical Alpine Fault mylonite sequence; in this case the Gaunt Creek section.

the surface that originated at depths of 35 km have been exhumed within the last 4 million years. Plate boundary kinematics have changed little over this period (DeMets et al., 1994; Beavan et al., 1999; Cande and Stock, 2004), so the exhumed mylonites were deformed under similar conditions as those currently undergoing deformation in the fault zone at depth. Consequently, the exposed fault rocks are ideal candidates for examining the development of shear zone fabrics under known boundary conditions.

In this contribution we address how all the various components of a fabric in exhumed mylonite zones may reflect the kinematics of crustal scale fault zones, using the Alpine Fault Zone (AFZ) as a test case. In particular we determine the orientation of the syn-mylonitic strain ellipsoid, including how it may have changed over the course of deformation, and attempt to differentiate kinematic models by examining and comparing the orientation distributions of object lineations and other sorts of kinematic indicators.

1.3. *Outcrop appearance of the fault rocks*

Most AFZ rocks are derived from amphibolite facies Alpine Schist, from a particularly pelite, metabasite, and chert-rich part of the Rakaia Terrane (Cox and Sutherland, 2007). The Schist has a composite Mesozoic ($D_{1\text{-}3}$) and Cenozoic ($D_{4\text{-}m}$) fabric (Little et al., 2002a), characterised by a spaced foliation of alternating layers of quartz + feldspar or mica-rich material, that is variably planar or crenulated according to its position on the limb or hinge region of large-scale Mesozoic folds, and its orientation with respect to the Cenozoic strain ellipsoid. A distinctive quartz rod lineation resulting from D_3 crenulation of D_2 fabrics has been preserved through $D_{4\text{-}m}$ (Little et al., 2002b).

The brittle part of the Alpine Fault outcrops as a thin clay gouge zone (1–50 cm thick) overlain by a 10–50 m thick cataclasite package within which the density of brittle structures decreases with increasing distance into the hangingwall. Above this there is a mylonite zone (Fig. 1(b)). Norris and Cooper (2003) calculated that the mylonites have accommodated simple shear strains, γ, ranging from 12–300. The lowest strains were measured in protomylonites that outcrop up to 1 km to the SE of the brittle trace of the fault; these strains gradually increase into mylonites then ultramylonites that immediately overlie the cataclasites.

Protomylonite foliation is characterised by very low angle anastomosing foliations (Fig. 2(a)). Individual anastomosing planar fabric components are probably shear zones. Alpine Schist layering and other Mesozoic structures such as folds and crenulations are commonly preserved in microlithons between the anastomosing shear zones. Anastomosing foliations, preserved schist fabrics and microlithons are all affected by cm to mm-spaced, top-to-the W shear bands (Fig. 2(a)) (also known elsewhere as an S-C fabric; Berthe et al., 1979; Type I S-C′ fabric; Lister and Snoke, 1984; or extensional crenulation cleavage, *ecc*; Platt and Vissers, 1980).

Planar-foliated mylonites and ultramylonites outcrop respectively within 300 m and 100 m cross-strike distance of the surface trace of the brittle fault. Within these rocks, progressive tectonic grain size reduction resulted in destruction of remnant Alpine Schist structures, so that, macroscopically, layering and anastomosing shear bands are still just visible in mylonites (Fig. 2(b)), and are completely transposed to a laminar, continuous foliation (S_m) in the ultramylonites (Fig. 2(c)). Mylonite zone rocks have an average foliation of 055/45SE, interpreted to reflect the shear zone orientation at depth (Sibson et al., 1979; Norris and Cooper, 2007). Note that the latter authors also document a more shallowly-dipping average foliation, with a standard deviation of 30–36° (depending on

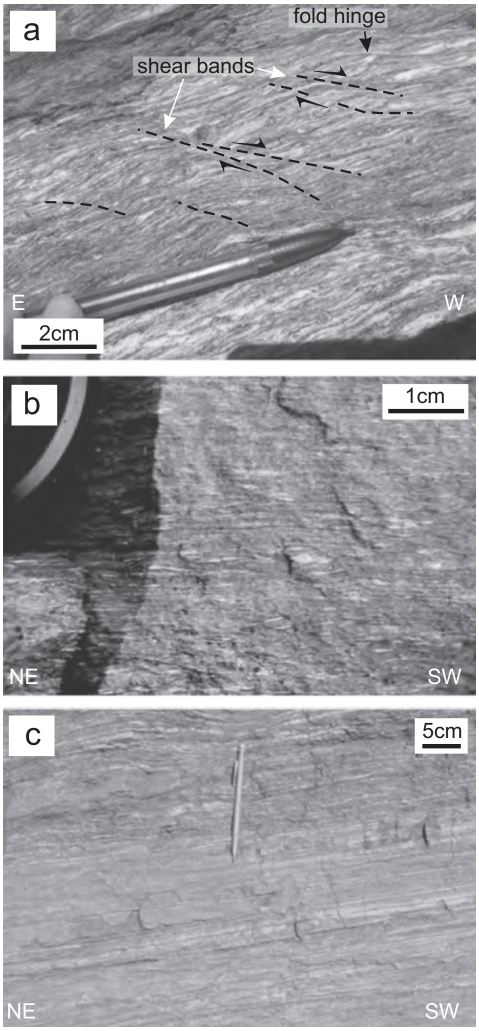

Fig. 2. Typical outcrop photographs of (a) protomylonite, (b) mylonite, and (c) ultramylonite. Shear bands and a fold hinge remnant from $D_{2\text{-}3}$ in the Alpine Schist are labelled in (a).