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Short Note

Pseudotachylytes: Rarely Generated, Rarely Preserved, or Rarely Reported?

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Abstract Pseudotachylyte is the only fault rock that is known to form exclusively at seismic slip rates, so it is unique in preserving direct evidence of the dynamic processes in action during earthquakes. It is commonly assumed that pseudotachylyte is rare, and debate has centered on whether it is rarely generated or commonly generated but rarely preserved. We present field and electron microscope observations of eight new pseudotachylytes from faults in the Sierra Nevada that have previously been the focus of many detailed studies of fault growth and mechanics. These pseudotachylytes range from being abundant and easy to recognize in outcrop to being impossible to identify without microscope observations. Our data show that pseudotachylytes are much more common in the Sierra Nevada than has previously been reported. We suggest that pseudotachylytes may be present within many fault zones but remain unreported primarily due to difficulty in identifying very thin or reworked pseudotachylytes in the field; and therefore the use of these fault rocks to interpret dynamic earthquake processes must be revisited.

Introduction

Tectonic pseudotachylytes form by frictional heating during slip events with velocities of 0.1–1 m/sec^{-1} and are the only fault rocks that unequivocally preserve direct evidence of the dynamic processes operating during earthquakes (Sibson, 1975; Cowan, 1999). Lubrication by friction-induced melting is one of the potential mechanisms by which the level of friction is dynamically reduced during an earthquake, and physical models show that melting could occur during coseismic slip if the slipping zone is of the order of a few millimeters thick (McKenzie and Brune, 1972). McKenzie and Brune (1972) argued that given the frequency of moderate to large earthquakes, pseudotachylytes should be widespread in crust exhumed from seismogenic depths, that is, 5–15 km.

In a comprehensive review of reports of pseudotachylytes from the geological literature, Sibson and Toy (2006) argued that pseudotachylyte is a rare fault rock type and debated whether pseudotachylyte was rarely generated or is rarely preserved in recognizable form. They argued that the quantity of reported pseudotachylytes, even in well-studied and well-preserved fault rocks, was low, suggesting pseudotachylytes are rarely generated. Sibson and Toy (2006) went on to conclude that melt lubrication is mostly limited to relatively immature faults or faults cutting mainly dry, crystalline rocks, and therefore, alternative slip weakening mechanisms must be sought for other fault rock types.

Identifying fault rocks as pseudotachylytes is not straightforward and strictly requires evidence that the fault rock has passed through a melt phase (Magloughlin and Spray, 1992). Some outcrop-scale characteristics of pseudotachylytes are diagnostic (Table 1). Dark gray to black pseudotachylyte veins are often arranged in a distinctive geometry of approximately planar generation surfaces (also called fault veins) associated with shorter (often centimeters long), high-angle injection veins that contain the same material as the generation surfaces (Sibson, 1975; Swanson, 1992). Pseudotachylytes may display color banding due to quenched margins. The vein matrix is very fine grained (aphanitic), and freshly exposed surfaces may be glassy with conchoidal fracture. Clasts are predominantly rounded and embayed quartz, feldspar, or aggregates of the two, and the proportion of clasts visible with the naked eye is often low. Preferential melting of low-melting temperature minerals means that mica and hornblende are generally absent in clasts. Optical microscope and Scanning Electron Microscope (SEM) analyses are also often required to distinguish pseudotachylytes from other fault rocks such as ultracataclasites or very fine-grained gouges, which can show similar outcrop-scale features (Maddock, 1983). In particular, the presence of microscopic skeletal microcrystallites arranged either singly, paired, or in radial clusters known as spherulites is considered to be diagnostic. In addition very thin

Table 1
Identification Criteria for the Sierra Nevada Pseudotachylyte-Bearing Faults

		Obvious in Outcrop			Hard to Interpret in Outcrop				Not Apparent in Outcrop
		GPF	LLF	SKF	SGF	EBF	DBF	BBF	GLF
Fault characteristics									
Mapped trace length (km)	Fig. 1	6.7	2.3	1.4	0.87	0.54	0.08	2.1	8.2
Maximum observed offset (m)	Fig. 1	80	36	22	—	—	0.7	—	125
Pseudotachylyte identifying characteristics—field observations									
Generation surface/injection vein geometry	Fig. 2, 3	×	×	×	×			×	
Sharp edges	Fig. 2, 3	×	×	×	×	×	×	×	
Quenched margins	Fig. 2, 3	×	×	×	×	×		×	
No grains visible with naked eye in matrix	Fig. 2, 3	×	×	×	×	×	×	×	
Embayed clasts	Fig. 2	×	×	×	×	×	×	×	
Glassy lustre/conchoidal fracture surface	Fig. 3					×	×		
Pseudotachylyte identifying characteristics—microscope observations (after Magloughlin and Spray, 1992).									
Quenched margins		×	×	×	—	—	×	—	
Microcrystallites/ spherulites	Fig. 2, 4		×	×	—	—	×	—	×
Microcrystallite texture varies at vein margin			×	×	—	—	×	—	×
Dendritic crystal habit	Fig. 3				—	—	×	—	
Sulphide droplets	Fig. 3	×	×	×	—	—	×	—	×
Injection veins		×	×	×	—	—	×	—	

Because rock samples could not be collected using power tools in the Mount Abbot wilderness area, microscope observations of the SGF, EBF, and BBF were not available.

pseudotachylytes or those that have been reworked cannot be identified without detailed microscale studies.

We have recently identified eight occurrences of pseudotachylytes from two study areas in the Sierra Nevada (Fig. 1). Pseudotachylytes have been reported from the Bench Canyon shear zone (McNulty, 1995) and the Kern Canyon fault (R. Sibson, person comm., 2005). However, despite the relatively large number of published studies on the faults in our study areas, reports of pseudotachylytes have only recently emerged (Kirkpatrick *et al.*, 2008; Griffith *et al.*, 2008). Indeed, Di Toro and Pennacchioni (2005) and Sibson and Toy (2006) cited the Sierra Nevada as an area where pseudotachylytes were absent. Depending on the nature of the pseudotachylyte veins, pseudotachylytes in the Sierra Nevada faults are either (1) abundant in outcrop, (2) apparent in outcrop but difficult to identify as pseudotachylytes, or (3) impossible to identify from outcrop data alone. Our observations emphasize that pseudotachylytes are much more common than is currently appreciated but often remain unreported.

Field Observations

Faults in the Sierra Nevada cut 90–70 Ma granites and granodiorites (Bateman, 1992; Fig. 1a). The faults have been minimally altered during exhumation and are exposed in extensive glacially polished exposures particularly suited to the kind of detailed structural investigations that are likely to encounter pseudotachylytes according to criteria outlined in Di Toro *et al.* (2006) and Sibson and Toy (2006). Dating of fault rocks in the region suggests that the faults were likely to have been active at seismogenic depths around 6–8 km (Pachell and Evans, 2002), and references therein. Previous work in the Mount Abbot area (Fig. 1b) has focussed on development of the fault zones from preexisting cooling joints into complex structures accommodating up to 100 m of slip (Segall and Pollard, 1983; Martel *et al.*, 1988; Martel, 1990; Pachell and Evans, 2002) in the context of fracture mechanics (Martel and Boger, 1998). Previous work in the Kings Canyon area (Fig. 1c) focussed on describing the fault geometry, kinematics (Evans *et al.*, 2000; Kirkpatrick *et al.*, 2008), and microstructures (Shipton *et al.*, 2006).

To illustrate the reasons why we believe pseudotachylytes may be underreported, we present new field and microscope observations of pseudotachylytes from eight faults in these previously well-studied areas using the key field and microscope identification criteria listed in Table 1. Where it was possible to collect samples, microscope and SEM analyses provide additional evidence for a melt phase.

Pseudotachylytes That Are Clear in Outcrop

Pseudotachylytes are sufficiently abundant in the Granite Pass fault (GPF), Little Lake fault (LLF), and Skeeter fault (SKF) to be reliably identified from field data alone (Fig. 2, Table 1). The fault veins demonstrate a variety of geometries. In each of the faults pseudotachylyte is most common in ~1 – 10 mm thick, approximately planar fault veins with occasional high-angle injection veins that overprint cataclasites as well as relatively undeformed host rock. One exposure

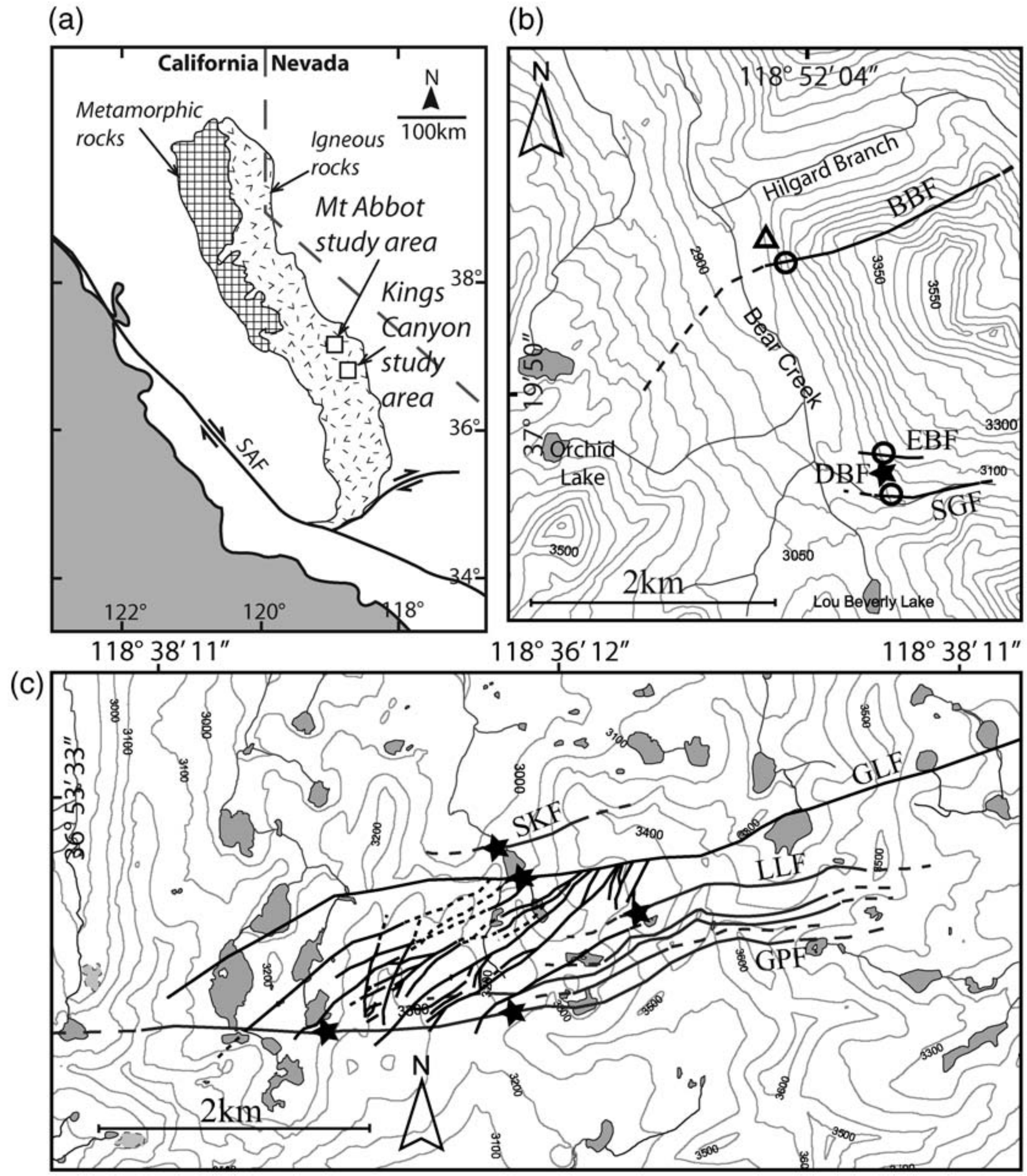

Figure 1. (a) Location and detailed fault maps of the study areas in (b) Mount Abbot quadrangle and (c) Kings Canyon National Park. Stars are pseudotachylytes analyzed with microscope and SEM; circles are pseudotachylytes identified from field observations alone. Labeled faults in the Mount Abbot quadrangle are the Big Bear fault (BBF), East Branch fault (EBF), Dancing Burn fault (DBF), and Seven Gables Trail fault (SGF). The locality described by Griffith *et al.* (2008) is represented by an open triangle. In Kings Canyon National Park two systems of faults are present as described by Kirkpatrick *et al.* (2008): Skeeter fault (SKF), Little Lake fault (LLF), Granite Pass fault (GPF), and the other gray faults predate the Glacier Lakes fault (GLF) and its subsidiary structures, which are shown in black.

of the SKF contains multiple generation surfaces up to 20 mm thick with accompanying injection veins, giving the rock a brecciated appearance (Fig. 2a). In the LLF, closely spaced generation surfaces bifurcate along strike forming an interconnected network of veins. In this exposure, injection veins are asymmetric around the primary surface.

Optical microscope analysis reveals variation in the vein properties that reflects their outcrop expression. Wider veins contain plagioclase microcrystallites up to ~100 μm long and 20 μm wide that are easily identifiable in thin section. Where pseudotachylytes are color banded in outcrop, domains of differing microcrystallite size are visible and microcrystallites are sometimes aligned, defining flow fabrics (Fig. 2b). In quenched vein margins, the vein is dominated by cryptocrystalline material. Clasts range in size from 10–600 μm and are composed of quartz, K-feldspar, and plagioclase feldspar. Some wide veins also contain spherulitic textures defined by radial arrangements of feldspar microcrystallites overgrowing lithic clasts of feldspar and quartz (Fig. 2c). The matrix between the spherulites is pale brown

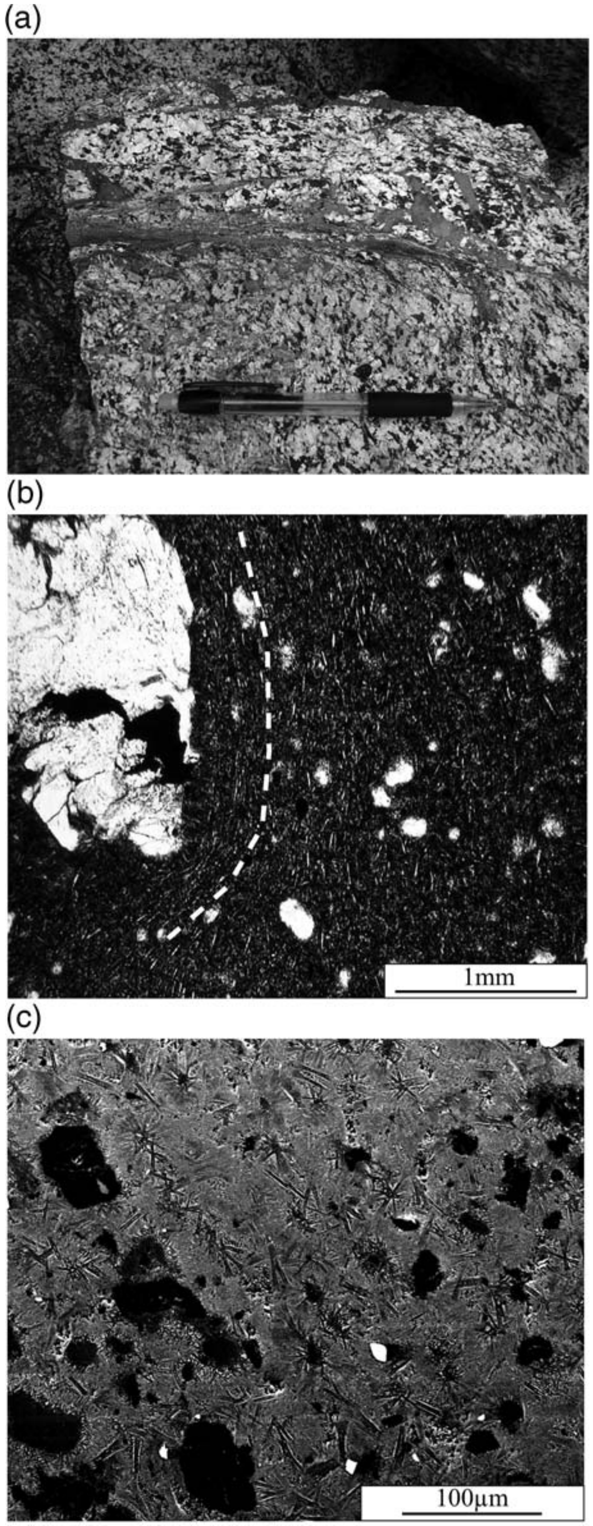

Figure 2. (a) Photograph of pseudotachylytes that are readily identifiable in an exposure of the SKF; the pen, to show scale, is 10 cm long. (b) Photomicrograph showing aligned microcrystallites of high-temperature feldspar composition indicative of flow in the melt phase in a sample from the SKF. The dashed line shows the approximate orientation of the long axes of the aligned microcrystallites as they wrap around a lithic clast. (c) Backscattered electron (BSE) image of spherulitic textures developed in a pseudotachylyte vein in the SKF.

or green in plane-polarized light, indicating alteration and replacement with epidote and chlorite. Elsewhere within the fault zone, there is abundant microscale evidence for reworking of solidified pseudotachylyte by brittle deformation mechanisms in the form of pseudotachylyte clasts in cataclasites.

Pseudotachylytes That Are Difficult to Interpret in Outcrop

Four faults in the Mount Abbot quadrangle contain pseudotachylytes that are apparent in outcrop but that cannot be unequivocally identified as such from field data alone (Fig. 3, Table 1). The Seven Gables Trail fault (SGF), Big Bear fault (BBF), and East Branch fault (EBF) contain 1–6 mm thick, dark gray to black pseudotachylytes often displaying banding (Fig. 3a). Rare, high-angle injection veins branch off from the main pseudotachylyte generation surfaces that are only centimeters long. The pseudotachylytes are generally associated with cataclasites but also crosscut undeformed host rock in places.

In very thin pseudotachylytes with few injection structures, the geometry is not obviously intrusive, so it is difficult to distinguish pseudotachylytes from ultracataclasite even with optical microscope observations. SEM analyses are essential for positive identification of the thinnest pseudotachylytes. The Dancing Burn fault (DBF) is composed of a 25 mm wide network of narrow (0.15–1.28 mm) veins filled with black, crystalline material (Fig. 3b) that frequently displays conchoidal fractures but no injection veins. The pseudotachylyte veins are filled with brown to pale brown, aphanitic material displaying flow banding in places and chilled margins of cryptocrystalline material (Fig. 3c). Injection veins <0.5 mm long are evident under the optical microscope. Replacement of the groundmass by chlorite has been extensive, so microcrystallites are difficult to distinguish. However, extremely fine arrangements of spherulites and crystallites of feldspar with skeletal crystal morphologies are observed under the SEM, between which sulphide droplets are abundant (Fig. 3c). Combined with the field observations, these microscale characteristics confirm that the DBF contains pseudotachylyte.

Pseudotachylytes That Are Impossible to Identify in Outcrop

Pseudotachylytes were not observed at the outcrop scale in the Glacier Lakes fault (Fig. 4, Table 1). Deformed rocks in the fault are primarily gray-green cataclasites composed of comminuted clasts of host rock, epidote, and chlorite (Fig. 4a). However, optical microscope analysis reveals a pseudotachylyte vein that cuts across a cataclastic fabric contained within a seam of cataclasite (Fig. 4b). The vein is 0.3–2 mm thick. Injection veins are not observed at the scale of the thin section, though the vein is subparallel to the trend of the cataclasite suggesting the vein is a fragment of a genera-

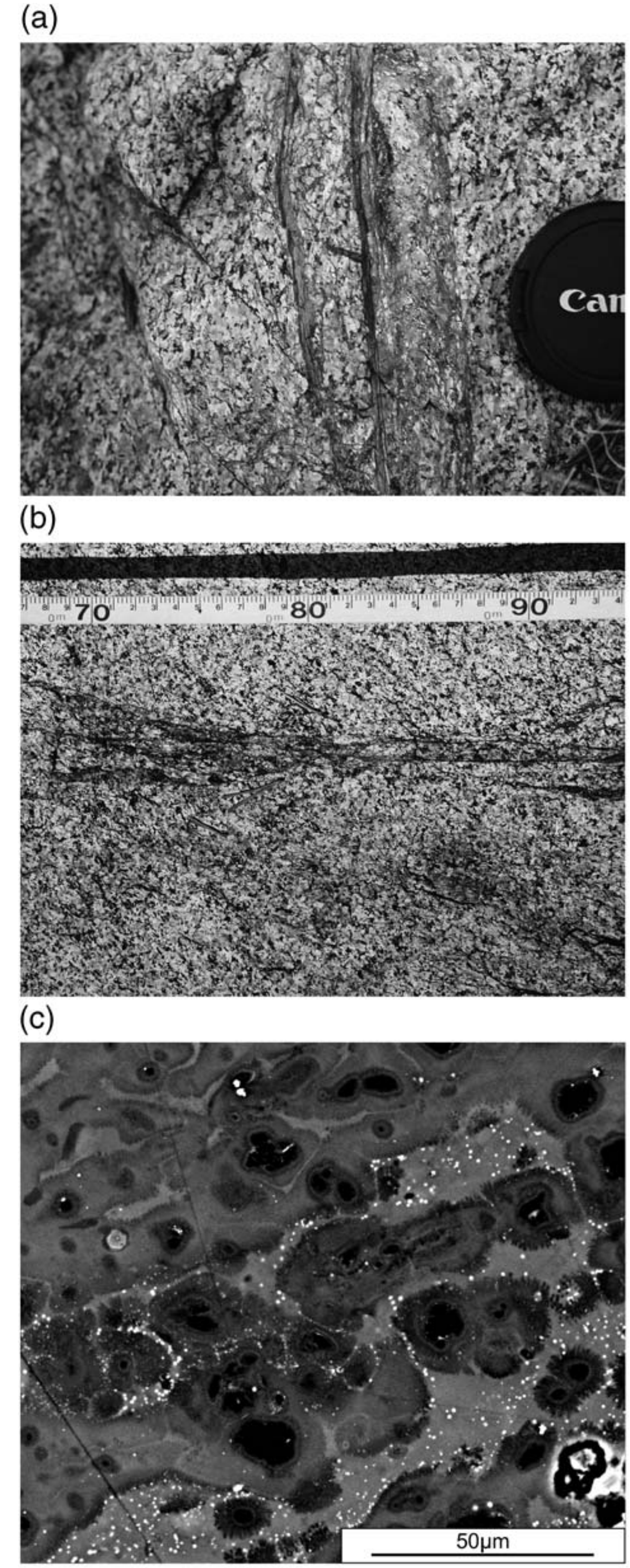

Figure 3. (a) Photograph of a pseudotachylyte generation surface and associated injection vein in the SGF; the camera lens, to show scale, is 5 cm in diameter. (b) Photograph of an exposure of the DBF containing a network of narrow pseudotachylyte veins. (c) BSE images of the DBF pseudotachylyte showing dendritic habit crystallites of feldspar and small spherulites overgrowing predominantly feldspar lithic clasts.

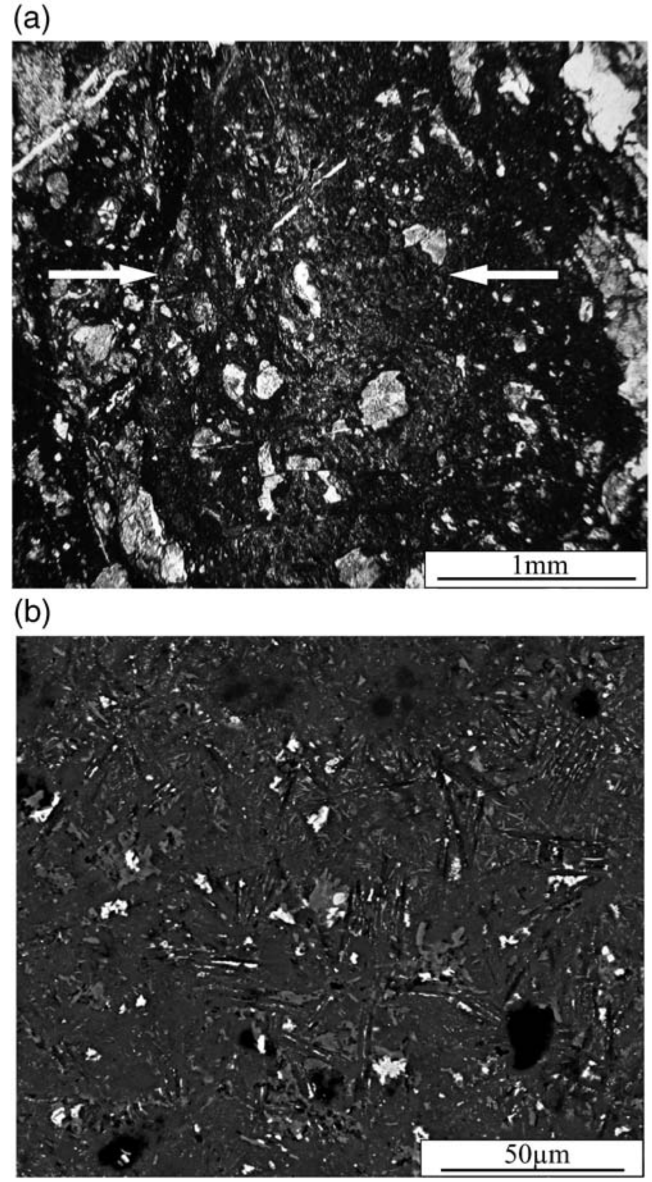

Figure 4. (a) Photomicrograph of the pseudotachylyte vein in the GLF plane polarized light (PPL). The pseudotachylyte vein (between arrows) is contained within a cataclasite seam. Rounded and embayed clasts are evident within the pseudotachylyte. (b) BSE image of the GLF pseudotachylyte showing microcrystallites present in a groundmass that is extensively replaced with chlorite.

tion surface. The pseudotachylyte material is mostly brown in plane-polarized light or patchy green where the matrix is replaced with chlorite. Microcrystallites are difficult to identify with an optical microscope, but S.E.M analysis shows lath-shaped alkali feldspar microcrystallites up to ~20 μm long and ~5 μm wide (Fig. 4b). The arrangement of microcrystallites into spherulites is rarely evident as the groundmass is extensively disrupted by chlorite development. Although the pseudotachylyte vein was hidden in outcrop, microscope and SEM observations strongly suggest a melt origin for this vein.

Discussion

Both of our study areas have previously been the focus of detailed structural investigations. The fact that none of these studies reported the presence of pseudotachylytes demonstrates that it is possible for pseudotachylytes to be present within a study area but remain unidentified and/or unreported. As pseudotachylytes are present in the majority of faults we studied (Fig. 1), we suggest that pseudotachylytes are not limited to the faults that we describe and are probably common throughout the Sierra Nevada (cf. Griffith *et al.*, 2008). The Sierra Nevada has been cited as an area lacking pseudotachylytes in support of the hypothesis that pseudotachylytes are rarely generated (Sibson and Toy, 2006). However, our results show that the Sierra Nevada cannot be used as a case study to support this hypothesis. If other areas are similarly misinterpreted as lacking pseudotachylytes, then pseudotachylytes may be apparently scarce because they are rarely reported.

Pseudotachylytes remain enigmatic fault rocks because they are difficult to identify in both outcrop and thin section and are often poorly preserved. They may be potentially recognizable in a fault zone but may not be identified by investigators due to lack of experience in field identification of pseudotachylyte and/or due to ambiguous field exposures. Most previous studies of pseudotachylyte are based on meter to tens of meters long generation surfaces (e.g., Sibson, 1975; Swanson, 1992; Di Toro and Pennacchioni, 2005). Some of the occurrences documented here are substantially shorter and/or thinner than many previous reports. Smaller volumes of melt will be much harder to identify from field observations alone as injection veins will be rare and so intrusive relations will be much less obvious. The volume of pseudotachylyte is proportional to the slip accommodated across a pseudotachylyte vein (Sibson, 1975; Di Toro and Pennacchioni, 2005), so melt generated in small earthquakes is almost certainly underreported in the literature. An additional reason that might explain the underreporting of pseudotachylytes is that even where investigators positively identify them in the field if pseudotachylytes are not the main focus of an investigation, their presence may not prompt reporting. This is the likely reason for the lack of reporting in the Sierra Nevada, as previous studies have focussed on the geometry and mechanics of the faults rather than the details of the fault rock types and compositions.

The observations of altered and reworked pseudotachylytes that we present confirm that continued deformation will almost certainly obliterate primary evidence for melt generation. Pseudotachylytes are more likely to be generated at significant depths in the crust where normal and shear stresses are higher (i.e., >5 km; Fialko and Khazan, 2005). However, pseudotachylytes are susceptible to hydrothermal alteration, and exhumation through the fluid-saturated shallow crust is unlikely to preserve glassy material. Additionally, faults that continue to accommodate deformation while being exhumed are unlikely to preserve pseudotachylytes. Even detailed microscope and SEM analyses would be unable to discern any trace of ancient melt if pseudotachylytes have been comminuted at shallow depths. The Sierra Nevada faults are exceptional in this respect as they were exhumed after deformation and fault-hosted fluid flow had ceased. Without a systematic study of fault rocks exhumed from seismogenic depths focusing on their depth of formation and exhumation history, it is not currently possible to say whether pseudotachylyte, and therefore, melting as a slip weakening phenomena, is rare or common.

Pseudotachylyte generation requires energy input in the form of heat to raise the temperature of the slip surface, to overcome the latent heat of fusion, and to raise the temperature of a melt beyond its melting temperature (Fialko and Khazan, 2005; Nielsen *et al.*, 2008). The source of heat energy during coseismic slip is frictional heating across the slip surface (premelt lubrication) or shearing of a viscous layer of melt (postmelt lubrication). The dissipation of energy released by an earthquake is difficult to constrain (e.g., Chester *et al.*, 2005; Kanamori and Rivera, 2006), but McGarr (1999) showed that the radiated energy probably accounts for less than 6% of the total energy released. Recent investigations (e.g., Shipton *et al.*, 2006; Pittarello *et al.*, 2008) have sought to provide geologic insight into the earthquake energy balance by discussing coseismic processes that might consume energy. The present study shows that as pseudotachylytes are likely more commonly generated than is often appreciated; the melting of fault rocks may well account for a significant proportion of heat energy in an earthquake event.

Data and Resources

All data used in this article came from published sources listed in the references.

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