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Rethinking conditions necessary for pseudotachylyte formation: Observations from the Otago schists, South Island, New Zealand

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ABSTRACT

Pseudotachylytes and two distinct types of cataclasite in the Otago Schist at Tucker Hill, South Island, New Zealand, provide evidence for both seismic slip and aseismic creep on a normal fault zone during regional crustal extension in late Cretaceous time. Regional geologic evidence suggests that the fault had its present low-angle dip (ca. 10°) at the time it was active. 'Type A' cataclasites, presumably aseismic, can be recognized by bi-fractal grain size distributions, monomict composition, angular clasts of uniform textural maturity, and a crude fabric defined by oriented grains and transgranular fractures. 'Type B' cataclasites, possibly cosesimic, have characteristics consistent with fluidized grain flow, including heterogeneous clast shapes and types, a bimodal grain size distribution, intrusive relationships with other rocks, and the absence of any fabric or transecting fractures. Pseudotachylyte, which occurs as fault veins, injection veins and more complex types of intrusive structures, consistently cuts across and invades Type A cataclasites but is both intrusive into and included as clasts in Type B cataclasites.

These relationships are consistent with a fault evolution model in which the development of a damage zone through aseismic cataclasis (Type A) facilitates the formation of pseudotachylyte in a subsequent seismic event by providing a permeable matrix through which fluids can drain in the early stages of slip, thereby maintaining frictional contact between rock surfaces. The formation of pseudotachylyte, in turn, may seal the fault zone and lead to thermal pressurization in a later seismic cycle, forming fluidized (Type B) cataclasites. Seismic slip on the low-angle normal fault zone at Tucker Hill may have occurred by two distinct modes of dynamic weakening — melt lubrication and thermal pressurization — in successive seismic events.

Although there is a perception among geologists that pseudotachylyte is most likely to form in intact, crystalline rocks, geophysical models of fault zones clearly demonstrate that pseudotachylyte formation is actually suppressed in low-permeability rock because any fluids present would be unable to escape the fault zone and thermal pressurization would rapidly reduce frictional resistance. The paradigmatic occurrences of pseudotachylyte in otherwise pristine crystalline rocks probably represent somewhat exceptional circumstances (single rupture events at very high effective stress in dry rock). Coseismic frictional melts may actually be more common in hydrated rocks like the schist at Tucker Hill, but harder to recognize and also vulnerable to overprinting as a fault zone matures. In such rocks, pseudotachylyte may represent an intermediate stage in the evolution of a fault zone, the period between the formation of a high-permeability damage zone and the development of a low-permeability fault core.

1. Introduction

Pseudotachylyte — glassy rock representing frictionally-generated melt — is considered the only unambiguous indicator of seismic slip on ancient faults (Magloughlin and Spray, 1992; Cowan, 1999), and as such it provides a rare window into processes that occur at the source of an earthquake. The radiated energy of an earthquake, recorded instrumentally, probably represents only about 10% of the total energy released in a seismic slip event (McGarr, 1999), with the remainder absorbed along the fault by fracturing and frictional dissipation. Of this absorbed energy, less than 3% is thought to be consumed by fracturing (Pittarello et al., 2008), and thus frictional heating is by far the largest component of the earthquake energy budget.

Assuming adiabatic conditions (appropriate for seismic events, for which slip duration is much shorter than the time scale for thermal diffusion), the relationship between the heat generated per unit area (Q) along a fault and the thickness (z) of any resulting frictional melt is:

$$Q(\text{per unit area}) = \tau_f D = z\rho(c\Delta T + \Delta h_{\text{fus}}(1-\Phi)) \tag{1}$$

where τ_f is shear resistance, D is coseismic displacement; ρ is rock density, c is specific heat capacity, ΔT is the temperature rise required for melting, Δh_{fus} is the heat of fusion, and Φ is the fraction of unmelted material within the pseudotachylyte (O'Hara, 2001). For values of shear resistance (10–100 MPa) and coseismic slip (0.1–1 m) corresponding to moderate-sized (M6–7) earthquakes, Eq. (1)

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predicts that such events should produce enough heat to form pseudotachylyte lenses on the order of 0.1–1-cm thick (Sibson and Toy, 2006). Larger earthquakes would be even more likely to yield significant amounts of frictional melt.

Yet pseudotachylyte is comparatively rare. Although evidence of frictional melting has been found in a wide array of igneous and metamorphic rock types from a large range of inferred depths (from 2 to >50 km) (Sibson and Toy, 2006), the occurrence of pseudotachylyte in ancient fault zones is the exception rather than the rule. This in itself is an important observation about coseismic processes, indicating that in most fault zones, one or more factors must act to suppress frictional melting. Among these is the thickness of the work zone during the slip event (Spray, 1995; Kanamori et al., 1998). The instantaneous local temperature rise along a fault zone for a slip event of duration t_e is a linear function of the shear strain rate ($d\varepsilon/dt$), which is equivalent to the slip rate (v) divided by the thickness of the processed rock (w):

$$\Delta T = [\tau_f (d\varepsilon / dt) t_e] / c\rho = [\tau_f t_e / c\rho][v\, w] \tag{2}$$

This means that melting is less likely in faults with wide damage zones. However, the absence of melts even along faults where slip has been highly localized indicates that there must be other variables that inhibit frictional melting.

The consensus among geologists has been that fluids in fault zones are the primary explanation for the relative rarity of pseudotachlytes. In a review of the published studies of pseudotachylyte occurrences, Sibson and Toy (2006) stated: “Thermal pressurization of fault fluids during seismic slip inhibits melt generation…Pseudotachylyte represents high-stress (τ>100 MPa) rupturing associated with fault initiation or reactivation in dry, intact (or metamorphically reconstituted) crystalline crust. Its scarcity is accounted for by the progressive infiltration of aqueous fluids into evolving fault zones.” Although many of the classic occurrences of pseudotachylyte fit this description (e.g., Swanson, 1992; Di Toro and Pennachioni, 2005), and their formation has been replicated in geophysical models (e.g., Fialko, 2004), pseudotachylytes have also been found in rocks that were not obviously ‘dry’ (e.g., in subduction settings [Austrheim and Anderson, 2004; Ujiie et al., 2007]) — or ‘intact’ (e.g., strongly cataclasized granite [Otsuki et al., 2003]) when the frictional melts formed. These occurrences suggest that there must be another set of conditions that favor the generation of pseudotachylytes in some fault zones.

The purpose of this paper is to describe the relationships among texturally distinct types of fault rocks, including pseudotachylyte, within a shallowly dipping normal fault zone in schists in central Otago, South Island, New Zealand and to suggest a new model for the geologic conditions under which pseudotachylyte may form. The rocks in the study area indicate that fault rock permeability and transient fluid pressure effects — with and without the formation of frictional melt — dominated the co- and inter-seismic behavior of the fault zone, and that the textures produced by these dynamic processes dictated the subsequent evolution of the fault over several earthquake cycles. These rocks may also provide insights into the puzzle of slip on low-angle normal faults, and the mechanisms of dynamic weakening along fault zones during seismic events.

2. Geologic context

Central Otago on the South Island of New Zealand is underlain by a thick sequence of lower Mesozoic greenschist-facies psammites and pelites known as the Otago Schist, part of the late Permian to Jurassic Haast Schist Group (Mortimer, 1993). Regional differences in lithology and whole rock geochemistry of the Otago schists have made it possible to delineate terrane boundaries within these strongly deformed, predominantly turbiditic rocks (Mortimer and Rosen, 1992). The present study area, at Tucker Hill near the town of Alexandra (45°14′ S, 169°22′ E; UTM coordinates 5544400 N; 2227900 E), lies on the northern edge of the Caples Terrane, which consists of sediments derived from an island arc, and close to the boundary with the Torlesse Terrane, whose sediments have a continental signature (Fig. 1).

The various terranes within the Otago Schist were brought together on the margin of Gondwana during the Rangitata orogeny in middle Jurassic through early Cretaceous time (Norris and Craw, 1987) and developed strong tectonic fabrics as a result of protracted, polyphase deformation during this event. Regional metamorphism of the Otago Schist began at ca. 199 Ma and reached its peak at 180–170 Ma (Adams et al., 1985; Little et al., 1999). Although the metamorphic grade of the Otago Schist is nowhere higher than greenschist facies, distinctive textural zones (I–IV) have been defined on the basis of mica grain size and the character of foliations, and these allow mapping of regional post-metamorphic structural features (Hutton and Turner, 1936; Bishop, 1972; Turnbull et al., 2001). The textural zones define a broad, NW-striking antiformal structure that runs across much of the width of the South Island, from the east flank of the Southern Alps to the east coast (Fig. 1), and rocks with the most intensely reconstituted textures (zone IV) crop out at its center. The rocks in the present study area occur just southwest of the crest of this antiform (Fig. 1) and represent the textural transition from zones III to IV, in which foliation-parallel quartz lenses become continuous subplanar elements and micas begin to become coarse enough to be seen in hand specimen (Turnbull et al., 2001).

The rocks at Tucker Hill have a prominent sub-cm-scale foliation defined by irregular bands of quartz and subordinate feldspar, typically 3–5 mm thick, alternating with muscovite-rich domains that include finer quartz, plagioclase, chlorite and minor epidote and graphite (Barker, 2005). Fluid inclusions are common in the coarser-grained quartz. These minerals indicate that the rocks at Tucker Hill experienced peak metamorphic conditions in the range of 4–5 kbar and 300–350 °C (Mortimer, 2000). The foliation is locally folded and kinked at the meter scale, but to a first approximation it is subhorizontal, with dips ranging from about 10 NE to 25 SW (Means, 1963, 1966; Barker, 2005). The faults and fault rocks described in this study postdate all of the metamorphic fabrics and ductile deformation features in the schist, and formed long before the modern transpressional plate boundary, the Alpine fault (Fig. 1), was established ca. 6 Ma (Norris and Cooper, 2003).

Thermal models based on $^{40}Ar/^{39}Ar$ dating of micas in the Otago schists suggest that the rocks experienced a period of rapid (0.6–1.0 mm/year) post-metamorphic exhumation beginning at about 135 Ma (Little et al., 1999). Over a period of 30–40 million years, regional extension and erosion brought mid-crustal rocks close to the surface. Crustal extension appears to have been accommodated by a combination of shallow and steeply dipping normal faults with variable strikes (Deckert et al., 2002; Forster and Lister, 2003; Cox et al., 2006), including the low-angle, NW-striking faults at Tucker Hill (see below for more discussion of the age of faulting in the study area). By ca. 85 Ma, exhumation had slowed and the regionally recognized Waipounamu Erosion Surface had begun to develop (Landis et al., 2008). This low-relief surface constitutes a useful datum for determining whether Cenozoic deformation has changed the orientation of earlier features. The fact that the Waipounamu Erosion Surface remains nearly horizontal in the Tucker Hill area indicates that the present orientation of observed structures is close to their orientation at the time of mid- to late Cretaceous faulting.

3. Characteristics of faults and fault rocks at Tucker Hill

3.1. Field description

There are at least five subhorizontal to gently (<15°) north-dipping, pseudotachylyte-bearing fault zones exposed in an area of about 6