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Thin pseudotachylytes in faults of the Mt. Abbot quadrangle, Sierra Nevada: Physical constraints for small seismic slip events

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A B S T R A C T

We document the occurrence of pseudotachylyte (solidified melt produced during seismic slip) along strike-slip faults in the Lake Edison granodiorite of the Mt. Abbot quadrangle, Sierra Nevada, California and provide constraints on ambient conditions during seismic faulting. The pseudotachylytes are less than 0.3 mm thick and are found in faults typically up to 1 cm in thickness. Total measured left-lateral offset along sampled faults is approximately 20 cm. Field and microstructural evidence indicate that the faults exploited pre-existing mineralized joints and show the following overprinting structures (with inferred ambient temperatures): mylonites are more or less coeval with quartz veins (>400 °C), cataclasites and pseudotachylytes (~250 °C) more or less coeval with epidote veins, and zeolite veins (<200 °C). Based on observations of the microstructural textures of faults combined with theoretical heat transfer and energy budget calculations, we suggest that only a fraction (<30%) of the total offset was associated with seismic slip (i.e. pseudotachylyte). The presence of pseudotachylyte in sub-millimeter thick zones lends support for the concept of extreme shear localization during seismic slip. The elusive nature of these pseudotachylytes demonstrates that observations in outcrop and optical microscope are not sufficient to rule out frictional melting as a consequence of seismic slip in similar fault rocks.

1. Introduction

Faults within the Bear Creek drainage of the Mt. Abbot Quadrangle, Sierra Nevada, California (Fig. 1) have received considerable attention during the past two decades as a natural laboratory for investigations of fault mechanics and the evolution of fault architecture in granitic rocks. Most work on the Bear Creek faults has focused on explaining the outcrop-scale fault structure based on continuum and fracture mechanics models (e.g. Segall and Pollard, 1983b; Martel and Pollard, 1989; Bürgmann and Pollard, 1994; d'Alessio and Martel, 2004). Recently these faults have been included in studies of short term dynamic (i.e. coseismic) mechanisms operating near the base of the seismogenic zone (e.g. Shipton et al., 2006a,b). However, evidence that seismic slip occurred along these faults (i.e. the presence of pseudotachylytes: Cowan, 1999) has not been documented.

This paper reports the occurrence of thin pseudotachylyte veins in the faults described in detail by Martel et al. (1988). Our finding has been corroborated by the identification of other pseudotachylytes within several kilometers of the Bear Creek faults and nearby in the Bear Creek drainage (Kirkpatrick and Shipton, 2008). Here we describe the pseudotachylytes, the associated fault rocks, and the implications for fault deformation mechanisms and seismic slip.

2. Faults of the Bear Creek drainage: previous work

The left-lateral strike-slip faults in Bear Creek cut the 80–90 Ma Lake Edison granodiorite (25% quartz, 40% plagioclase, 25% K-feldspar, and 10% hornblende and biotite; Lockwood, 1975). K-Ar ages of muscovite date the Bear Creek faults at 79 Ma, and these faults have been interpreted as having grown soon after pluton emplacement (Segall et al., 1990). Segall and Pollard (1983b) concluded that the Bear Creek faults developed by slip along pre-existing joints rather than by propagating as shear fractures through unbroken granite. The pre-faulting joints of Bear Creek are filled with hydrothermal mineral assemblages consisting primarily of varying amounts of undeformed quartz, epidote, and chlorite, and have been related to cooling of the plutons (Segall and Pollard, 1983a; Bergbauer and Martel, 1999). Three stages of faulting are recognized. The first stage is marked by "small faults" (Segall and Pollard, 1983b; Martel et al., 1988), which are several millimeters thick and accommodate as much as 2 m of slip. The second stage is marked by "simple fault zones" (Martel et al., 1988), tabular

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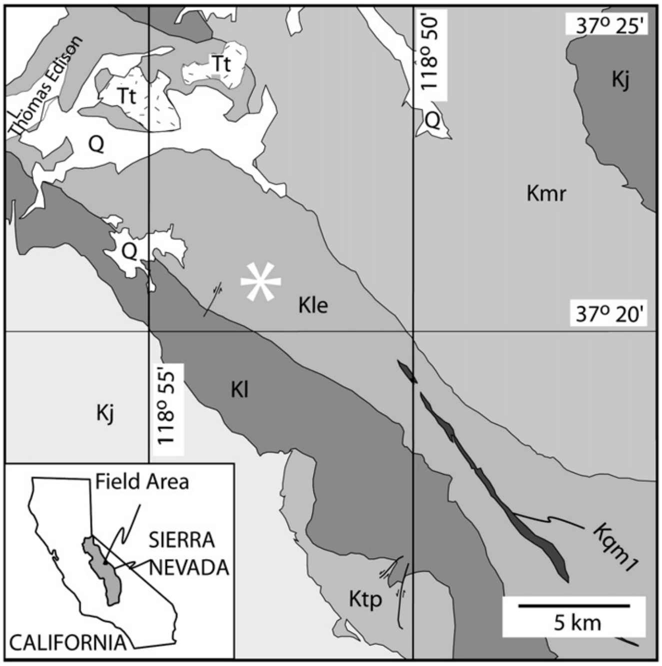

Fig. 1. Simplified geological map of a portion of the Mt. Abbot quadrangle (modified from Bergbauer and Martel, 1999 and Lockwood and Lydon, 1975). The Waterfall site discussed in this paper is indicated by the white star. The main geologic units shown are, from oldest to youngest, unspecified Cretaceous and Jurassic plutons (Kj), the Lamarck granodiorite (Kl), the Mount Givens granodiorite (Kmo), the Lake Edison granodiorite (Kle), Quartz monzonite of Mono Recesses (Kmr), Cretaceous quartz monzonite and granite (Kqm1), Granitic rock of uncertain affinity (Ktp), Tertiary olivine trachybasalt (Tt), and Quaternary deposits (Q).

volumes of moderately to highly fractured rock typically 0.5–3 m thick bounded by former "small faults" millimeters to several centimeters thick. The simple fault zones accommodate as much as 20 m of slip. The third stage is marked by "compound fault zones" (Martel, 1990). These have widths as great as several meters, and accommodate up to 140 m of slip (Pachell and Evans, 2002). Small faults and boundary faults of fault zones of the Bear Creek area are associated with mylonites (Segall and Pollard, 1983b; Segall and Simpson, 1986; Bürgmann and Pollard, 1994), and in some faults the mylonitic fabric has a cataclastic overprint.

Evans et al. (2000) noted that microstructures and geochemical alteration of the Bear Creek faults are similar to mature crustal-scale faults such as the San Andreas as exposed in the San Gabriel Mountains. More recently, Shipton et al. (2006b) compared fault thicknesses measured in the Bear Creek region to the principal slip zone thickness theoretically estimated using typical breakdown energies during earthquake rupture. They concluded that both observations and theoretical estimates support the interpretation that deformation during seismic slip tends to localize in very thin ($\ll$1 cm) zones.

3. Pseudotachylyte-bearing faults

The pseudotachylyte veins were found in left-lateral "small faults" from the "Waterfall Site" of Martel et al. (1988) with ~20 cm strike separation (Fig. 2) that closely approximates the net slip. These millimeter-thick faults contain sub-parallel mylonites, cataclasites, pseudotachylytes and veins of quartz, epidote and zeolite (Fig. 2), that testify to several episodes of fluid infiltration and slip exploiting the same tabular structure. The fault rocks and their overprinting relationships are described and the ambient conditions during faulting based on mineral assemblages and microstructural constraints are estimated.

3.1. Mylonites

Granodiorite–mylonites and quartz mylonites (Fig. 3A) show evidence of recrystallization of biotite, plagioclase, and quartz. Stress-induced quartz-plagioclase myrmekites are developed along grain boundaries between K-feldspar and plagioclase in the wall rock adjacent to mylonites (Fig. 3B) oriented as contractional surfaces relative to the sense of shear of the associated mylonite. The recrystallized plagioclase in the granodiorite–mylonites and myrmekites is oligoclase (Table 1).

Quartz mylonites make up the majority of the thickness of the small faults at most points along strike (e.g. Fig. 2B) and consist of dynamically recrystallized fine-grained (10–100 μm, Fig. 3A) aggregates with an oblique shape fabric, indicative of the same left-lateral sense of shear as in the cataclasites, and a strong crystallographic preferred orientation (Fig. 4). The microstructures show high aspect ratio grain shapes and optically visible subgrains in core-mantle textures (Fig. 3A), characteristic of subgrain rotation recrystallization (Stipp et al., 2002). Electron backscattered diffraction (EBSD) pole figures (Fig. 4) show an oblique single *c*-axis girdle with asymmetry consistent with left-lateral slip.

Mylonites are commonly overprinted along boundaries with the host rock by thin sub-parallel cataclastic layers (Fig. 2A). Mylonitic faults with no cataclastic overprint are similar in appearance to the pseudotachylyte-bearing small faults studied here: they form very sharp discrete boundaries with apparently undeformed host rocks and commonly accommodate over a meter of strike separation in some cases (e.g. Segall and Simpson, 1986).

3.2. Cataclasites and epidote veins

Cataclasites generally form green layers a few millimeters thick in sharp contact with the host rock and the mylonites and typically are associated with epidote-rich veins (e.g. Martel et al., 1988). Cataclasites consist of angular clasts of the host granodiorite and quartz mylonites (Fig. 5A and B), set in a matrix of quartz, K-feldspar, epidote, and minor titanite and chlorite (Fig. 5B).

3.3. Pseudotachylytes

Pseudotachylytes occur as ultra-thin (<300 μm thick) fault veins either forming paired or single slip surfaces oriented sub-parallel to the fault. Pseudotachylytes were found along narrow bands between quartz mylonites and the host rock (Fig. 2), whereas cataclasites were either not present or extremely thin (<100 μm) in samples containing pseudotachylyte (e.g. Fig. 6A and B). Pseudotachylytes were identified based on the presence of typical features summarized by Magloughlin and Spray (1992):

(1) sharp contacts with the host rock and presence of small injection veins (Sibson, 1975) (Figs. 3C and 6A) that typically intrude towards the interior of the fault zone rarely connecting two bounding fault veins (Fig. 2C) (Swanson, 1988);
(2) some embayed clasts of high melting temperature minerals (quartz, feldspar) (Fig. 6C) suggesting assimilation by the melt (e.g. Shand, 1916);
(3) sub-angular clasts of K-feldspar, plagioclase, and quartz in the pseudotachylyte matrix, and absence of hydrous minerals common in the host rocks such as biotite and chlorite (Fig. 6C) and enrichment of Fe, Mg, K, and Loss On Ignition (interpreted as water), along with depletion of Si and Ca, of the pseudotachylyte matrix compared to the host rocks (granodiorite and mylonites, Table 1). This results from selective melting of