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Pseudotachylyte-generating faults in Central Otago, New Zealand

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Abstract

In Central Otago, New Zealand, a series of subparallel, NNE–SSW trending, gently dipping (10–30° E) brittle faults are hosted in quartzofeldspathic schist. These faults contain numerous (n>100) pseudotachylyte veins. Pseudotachylyte fault veins are traceable along strike for distances of up to 200 m, and are between <1 mm and 5 cm thick. Fault separations inferred from offset quartz veins, dilational jogs and a piercing point analysis suggest that pseudotachylyte was generated by slip increments of <1 cm to 20 cm, comparable to those believed to occur during small to moderate-sized earthquakes [Sibson, R.H., 1989. Earthquake faulting as a structural process. Journal of Structural Geology, 11 (1–2) 1–14.]. Dilational jogs, fault drag and quartz vein separations imply a top-to-the-north (normal) sense of shear. Evidence for melting is provided by chilled margins, microlites and the formation of mineral phases not present in the host rock. Melting temperatures of 900–1100 °C are inferred from petrological observations. Heat-work calculations, utilising displacements on pseudotachylyte-bearing faults, and inferred melting temperatures suggest that the faulting occurred at depths of 6–12 km, with average frictional shear resistance exceeding 100 MPa on pseudotachylyte-generating faults. These inferred depths and relatively high levels of frictional shear resistance on pseudotachylyte-generating faults are similar to those inferred by some previous studies of pseudotachylyte (e.g. [Sibson, R.H., 1975. Generation of pseudotachylyte by ancient seismic faulting. The Geophysical Journal of the Royal Astronomical Society, 43 (3) 775–794; Killick, A.M. and Roering, C., 1998. An estimate of the physical conditions of pseudotachylite formation in the West Rand Goldfield, Witwatersrand Basin, South Africa. Tectonophysics, 284 (3–4) 247–259.]).

Keywords: Pseudotachylyte; Earthquakes; Faulting; Stress drop; Frictional shear resistance

1. Introduction

Friction melts, inferred to have formed during episodic seismic slip, have been described from various fault zones. They are commonly associated with cataclasites (Sibson, 1975; Magloughlin, 1989, 1992; Swanson, 1989; O'Hara, 1992; Fabbri et al., 2000), but have also been reported interlaced with mylonites (Sibson, 1980; Passchier, 1982; Wenk and

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Weiss, 1982; Hobbs et al., 1986; Koch and Masch, 1992). Despite theoretical calculations, which suggest that friction melting should be a common occurrence in seismically active crustal fault zones (Jeffreys, 1942; McKenzie and Brune, 1972), pseudotachylytes are supposedly a rare phenomenon, and are a minor fault zone product compared to cataclasite and mylonite (Magloughlin and Spray, 1992; Sibson, 2003). This raises the important question of whether pseudotachylytes are a genuinely rare phenomenon (i.e. their formation requires special crustal conditions e.g. 'dry' crust), or whether pseudotachylytes are simply infrequently recognised (due to subsequent deformation and hydrothermal alteration; see Sibson, 2003 for discussion).

Previous studies of pseudotachylyte have concentrated on the petrography (Maddock, 1983; Camacho et al., 1995; Petrik et al., 2003), geochemistry (Maddock, 1992; O'Hara, 1992; O'Hara and Sharp, 2001), and geometry of pseudotachylyte-bearing fault zones (Grocott, 1981; Swanson, 1988, 1989, 1992). Several studies have attempted to determine the generation depth of pseudotachylyte (Sibson, 1975, 1980; Seward and Sibson, 1985; Maddock et al., 1987; Austrheim and Boundy, 1994; Killick and Roering, 1998; Wenk et al., 2000; Boullier et al., 2001), with estimates ranging from less than 1.5 km (Maddock et al., 1987) to depths of greater than 60 km (Austrheim and Boundy, 1994). Furthermore, few studies have attempted to determine the frictional shear resistance on pseudotachylyte-generating faults (Killick and Roering, 1998), or the static shear stress drops accompanying pseudotachylyte-producing earthquakes. In this paper, the structural features (size, distribution, orientation, shear sense, displacement) and petrography of some pseudotachylyte veins from Central Otago, New Zealand are described. This information is used to estimate the average frictional shear resistance ($\bar{\tau}_{fr}$) on pseudotachylyte-bearing faults, the static stress drop ($\Delta\tau$) accompanying pseudotachylyte-producing earthquakes, and the depth of pseudotachylyte formation.

Direct measurements of pseudotachylyte vein thickness and length were made in the field and in thin section. Scanning electron microscope observations were made on a Cambridge S360 SEM at the Research School of Biological Sciences, Australian National University.

2. Geological setting and regional context

This study focuses on pseudotachylyte veins in a brittle shear zone on Tucker Hill, near the township of Alexandra, Central Otago, New Zealand (Fig. 1). Tucker Hill is well exposed (30–40% outcrop). The pseudotachylytes are hosted in strongly foliated, quartz-albite-muscovite-chlorite-epidote-titanite bearing schist, which is part of the regionally extensive Otago Schist Belt (Mortimer, 1993). One major cataclastic fault zone (CFZ) and four principal pseudotachylyte-bearing fault zones (PFZ) occur. White (1998) has previously described in situ pseudotachylyte in the Otago Schist. Moreover, pseudotachylyte veins are locally widespread in boulders collected from creek and riverbeds in northwest Otago (R.H. Sibson, personal communication). A preliminary $^{40}Ar/^{39}Ar$ study suggests a formation age of 96±2 Ma for the pseudotachylyte veins (Barker, 2004; Barker et al., in preparation). The duration of faulting is uncertain. This formation age, coupled with the low-angle, apparently normal sense-of-shear on pseudotachylyte-bearing faults suggests that pseudotachylyte formation was associated with regional extension in the Otago Schist during the mid to late Cretaceous (Deckert et al., 2002; Forster and Lister, 2003).

3. Pseudotachylyte classification and geometry

The CFZ is at least 400 m long, 5–10 m thick, and is composed of shattered and incoherent schist. It contains at least 100 pseudotachylyte veins. The majority of these pseudotachylyte veins cannot be traced for more than 5 m, due to the friable nature of the CFZ. The PFZ comprise 1–3 pseudotachylyte veins, spaced 0.1–0.5 m apart. The PFZs contain no macroscopic cataclasite. Following the classification schemes of Sibson (1975) and Magloughlin and Spray (1992), pseudotachylyte veins at Tucker Hill are defined as either:

(1) Fault veins: Veins generated on a shear surface, with petrographic evidence for a melt origin. Fault veins are sharp, planar features, which are traceable for up to 20 m in individual outcrops, and are both concordant (parallel to foliation) and discordant. Fault veins have much larger length/