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Disappearing ink: How pseudotachylytes are lost from the rock record

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ABSTRACT

Melt-origin pseudotachylytes are the most widely accepted feature recording earthquake slip in the fault rock record. However, reports of pseudotachylytes are rare compared to the frequency and distribution of earthquakes in active faults, suggesting melting occurs only under exceptional circumstances and therefore that pseudotachylytes are rarely formed. In this paper, we document the processes whereby pseudotachylytes are overprinted, destroyed and otherwise removed from the rock record. We present examples of recrystallized, altered, and cataclastically and crystal plastically deformed pseudotachylytes from a variety of ancient faults. Based on these observations, we identify characteristics of pseudotachylytes that are resistant to change over geologic time and develop criteria to allow recognition of relict pseudotachylytes. Our results imply that pseudotachylytes are vastly under-reported due to their vulnerability to destruction and the resulting difficulty in identification. As a consequence, the significance of frictional melting is underestimated. The criteria we propose to distinguish relict pseudotachylytes can help to reconcile the observed frequency of earthquakes with the difficulty of demonstrating ancient seismic slip in the rock record.

1. Introduction

Fault rocks that undergo rapid shear at depth during an earthquake should preserve a record of, and be useful for elucidating, the processes operating *in situ* on a fault plane during slip. However, identifying and interpreting the record of earthquakes in exhumed faults requires an understanding of the characteristic textures and mineralogy that form at high strain rates typical of seismic slip rates (ms^{-1}) localized onto thin faults (mm to cm). A variety of approaches are being developed by characterizing and comparing field observations to the products of high velocity rock friction experiments (e.g. Han et al., 2010; Ujiie et al., 2011; Niemeijer et al., 2012; Rowe et al., 2012a), but the most widely accepted and frequently utilized indicator of paleo-seismicity that may be present in an exhumed fault is pseudotachylyte (Cowan, 1999).

Tectonic pseudotachylytes are unique fault rocks in that they require slip at seismic rates to cause melting (Philpotts, 1964; Sibson, 1975; Maddock, 1983). In this study, we restrict our definition of "pseudotachylyte" to a fault rock that has undergone frictional melting. Other workers include amorphous or micro-granular material that displays some similar meso- and micro-scale characteristics to melt-origin pseudotachylytes in their definition ("crush-origin" pseudotachylytes, e.g. Wenk (1978), Lin (1997), Ozawa and Takizawa (2007) or micro-scale amorphization e.g. Pec et al. (2012)). However, the transition through a melt phase places important constraints on seismic energy dissipation (e.g. Pittarello et al., 2008; Griffith et al., 2010), seismic source parameters (e.g. Kirkpatrick et al., 2012) and fault rock rheology (Fialko and Khazan, 2005; Nielsen et al., 2010) on the fault plane during slip. Identifying this transition is crucial because crush-origin fault rocks can theoretically result from a number of processes at a variety of strain rates (including sub-seismic strain rates) so could form at any stage during the seismic cycle (Yund et al., 1990; Hayashi and Tsutsumi, 2010; Hirose et al., 2012; Pec et al., 2012). Furthermore, the implications of the presence of such material for the micro-mechanics of fault friction are not well established. Melt-origin pseudotachylytes, which record extreme frictional heating, are distinctly seismic.

Pseudotachylytes are apparently rare in the rock record, but it is not clear whether this relative absence is due to the rarity of frictional melting during earthquakes or preservation bias caused by rapid destruction and recycling of pseudotachylyte veins in active faults (Sibson and Toy, 2006; Kirkpatrick et al., 2009). Pseudotachylytes are difficult to decisively identify in faults, primarily

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because they are only one of a suite of ultra fine-grained, dark-colored rocks such as ultracataclasite and ultramylonite which are found in fault zones. Complicating matters, these fault rocks are often found in combination, and cataclastic or plastic shear strain may overprint pseudotachylyte veins. In general, only microscale observations can conclusively differentiate between these rocks, and then, only if primary cooling textures are preserved. However, the primary microtexture of frictional melt may be short-lived over geologic time. As noted by Wenk (1978), most examples of pseudotachylytes contain no glass (*cf*. Maddock, 1986).

The clear seismic origin of pseudotachylytes has resulted in disproportionate importance being placed on their presence in a fault zone. However, the absence of pseudotachylyte does not imply non-seismic deformation. The majority of fault displacements are observed to occur during earthquakes, and very few faults globally show sustained creep (Sibson, 1989), suggesting most fault rocks form during, or may be affected by, seismic slip. The apparent scarcity of pseudotachylytes in the rock record implies that other coseismic fault rocks, which may be difficult to distinguish from inter-seismic fault products, are produced during earthquakes and/or that pseudotachylytes are currently under-reported. Assessing the frequency of pseudotachylyte formation is essential to evaluating the importance of frictional melting as a coseismic process. It may also begin to reconcile the observed seismicity with the fault rock record by providing a better representation of the frequency of earthquake deformation. Furthermore, if pseudotachylytes can be readily identified, they may provide indirect evidence regarding the conditions of formation of other associated fault rocks. These outcomes depend on reliable, and equally as importantly, inclusive identification of pseudotachylytes in ancient and recent faults.

Here, we present an overview of the mechanisms that cause pseudotachylytes to vanish from the rock record. We begin with an overview of the identification criteria for pristine pseudotachylytes. We then provide examples of alteration and deformation processes at various stages, and suggest criteria for identification of overprinted pseudotachylytes in outcrop and thin section. Finally, we explore the implications for interpretation of the rock record of earthquakes in ancient and modern faults.

2. Identification of pristine pseudotachylytes

In this section we review the established criteria for identifying pseudotachylytes from field and micro-scale observations in order to provide an overview of the primary characteristics of pristine solidified frictional melts (Fig. 1; Table 1A). Some exposure-scale characteristics are useful for recognizing pseudotachylytes but

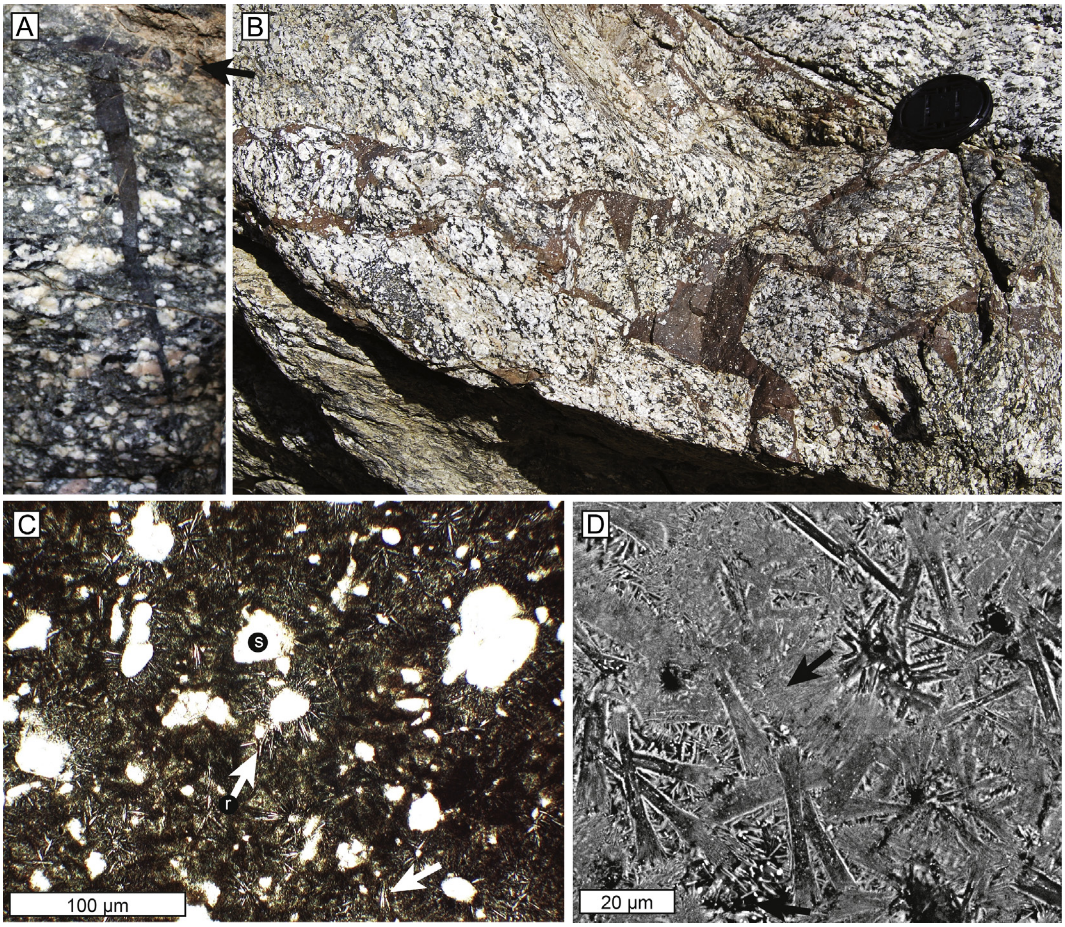

Fig. 1. Pristine pseudotachylytes in exposure and microscope. A. An example pseudotachylyte with a fault vein – injection vein geometry from the Asbestos Mountain fault, California. The black arrow indicates the location and orientation of the fault vein. Widest part of injection vein is ~5 mm across. B. A chaotic pseudotachylyte breccia containing angular clasts of tonalite wall rock ~6 cm across in a brown pseudotachylyte matrix, near La Quinta, California. C. Photomicrograph (plane polarized light) showing lath-shaped microcrystallites in a fault vein from Kings Canyon National Park, California. The white arrows indicate microcrystallites growing radially (r) from a survivor clast (s) boundary. D. Back-scattered electron image of a pseudotachylyte showing tiny lath-shaped microcrystallites, some with a bow-tie geometry. The laths ends have brush-like textures. The black arrow indicates an interstitial area between microcrystallites where no crystal structure can be identified at this scale of observation indicating cryptocrystalline or amorphous material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Table summarizing the characteristics of pseudotachylytes and their resilience to change during recrystallization or reactivation by cataclastic or plastic deformation. A: Diagnostic features for identifying melt-origin pseudotachylyte. This list is not exhaustive, but includes most features that provide direct evidence for a rock having been through a melt phase. Many features will persist with mild to moderate overprinting, and if they are identified with confidence, may define the fault rock as a reworked pseudotachylyte. B: Characteristics of pseudotachylyte that are similar to other fine-grained fault rocks, so cannot be used to conclusively identify a melt-origin pseudotachylyte even when fresh. However, recognition of these features, especially when combined with identification of characteristics in Table 1A, may strengthen the case for identifying a relict pseudotachylyte.

1A. Diagnostic of melt-origin pseudotachylyte

Confidence in seismic origin		**Certain**	**Probable**		**Possible but inconclusive**	
Primary feature	*Process it records*	*Primary identifying characteristics*	*Potential identifying features after moderate recrystallization*	*Potential identifying features after moderate deformation*	*After significant recrystallization*	*After significant deformation*
Quenched margins	Extreme thermal gradient between melt and host rock	Fining of crystallites toward vein margins, may approach cryptocrystalline or glassy. In outcrop margins appear darker (Fig. 4A,B), and may be dark or opaque in thin section.	Grain size gradient may be conserved in alteration assemblage. Differential alteration reflecting either grain size-related susceptibility to alteration, or concentration of water toward center as a quenching artifact. (Figs. 2A and 3B).	Fragments containing cryptocrystalline-microcrystallite margin, glassy or cryptocrystalline fragments. Limited plastic creep parallel to fault vein may conserve grain size gradients.	Equilibration of grain size across vein tends to wipe out primary texture.	If grain size is reduced below the width of the quenched margin, it will no longer be preserved in fragments. Grain growth during crystal plastic deformation destroys grain size variation but dislocation density may be anomalously low in crystals grown post-deformation.
Euhedral microcrystallite grains	Isotropic stress in fluid melt during crystallization	Euhedral habits, zonation (e.g. oscillatory or irregular), tendency for forms associated with volcanic rocks (e.g. sanidine). Microcrystallites may be distributed in amorphous or cryptocrystalline groundmass.	Euhedral crystals may survive while matrix is recrystallized or overprinted. Pseudomorphism is possible if microcrystallite phase is unstable at ambient conditions.	Diagnostic textures may persist if fragmented grains are sufficiently large. Large microcrystallites may persist as porphyroclasts after plastic overprinting. Matrix may develop CPO but porphyroclasts show little evidence of shear strain.	Matrix completely recrystallized to new equilibrium assemblage.	If grain size is reduced below the characteristic size of microcrystallites, primary habits will no longer be identifiable in fragments. Porphyroclast rotation, growth or destruction obliterate primary habits.
Sulfide/oxide droplets dispersed in matrix	Immiscibility in silicate melt	Sulfides/oxides tend toward sub-spherical or acicular forms with radial or random orientations.	Sulfides/oxides often survive metamorphism and may retain their original forms and spacing.	Probably not diagnostic after deformation.	New assemblage in vein matrix may be consistent with oxides/sulphides so melt phase unclear.	Dispersed sulfides/oxides in (porphyro) clasts or matrix are not diagnostic if other textures are lost.
Anomalously high temperature minerals	Peak temperatures greatly in excess of ambient wall rock temperature	Typical high-temperature phases include mullite, Ca-rich plagioclase, sanidine. Partially melted quartz or feldspar survivor clasts require high *T* (Fig. 3E)	Persistence, or pseudomorphism by lower temperature phases of the high-temperature phase. Possible identification from its lower-grade breakdown products.	Anomalous high temperature phases in a cataclastic or mylonitic assemblage (compared to host rock thermal history).	Equilibration of vein material to wall rock equilibrium conditions erases high *T* record.	Small clasts are unlikely to contain (identifiable) high *T* phases. Crystal plastic deformation facilitates metamorphic re-equillibration.

(*continued on next page*)

Table 1 (*continued*)

1A. Diagnostic of melt-origin pseudotachylyte

Confidence in seismic origin		**Certain**	**Probable**		**Possible but inconclusive**	
Primary feature	*Process it records*	*Primary identifying characteristics*	*Potential identifying features after moderate recrystallization*	*Potential identifying features after moderate deformation*	*After significant recrystallization*	*After significant deformation*
Microcrystallites with dendritic habit or spherulites	Extreme thermal gradient during cooling and/or fast cooling rates	Dendritic shapes of primary silicate crystals, radial arrangement of crystals grown onto clasts or wall rock, spinifex texture (Fig. 1C,D)	Survivor clasts rims of different composition than matrix may persist after recrystallization. (Fig. 2C).	Fragments may contain habits indicative of earlier quenching from melt. Compositional variation at porphyroclast rims after limited crystal-plastic deformation.	Matrix completely recrystallized, destroying diagnostic crystal shapes.	If grain size reduced to the scale of relevant grains, diagnostic patterns no longer detectable.
Vesicles or amygdules	Exolution of a vapor phase from the silicate melt	Smooth rounded cavities with or without crystals growing in from the walls. Zeolites and calcite are common amygdule filling minerals.	If zeolite-filling minerals are otherwise not present in the rock, may still be identifiable after recrystallization.	Unlikely because geometry is the primary criterion for identification	If minerals are intergrown destroying the bubble geometry, not identifiable.	Not preserved.
Embayed edges, partial melting of clasts	Peak temperatures high enough to induce some melting even in refractory phases.	Edges of survivor grains are optically "fuzzy" or isotropic due to partial melt diffusive mixing with the surrounding matrix. Grains are embayed with scalloped edges and intragranular cracks may be filled with melt.	Clast shape and edges may be maintained as refractory clasts tend to be immune to recrystallization. Overgrowths of recrystallized matrix may obscure edges of clasts, but melt-filled cracks within clasts preserved.	Comminution results in clasts with some fracture edges and some partially melted edges, interior intrusions remain. After plastic creep, porphyroclast habits maintain melted margins. Survivor grains may have weakly developed tails compared to porphyroblasts in surrounding mylonites (Fig. 5E).	Survivor clast edges completely overgrown, interior intrusions are recrystallized and show no evidence for melting.	Any cataclastic or plastic modification of grain margins would destroy evidence of survivor grain morphology.
Spaced survivor clasts - no/weak size or shape sorting	Mixing, dispersal in near-hydrostatic melt; flow was laminar or locally turbulent	Smooth grains approaching ellipsoidal to embayed shapes, weak or no alignment of clast long axes. Clasts are spaced somewhat evenly in matrix, clast–clast contacts very rare.	Increased tortuosity by overgrowths may obscure rounded edges.	Clast spacing and composition maintained even during matrix deformation. Survivor grains may have weakly developed tails compared to porphyroblasts in surrounding mylonites. (Fig. 5).	Coarsening of the matrix and overgrowth/grain shape changes of survivor clasts destroy texture	With sufficient strain, clast tails will grow to resemble those in surrounding mylonites

1B. Features common to melt-origin pseudotachylyte and other fine grained fault rocks

Confidence in seismic origin		**Possible**	**Possible**		**Inconclusive**	
Primary feature	*Process it records*	*Primary identifying characteristics*	*Potential identifying features after moderate recrystallization*	*Potential identifying features after moderate deformation*	*After significant recrystallization*	*After significant deformation*
Exposure-scale injection vein-fault vein geometry and intrusive contacts	Effectively fluid-like and pressurized fault rock (at least transiently)	Fault vein may be thinner than injections, which follow existing cracks in rock or form at high angles to fault. Often show flow banding continuity from fault vein into injection	Geometry persists after grain-scale recrystallization or metamorphism (Fig. 5A,F)	Brittle or ductile shear preferentially affects fault veins, so isolated beheaded injection veins may be preserved, even if moderately deformed (Fig. 5G–H)	May be destroyed by metamorphism of vein and wall rock	Deformation of the wall rock by cataclasis or plastic creep destroys characteristic geometry. Injection veins become isolated from source fault vein making original geometry difficult to identify.
Flow banding and mixing textures in matrix	Incomplete mixing of melt from heterogenous wall rock	Compositionally distinct layers in vein matrix (possibly with varying survivor clast content), folding of layers, flow bands from fault veins into injection veins, swirls around clasts.	Compositional banding preserved while grain size < flow band thickness. Variation in survivor clast content remains.	Fracturing may leave clasts containing flow banding. Fault-parallel banding may persist in mylonites, tortuous shapes, swirls and folds and banding orientations are distorted by shear but may differentiate melt flow bands from mylonitic foliation.	When grain size exceeds flow band width, flow bands in any geometry are obscured.	Cataclasis may destroy continuous bands or plastic creep rapidly transforms them to typical mylonite foliation
Refractory survivor clast assemblage	Preferrential destruction (by melting or crushing) of mafic and hydrous phases	Survivor clast population or coarse fraction dominated by quartz (strong, high flash melting point and no cleavage) and feldspars (strong, moderately high flash melting point and weak cleavage). Shape and size distribution may indicate melting.	Recrystallization of fine grained matrix may not affect less susceptible survivor clasts. Primary size distribution is maintained (Fig. 7).	Large fragments in a breccia may contain original survivor clast assemblage. Survivor clasts may resemble porphyroclasts with less-developed tails relative to surrounding mylonites and may have different size distribution.	Recrystallization may result in overgrowths/ replacement obscuring clast–matrix relationships	Survivor grains may become indistinguishable porphyroclasts in further plastic deformation. Cataclasis destroys diagnostic shapes and size distribution.
Fault rock bulk chemistry enriched in mafic/hydrous minerals relative to host rock	Differentiation of fault rock composition as a result of melting, comminution or flow of fault rock	Pseudotachylytes sometimes show compositional banding derived from different mineral sources in wall rock. Major and trace elements show enrichment in less refractory mineral components (e.g. phyllosilicates)	Compositional differentiation and even compositional banding often preserved.	Chemical differentiation from wall rock may persist, but progressive change in fault rock microstructure (and composition) due to deformation will inhibit interpretation.	As gouge/mylonite with finer grain size than wall rock may also be compositionally differentiated, origins may be inconclusive	Eventual mechanical mixing or diffusion during deformation may destroy discrete vein composition

optical and scanning-electron microscope observations are considered essential to providing evidence for a fault rock having passed through a melt phase (Magloughlin and Spray, 1992). Amorphous materials observed in deformation experiments and in some faults (Janssen et al., 2010, 2013; Viti, 2011, Pec et al., 2012) share some of the characteristics of melt-origin pseudotachylytes. We therefore begin with those criteria that are diagnostic of a melt phase, which differentiate melt-origin pseudotachylytes from other brittle fault rocks.

Textures indicative of rapid cooling in response to an extreme thermal gradient between a high temperature melt and cooler host rock are most useful for recognizing solidified melts. They include quenched margins defined by cryptocrystalline or glassy (isotropic) material at the edges of veins in thin section. The dark groundmass of the matrix of most pseudotachylyte veins is composed of microcrystallites, tens to hundreds of μm long, which may be aligned within flow bands, randomly oriented, or arranged radially around survivor clasts as spherulites (Fig. 1C). Symmetric layers of microcrystallites around a central layer of spherulites may also form in response to rapid quenching (e.g. Di Toro and Pennacchioni, 2004). Microcrystallites have a variety of habits, depending on crystal chemistry, volatile content of the melt, melt cooling rate, and crystal growth rates and available nucleation sites. Habits diagnostic of quenching from a melt include lath-shaped (e.g. Fig. 1D), prismatic and dendritic, and at higher grades, spinifex textures (e.g. Andersen et al., 2008). Sulfide droplets occur because the sulfide melt may be immiscible in silicate melt. Some pseudotachylyte veins contain euhedral micro-crystals of phases that quench from a melt and display oscillatory or irregular zoning. These euhedral crystals often form assemblages at equilibrium temperatures greater than the wall rock experienced, demonstrating that the vein temperature exceeded that of adjacent wall rock. Clasts that survived melting sometimes display partial melting textures, with isotropic or gradational rims, embayed margins and incipient melt veins within the clasts. In all cases, these features are interpreted as products of non-equilibrium crystallization under conditions of rapid heating and cooling.

Many characteristics of melt-origin pseudotachylytes are common to other fault rocks and therefore are not uniquely diagnostic of a quenched melt (Table 1B; Magloughlin and Spray, 1992). Features that indicate flow may also form when fine-grained fault rock is fluidized, is subject to thermal pressurization, or becomes amorphous. Compositional segregation may occur during melting because of the different melting temperatures of different mineral phases in a rock, but may also result from extreme comminution, or crushing, where softer materials tend to amorphize more readily. The following identification criteria are consistent with frictional melting, but are also common to other deformation processes.

In exposure, melt-origin pseudotachylytes frequently form fault veins (sub-parallel) to the overall fault orientation, from which cm to 10's cm scale injection veins branch at angles of 70° or more (Fig. 1A, *c.f.* Sibson, 1975; Di Toro et al., 2005; Rowe et al., 2012b). Although this fault vein-injection vein geometry is commonly observed, various other geometries also occur. Pseudotachylyte lenses, breccias and irregularly shaped pockets that host substantial volumes of melt are developed at exposure scales (Sibson, 1975) and are also ubiquitous at mm–cm scale in thin section. Irregularly shaped bodies of melt containing angular to sub-rounded fragments of wall rock are frequently developed at the intersection of the main slip surface and subsidiary faults, as well as within fault veins (Fig. 1B). These breccias may be the most distinctive exposure-scale feature of pseudotachylyte as the more planar fault vein and injection vein geometries are also found in cataclasites (Rowe et al., 2012b). These geometrical characteristics are developed primarily from examples of pseudotachylytes formed in crystalline rocks, and may not be representative of frictional melts in all lithologies. For example, where melting occurs in low-grade metasedimentary rocks, the exposure-scale geometry of pseudotachylyte veins is more variable and may include features such as flame structures and mesh-like networks of fault veins and injection veins with a wide range of orientations (Rowe et al., 2005; Brodsky et al., 2009; Bjørnerud, 2010).

In any host rock type, fault and injection veins of melt-origin pseudotachylyte commonly have sharp edges, can display concentric color banding indicative of quenched margins, and form intrusive contacts with the surrounding rock. The vein material is typically composed of a brown or black, aphanitic matrix that contains rounded clasts of predominantly quartz and feldspars, which are the more refractory species from the host rock. Veins that are not weathered may have a glassy luster and form conchoidal fracture surfaces.

Glass, or amorphous material lacking long range order at the molecular scale, is occasionally reported in pseudotachylyte veins (e.g. Philpotts, 1964; Lin, 1994; Obata and Shun-Ichiro, 1995), but as mentioned previously may also form by other mechanisms than melting. Microscopic flow banding, defined by differences in the matrix composition or aligned microcrystallites, often forms folds and fluid-mixing textures (examples shown below). Vesicles, amygdules or bubble collapse structures (Magloughlin, 2011) may be present in some pseudotachylyte veins. Survivor clasts tend to be rounded in pseudotachylytes compared to cataclastic rocks without melting (Lin, 1999) and clast-size distributions show some differences between survivor clasts and precursory cataclasites (Ray, 2004). However both of these characteristics may be similar for amorphous materials, though further work is required to confirm this possibility. Some observations show that liquid pseudotachylyte melt may be incorporated into adjacent gouge layers deforming by cataclastic flow synchronously with melting (Otsuki et al., 2003; Rowe et al., 2005), resulting in wisps or blobs of solidified melt that include clasts and may have tortuous boundaries. Compositional differentiation due to frictional melting depends on the flash-melting temperature of host rock constituent minerals, which is not the same as the equilibrium melting temperature (Spray, 2010). Minerals with lower flash melting temperatures (often hydrous or mafic phases) are preferentially melted, resulting in a survivor clast assemblage biased toward quartz and feldspars and a melt phase relatively enriched in hydrous phases and depleted in silica (Shand, 1916; Philpotts, 1964; Maddock, 1992; Magloughlin, 1992; O'Hara, 1992; Camacho et al., 1995; Hetzel et al., 1996).

3. Veins formerly known as pseudotachylyte

Pseudotachylytes are more vulnerable to deformation, alteration and overprinting than the surrounding rock because of the presence of metastable glass or extremely fine grain size that result from rapid quenching from a melt phase. Any amorphous material in a fault, regardless of the formation mechanism, will be similarly susceptible to change. The very fine grain size may make pseudotachylytes weaker than surrounding wall rock and favor localization of ductile flow along pseudotachylyte surfaces. Complex geometries are often seen in pseudotachylyte veins, so any subsequent deformation will fracture and rework pseudotachylyte material. In addition, pseudotachylyte vein boundaries present mechanical contrasts that may slip during reactivation. Faults are conduits for fluids, which promote the alteration of chemically unstable pseudotachylytes. Below, we define, describe and present examples of processes affecting pseudotachylytes that may cause some subset of the primary geometric features and/or grain scale characteristics to become unrecognizable, while other attributes are conserved. We use these observations to define characteristics that are likely to be conserved and that can be used to identify overprinted or reworked pseudotachylytes (Table 1).

3.1. Static recrystallization

Static recrystallization is the replacement of primary minerals or glass with a different crystal configuration, while retaining the same bulk composition of the vein (isochemical). This process could entail the same mineral phase growing to a new shape, or new phases growing at the expense of the initial assemblage. Pseudotachylytes are particularly susceptible to recrystallization because they tend to have finer grain sizes than the host rock resulting in faster reaction kinetics due to the extreme surface area:volume ratio. Any glass formed by quenching is thermodynamically metastable, and psuedotachylytes may also have greater water contents than the host rock. Additionally, coseismic melting may result in spatially variable composition due to incomplete mixing (e.g. Cosca et al., 2005), so chemical gradients may be inherently built into pseudotachylytes. All of these factors facilitate diffusion and recrystallization. Similar to metamorphic environments, static recrystallization may be interpreted from isotropic fabrics, general trends toward increasing grain size and minimization of grain boundary lengths (Passchier and Trouw, 2005).

Examples of isochemical pseudotachylyte recrystallization are reported from rocks that underwent seismic failure at high ambient temperatures. Lund and Austrheim (2003) show garnet, plagioclase and sodic clinopyroxene growing from fine grained, possibly glassy primary matrix in pseudotachylytes that cross-cut mafic eclogites. The veins have the same mineralogy as the wall rock, so the pseudotachylyte recrystallization occurred under the same *P*–*T* conditions and resulted in an equilibrium assemblage by static recrystallization. This behavior is distinguished from the formation of higher-temperature phases (e.g. mullite or Ca-plagioclase; Otsuki et al., 2003), which form directly from liquid melt at temperatures significantly above the ambient rock temperature and provide evidence for transient high temperatures in the melt. Moecher and Steltenpohl (2009) documented static replacement of pseudotachylyte formed at granulite facies by garnet + clinopyroxene + plagioclase + quartz. The same assemblage resulted from dynamic recrystallization in adjacent mylonites, showing that recrystallization was in equilibrium with local P/T conditions irrespective of the strain rate. Similarly, spherulitic omphacite overgrown by poikilitic garnet was documented by John and Schenk (2006) in eclogite-facies pseudotachylytes from Zambia, showing that this phenomenon is consistent across a variety of P/T conditions.

We know of no reported examples of pseudotachylyte veins identified after overprinting by pro-grade metamorphism. As mentioned above, pseudotachylytes formed at peak grade are observed (e.g. Moecher and Steltenpohl, 2009), but it is very likely that any veins would be unrecognizable after prograde metamorphism because both wall rock and pseudotachylyte veins will recrystallize and minerals would grow across vein boundaries obscuring textures and contacts. Conversely, on a retrograde path, the relative chemical instability of pseudotachylytes results in preferential recrystallization of the veins.

Hydrous mineral assemblages in recrystallized pseudotachylytes may or may not reflect primary water contents of the melt. Magloughlin (1992) demonstrated that in some cases, pseudotachylyte forms from parent cataclasite. This cataclasite may already be compositionally evolved with respect to the host rock, due to mechanical sorting of minerals and preferential hydrothermal mineralization and alteration of the granular rock. Similar relationships were reported by Magloughlin (1989) and Di Toro and Pennacchioni (2005) in pseudotachylytes cutting tonalite and schist. If the primary pseudotachylyte solid is volatile rich, as commonly occurs due to preferential melting of hydrous minerals, then static recrystallization may result in the growth of phyllosilicates from the glass without need for external sources of water. Where precursor cataclasites were melted, it may not be possible to differentiate the exact contributions of primary hydration of the melt phase from later hydration and alteration. Therefore, a continuum of processes and textures exists with the hydration described in the next section.

3.2. Hydration and alteration

Primary pseudotachylyte glass or microlitic textures are easily recrystallized in the presence of water. In some cases, the water may be readily available in the glass, quenched from a hydrous melt, as described above, while in others, external water is incorporated. In both cases, recrystallization textures statically overprint primary microstructure. New minerals partially or completely obscure the original microstructures. Hydration is distinct from isochemical recrystallization when the bulk vein composition changes. Cation exchange between solid and fluid phases causes alteration. In igneous or metasedimentary lithologies and at typical shallow to mid-crustal conditions, the most commonly observed hydration minerals are chlorite, illite/smectite, and epidote. Other alteration phases may depend on the bulk chemistry of the pseudotachylyte, the fluid chemistry and metamorphic grade (e.g. white mica; Moecher and Brearley, 2004).

Under conditions where phyllosilicate growth is favored and water is available, primary glass may incorporate water during devitrification to crystallize hydrous minerals. Fig. 2A shows a thick hydrated pseudotachylyte vein in granodiorite, forming perlitic texture in the center of the vein. Hydration along spheroidal fractures forms similar perlitic weathering textures in natural volcanic glass. Friedman et al. (1966) showed that in rhyolitic glasses with 2–3 wt.% water, concentric cracks and hydrated rims defining spheroidal perlite would form in about 250 years at 100 °C. A similar devitrification process is likely in hydrous pseudotachylyte in the shallow crust.

Most unambiguous pseudotachylytes reported in the literature have experienced some alteration or recrystallization of the primary matrix. Pristine samples of pseudotachylytes from faults in Kings Canyon National Park, California, contain a groundmass of interlocking microcrystallites with cryptocrystalline or amorphous (no crystallites visible in SEM at ~500 nm scale) material in the spaces between (Fig. 1D). When altered, the interstitial material and any areas that may have been glassy, are replaced by epidote and chlorite (Fig. 2B–D). Relative to the bulk chemistry, the alteration assemblage is depleted in potassium, suggesting interaction with a hydrothermal fluid, consistent with wall-rock alteration associated with faulting (Kirkpatrick et al., 2012). Euhedral epidote overgrowths, typically tens of μm long, preferentially nucleate on spherulitic fringes around survivor clasts and grow into the interstitial material (Fig. 2C). Spherulites and individual microcrystallites in the same samples remain unaltered, indicating that the cryptocrystalline or amorphous matrix material is much more susceptible to chemical changes. However, when alteration is further advanced, chlorite and epidote may overgrow the entire groundmass of microcrystallites and interstitial material obscuring the primary texture (Fig. 2D).

Meneghini et al. (2010) show chlorite-illite growth during hydration/devitrification of the matrix of subduction-thrust pseudotachylytes from Kodiak Island, Alaska. The chlorite and illite form random fabric mats between ~1 μm plagioclase phenocrysts, so grew from glass or crystallites much smaller than 1 μm, which

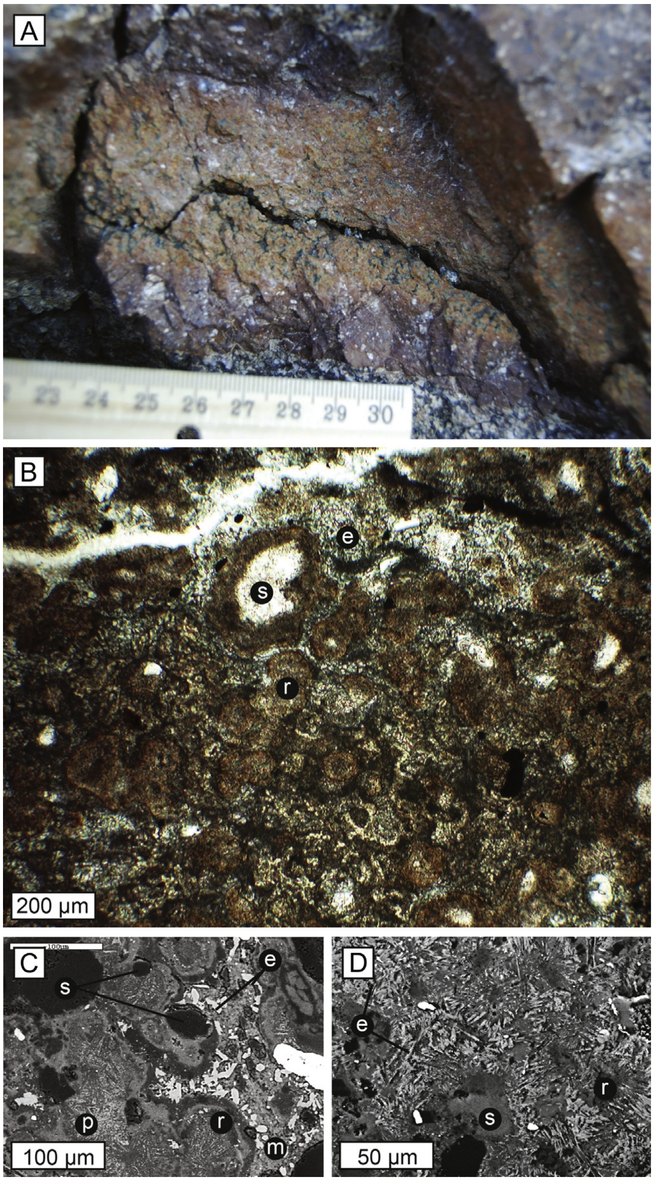

Fig. 2. Examples of hydration reactions in pseudotachylytes. A: Perlitic hydration texture in a thick, formerly glassy pseudotachylyte vein from tonalites near La Quinta, California. B–D: Epidote overgrowing primary pseudotachylyte microstructures from faults in granodiorite in Kings Canyon, California (as determined by SEM-EDS). B: Plane-polarized light image of primary radiating spherulitic microcrystallites (r) in pseudotachylyte. Some nucleated on survivor clasts (s) prior to progressive epidote overgrowth (e). C: Backscatter SEM image of same texture shown in (B), showing primary microcrystallitic texture of pseudotachylyte (p); similar to Fig. 1D with radial structure (r) with on left side of image. Thirty-micron epidote crystals (e) overgrowing amorphous or cryptocrystalline interstitial material (m) on right side of image. D: Backscatter SEM image of pseudotachylyte with more extensive epidote overgrowth (e) that completely obscures primary matrix but only partially obscures the radial structures (r). Lath-shaped primary microcrystallite texture can still be discerned where epidote has overgrown parallel edges of original microcrystallites (compare to Fig. 1D).

formed the primary matrix. These pseudotachylytes showed a slight enrichment in Na_2O and Sr and corresponding depletion in K_2O relative to the associated coeval microcataclasites, with no systematic changes in other measured elemental concentrations. This pattern has been produced experimentally in volcanic glasses by devitrification in the presence of an Na-rich aqueous fluid (Lofgren, 1970). Na_2O enrichment was also tied to alteration in mafic pseudotachylytes of the Alps (Techmer et al., 1992). Similar replacement of fine matrix with illite and carbonate has been reported from pseudotachylytes in the Anatolian Fault (Uysal et al., 2006) and illite/smectite/kaolinite in the Chelungpu Fault (Otsuki et al., 2005).

Pseudotachylyte formation and alteration are often broadly coeval, with mutually crosscutting relationships (Otsuki et al., 2003; Di Toro and Pennacchioni, 2005). Occurring in mid- to shallow-crustal faults, pseudotachylytes are commonly found in zones of hydrothermal alteration (Takagi et al., 2000; Otsuki et al., 2003; Di Toro and Pennacchioni, 2005; Mittempergher et al., 2009; Chu et al., 2012; Kirkpatrick et al., 2012). The pseudotachylytes of the Asbestos Mountain fault zone are all mildly to completely altered to chlorite and epidote (Rowe et al., 2012b) but the alteration is less complete than in the associated host rock, implying that the pseudotachylyte post-dates some of the alteration (Wenk et al., 2000). Kuo et al. (2009) showed that the pseudotachylytes in the Chelungpu Fault were formed by melting of an assortment of clay minerals, then rapidly altered to smectite. Alteration of primary smectite-composition pseudotachylyte to smectite has also recently been documented in the Nojima Fault (Janssen et al., 2013).

Different generations of pseudotachylyte in the same rock may have different susceptibility to alteration. In the pseudotachylytes of the Asbestos Mountain Fault, altered tonalite is cut by altered and epidote-cemented cataclasites, cut in turn by multiple generations of pseudotachylyte (Fig. 3). Folded flow banding within a single generation of pseudotachylyte (p_2, Fig. 3A) shows variable epidote content. The epidote concentration in particular flow bands may indicate greater water content in those bands at the time of quenching (Fig. 3B). The epidote-cemented cataclasite (Fig. 3C) is a probable source material for the pseudotachylyte melt. The fact that the older generation of pseudotachylyte (p_1, Fig. 3A,D) contains less epidote overgrowth than the younger (p_2) suggests that local variations in composition, not just age/exposure, play an important role in determining the degree of alteration.

In summary, the fine grain size, tendency toward elevated water content, likelihood of exposure to fluid flow through faults, and potential for microcrystallites that are out of metamorphic equilibrium all contribute to a tendency for pristine pseudotachylyte to be replaced with secondary minerals. As noted by Magloughlin and Spray (1992), Lin (1994) and others, this tendency may explain why so few studied pseudotachylytes contain primary glass, and this alteration may cause pseudotachylytes to remain unidentified in the rock record.

3.3. *Cataclastic reworking*

Pseudotachylytes can be fragmented and deformed by cataclasis, resulting in fragments of pseudotachylyte veins becoming distributed throughout a diverse fault rock assemblage. Rock deformation experiments show that failure tends to localize both at the edge of, and within, fault veins when they are optimally oriented with respect to the applied stress (Mitchell et al., 2010; Rabinowitz et al., 2011).

Pseudotachylyte veins that occur off the main fault in distributed sets of fault veins or in injection veins are locally cross-cut by shear fractures in damage zone of the Asbestos Mountain Fault (e.g. Fig. 4A; Rowe et al., 2012b). The damage zone shear fractures typically have relatively small offsets so that the separated parts of the pseudotachylyte are identifiable, and the original geometry and connectivity with nearby fault veins reconstructable. Multiple generations of pseudotachylytes are present in the fault and some fault veins are cross-cut by both later fault veins and also injection veins (Fig. 4B). Later deformation localized at the contact between fault veins and adjacent wall rock or gouge, and in some cases reoccupied an early-formed fault vein. In each of these scenarios,

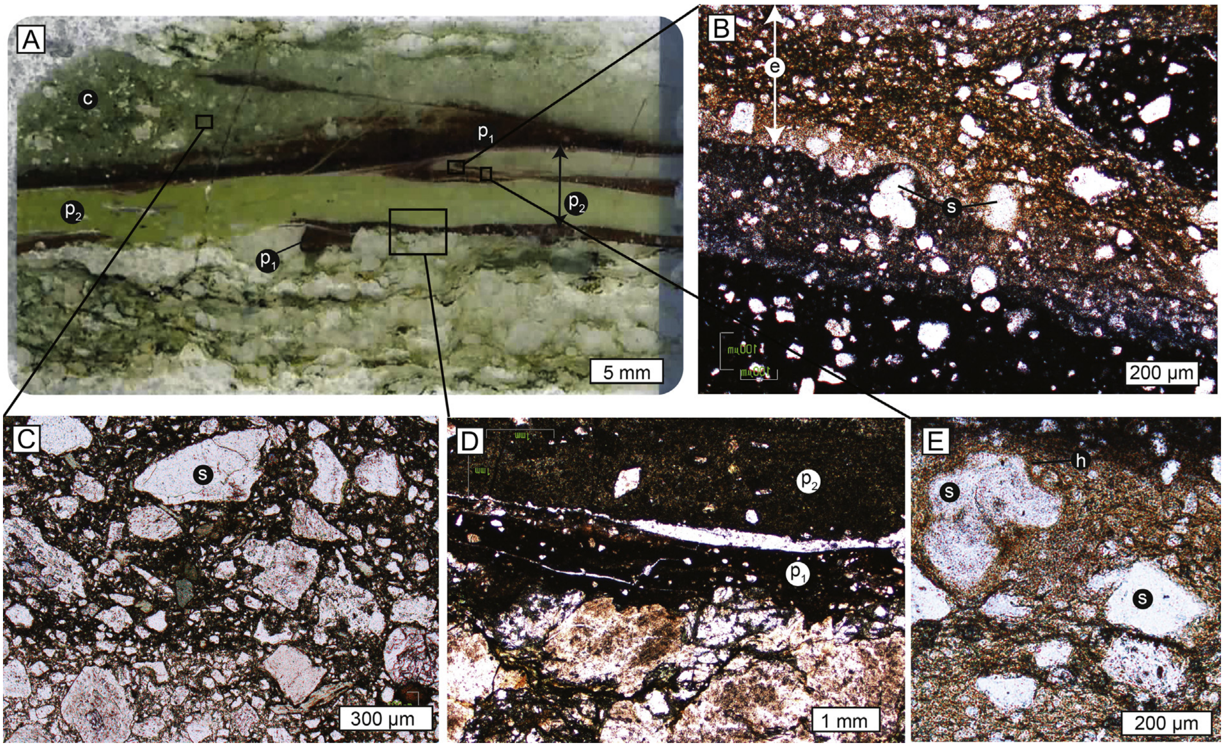

Fig. 3. Epidote alteration of a fault vein from the Asbestos Mountain fault zone, California, with cataclasite and multiple generations of pseudotachylyte. A: Thin section showing fault vein with epidote-cemented cataclasite (c) crosscut by two generations of pseudotachylyte. The older (p_1) is brown and is crosscut by the younger (p_2) which shows folded flow bands of green and brown pseudotachylyte. B: Plane-polarized light image of the detail of green/brown flow bands in pseudotachylyte. Green bands have small epidote crystals in groundmass (e) while brown bands do not. C: Detail of epidote-cemented cataclasite. Few-micron green epidote crystals fill pore space and overgrow on survivor clasts (s). Clast size distribution and roundness is distinct from pseudotachylytes (compare to B). D: Detail of contact between older (unaltered) and younger (epidote-altered) pseudotachylyte. Edge of older pseudotachylyte (P_1) against wall rock in lower half of photo is serrated by selective melting of altered tonalite. Faint flow banding is visible in matrix of brown pseudotachylyte. Younger pseudotachylyte (p_2) shows patchy appearance in plane-polarized light due to green epidote crystals. E: Survivor clasts are locally partially melted (s) as shown by diffuse clast boundaries, halos of melt around clast rims of different composition (h) and embayed clast edges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

melting may or may not have occurred, but the early fault vein is reoccupied and deformed. Injection veins branching from an early fault vein remain in the wall rock adjacent to a fault slip zone that cross-cuts them (Fabbri et al., 2000; Kisters et al., 2002).

Fragmented pseudotachylyte veins may become incorporated into gouge or cataclasite with continued deformation (Fig. 4B). In the Pasagshak Point thrust, Alaska, pseudotachylyte-bearing black fault rocks are recycled into very thick cataclasites (Fig. 4C). The fragmented fault veins occur as clasts that are rounded, abraded, and mixed with lithic fragments from the wall rock. Examination of the microstructures within an individual clast reveal its seismic origin, but the wider zone of cataclasite records a subsequent deformation event (Rowe et al., 2011). Other examples of clasts of pseudotachylyte within gouge or cataclasites are reported from a variety of settings (e.g. Macaudière and Brown, 1982; Magloughlin and Spray, 1992; Otsuki et al., 2003; Lin et al., 2005; Kirkpatrick and Shipton, 2009; Bjørnerud, 2010; Mambane et al., 2011). These examples show clasts of pseudotachylyte occur within gouge layers alongside intact pseudotachylyte veins (e.g. Fig. 4B), and as isolated fragments in cataclasites where no continuous pseudotachylyte fault veins are preserved nearby. Pseudotachylyte clasts in gouge are typically rounded, and are mixed with fragments of wall rock minerals, older cataclasites, altered wall rock and hydrothermal phases. They are typically green, grey, dark brown or black, aphanitic and contain isolated survivor clasts. Susceptible to recrystallization and brittle damage, the pseudotachylyte clasts may provide little definitive evidence for a melt origin (Table 1A).

3.4. *Plastic overprinting*

The formation of mylonites by grain growth and crystal plastic flow localized in pseudotachylytes is well documented (e.g. Passchier, 1982; Hobbs et al., 1986; Takagi et al., 2000; Price et al., 2012; White, 2012). As discussed by Hobbs et al. (1986), the transitional zone (brittle-plastic or frictional–viscous transition) is thought to experience a wide spectrum of strain rates, and this spectrum corresponds to a variety of deformation mechanisms. Thus, cataclastic or brecciated rocks, frictional melting, and crystal-plastic fabrics formed at fast and slow strain rates are expected to repeatedly crosscut or overprint one another in this zone. Sibson (1975) and Lin (2008b) suggested that mylonitized pseudotachylytes form when earthquake slip propagates down-dip from the seismogenic zone into the transitional zone and are subsequently overprinted, but that pristine pseudotachylytes from within or below the transition zone are very rare. This model was contradicted by White (2012), who showed some pseudotachylytes formed by plastic instabilities at temperatures typically considered too high for seismogenesis. Cooling curves calculated by Bestmann et al. (2012) also imply that following melting, high temperatures from coseismic frictional heating may persist long enough to enable crystal plastic deformation in the surrounding rock during pseudotachylyte cooling.

Pseudotachylytes formed in the lower seismogenic to transitional zone are preferred locations for plastic flow because they have similar bulk chemistry and mineralogy to the surrounding rock, but finer grain size (Chattopadhyay et al., 2008; Ueda et al., 2008). The gradual progression of plastic creep may result in multiple generations of pseudotachylytes preserved with different degrees of crystal growth and deformation. Melting, quenching and subsequent recrystallization produces mylonite or ultramylonite of similar grain size to the surrounding shear zone rocks that never melted. Somewhere along this transition, the evidence for a frictional melting origin becomes equivocal, then undetectable, and the rock is essentially fully recycled. Price et al. (2012) thoroughly documented this transition for pseudotachylytes formed in metasediments of the Norumbega Shear Zone in southern Maine. As they show, the specific path of fabric development during crystal plastic deformation of pseudotachylytes is sensitive to bulk chemistry, mineralogy, survivor grain composition, size and distribution, and the details of the primary fabrics (e.g. glass, microlitic textures) in the pseudotachylyte.

Pseudotachylytes deformed by crystal-plastic mechanisms have consistent characteristics, including alignment of newly formed or rotated grains, often at an angle to the pseudotachylyte-wall rock boundary, preservation of compositional flow banding, rounded clasts with poorly developed or no tails as compared to surrounding mylonites, and a fine-grained, well-mixed polymineralic matrix of grains with fewer dislocation densities relative to the wall rock (Passchier, 1982; Fabbri et al., 2000; Chattopadhyay et al., 2008; Lin, 2008a; Price et al., 2012). Outcrop-scale characteristics include a color change with recrystallization and preferential mylonitization of pseudotachylytes parallel to the surrounding shear fabric, also resulting in abandonment or transposition of injection veins (Fabbri et al., 2000). If the pseudotachylytes are parallel to the mylonitic fabric, sharp contacts are conserved (Price et al., 2012; White, 2012). Some new features develop, such as ragged grain boundaries from a core rounded survivor grain (Price et al., 2012), which form when matrix crystals preferentially grow onto survivor clasts of the same mineral. Tobisch et al. (1991) tracked the geochemical evolution of deforming granitoids as they developed gneissic to mylonitic to ultramylonitic fabrics with increasing strain. In their examples from different areas, the geochemical trends were consistent with increasing deformation from primary igneous textures through to mylonites. However, there is a significant change between mylonite and ultramylonite. This change may imply that the ultramylonites formed directly from pseudotachylytes rather than from grain-size reduction of mylonites, but depending on the compositional relationship, may also demonstrate preferential alteration of finer grain sized rock. Pittarello et al. (2012) were able to demonstrate that ultramylonite was derived from pseudotachylyte at the same metamorphic conditions by showing a very close compositional match between the two fault rocks, including an identical deviation from the host rock.

The Pofadder Shear Zone (South Africa–Namibia) contains examples of altered and plastically sheared pseudotachylyte veins. In outcrop, some veins show characteristic primary pseudotachylyte geometries (e.g. fault vein-injection vein patterns, Fig. 5A), and cataclastic recycling of old veins into younger ones (Fig. 5B; compare to Figs. 1A and 4B, respectively). The fine-grained matrix of the pseudotachylyte veins is densely overgrown with epidote, but the rounded survivor clast population, without tails, is readily distinguished from the surrounding mylonitic fabric (Fig. 5C–D). Epidote has grown as ~20 μm clusters of tabular laths, which are concentrated along specific vein-parallel surfaces (Fig. 5E), but also occur sparsely along grain boundaries and cracks in feldspars in the surrounding mylonite (Fig. 5C). In injection veins (Fig. 5F), compositional flow banding is concentric to the injection walls, and epidote clusters align along this primary banding (similar to folded flow banding in Fig. 3A). With further plastic shear along the fault, the epidote-rich, fine grained pseudotachylyte veins may be

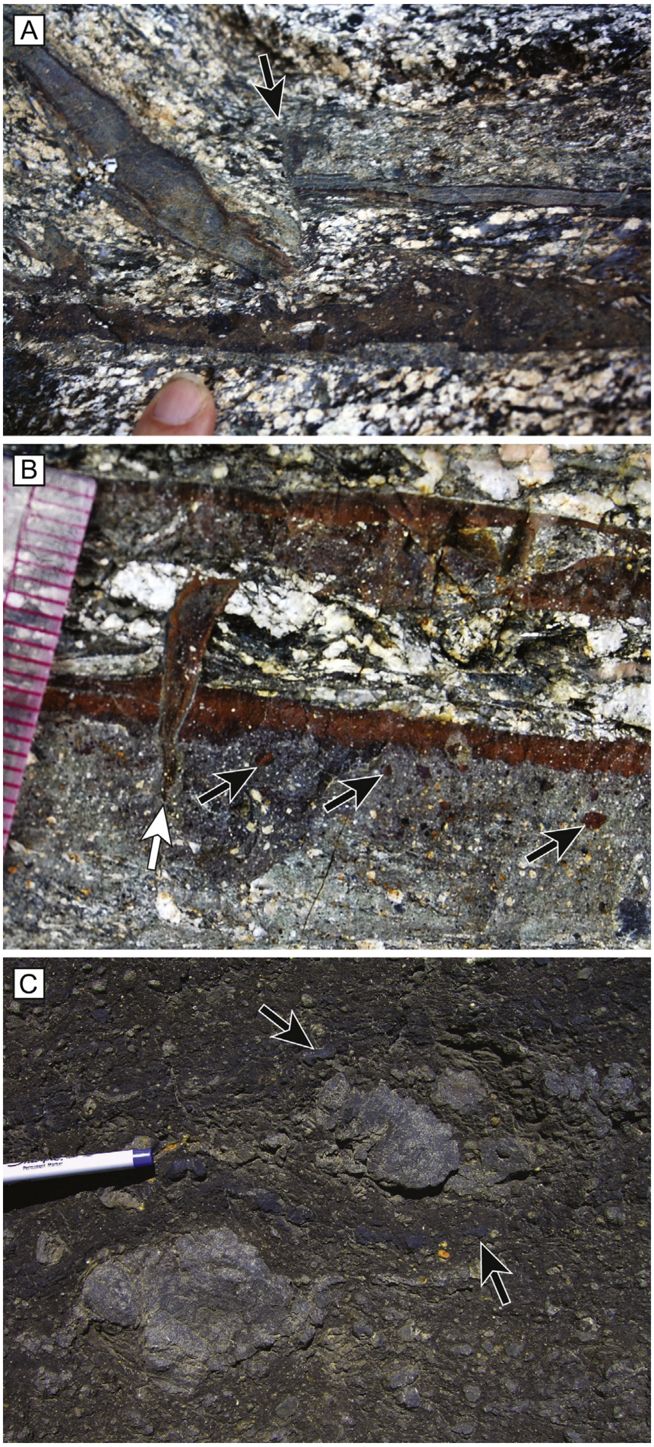

Fig. 4. Pseudotachylyte veins reworked by brittle deformation. A. Pseudotachylyte fault vein with color banded margins, possibly quenched, is cross-cut and separated across a subsidiary fault in the fault damage zone (black arrow). A later fault vein crosscuts the subsidiary fault (brown, clast-rich vein). B. An injection vein (white arrow) branching from a very narrow fault vein that cross-cut an earlier, sub-parallel fault vein (sub-horizontal in picture). Clasts of re-worked pseudotachylyte are distributed throughout the greenish grey cataclasite beneath the lower fault vein (shown by black arrows, image courtesy of Timothy J. Sherry). C. Reworked pseudotachylyte clasts in a cataclasite from the Pasagshak Point thrust, Alaska (at the end of the pen, and shown by black arrows) are mixed with sandstone fragments (mid grey) in argillitic matrix (dark gray-brown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

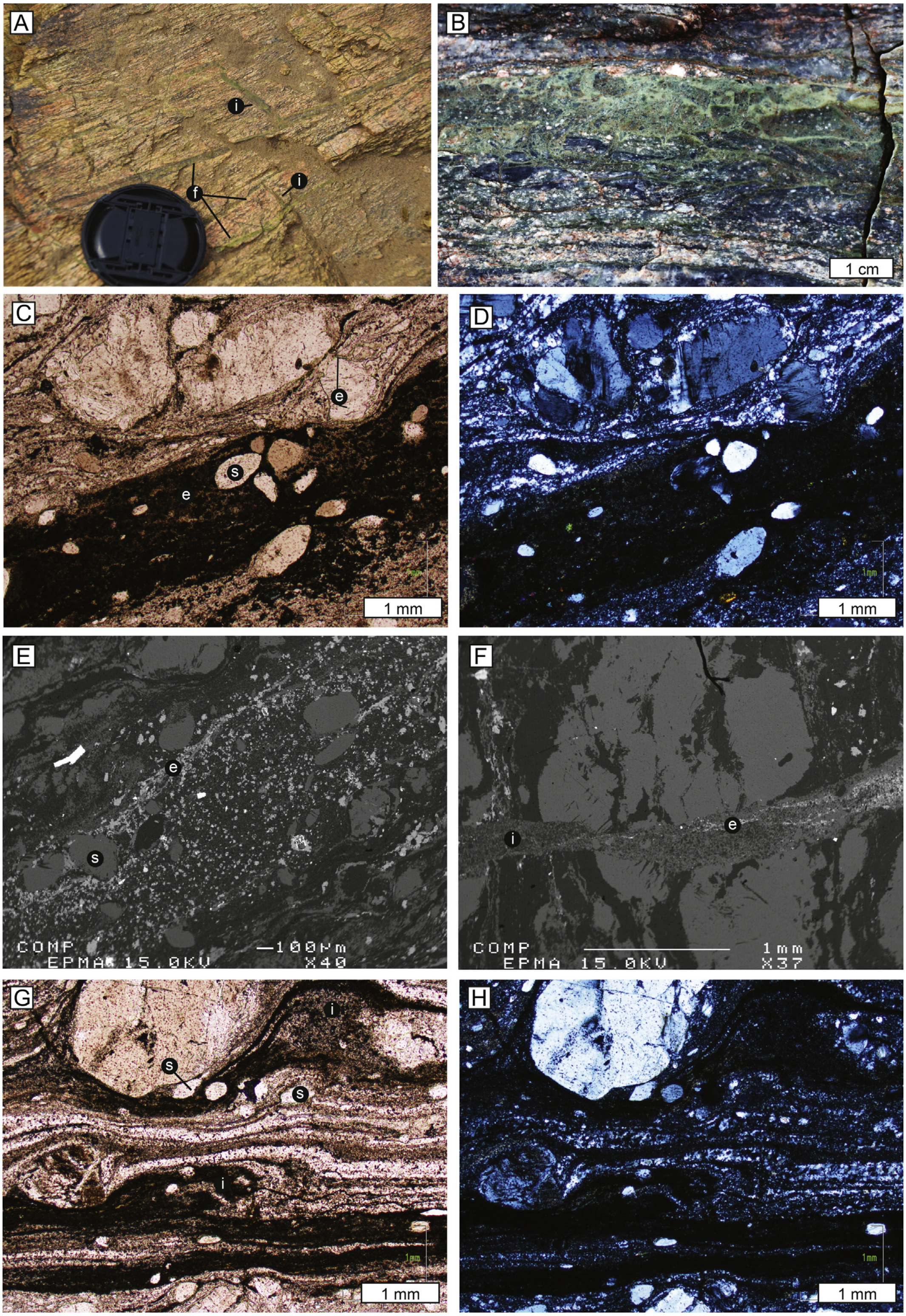

Fig. 5. Altered and mylonitized pseudotachylytes from the Pofadder shear zone, Namibia – South Africa. A–B: Outcrop appearance of the pseudotachylytes. A shows pseudotachylyte veins in pinkish granitic ultramylonite with classic fault vein (f) – injection vein (i) geometry (compare to Fig. 1A). Pseudotachylyte is now green due to epidote alteration (image courtesy of Timothy J. Sherry). B shows two generations of pseudotachylyte in a fault vein, each altered to different greenish shades by epidote growth. The older, darker green material forms clasts in the younger generation of pseudotachylyte. Plane- (C, G) and cross-polarized (D, H) light photomicrographs and backscattered electron images (E, F) of epidote altered (C–F) and subsequently mylonitized (G–H) pseudotachylyte veins. C–F: Compared to surrounding mylonite, relict pseudotachylyte veins have much finer-grained groundmass and rounded survivor clasts (s) without tails. Epidote overgrown on the fine groundmass is visible as small crystals (green in photomicrographs, bright in SEM images) concentrated in the pseudotachylyte vein highlighting primary flow bands and is also sparsely distributed in the surrounding mylonite (e). This attribute is particularly clear in F, which shows a pseudotachylyte injection vein (i, horizontal in image) crosscutting mylonite fabric (vertical in image). Epidote crystals (white, e) align along flow bands parallel to the walls of the injection. G–H: Epidote-altered pseudotachylytes after crystal plastic deformation. Epidote-rich bands are stretched out and groundmass is coarsened relative to C–D. Injection features are preserved but distorted by right-lateral shear (i). Rounded survivor grains (s) have developed weak tails. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

obscured by transposition, grain coarsening, and destruction of primary geometry (Fig. 5G–H). In the example shown in Fig. 5, right lateral shearing has deformed injection features and the rounded survivor grains are decorated with small tails. The epidote-rich, fine-grained relict pseudotachylyte veins are no longer geometrically distinguishable and with further deformation, would appear just as epidote-rich bands in the mylonite, perhaps similar to those in lower half of Fig. 5B.

4. Discussion

4.1. Vanishing veins

Our observations of melt-origin pseudotachylytes show that there are several evolutionary pathways along which they become progressively more dissimilar to a pristine vein and eventually transform into a different fault rock entirely (Fig. 6). Parameters that control the pathway(s) a pseudotachylyte vein follows include temperature, strain rate, pressure, and the availability of fluids (Table 1).

First-order changes to a pseudotachylyte vein occur by isochemical recrystallization, hydration alteration, cataclasis or plastic deformation. Isochemical recrystallization and hydration alteration occur without changes to the pristine vein geometry, so can occur without continued deformation along the host fault. Growth of new minerals in the matrix of a pseudotachylyte overprints many cooling textures, for example quenched vein margins, presence and variation of microlitic textures, microcrystallite habits, and presence of vesicles and amygdules (Magloughlin and Spray, 1992). The result is recrystallized pseudotachylyte veins, likely with a different color to pristine veins, that may have similar meso-scale vein geometries but non-pristine matrix assemblages.

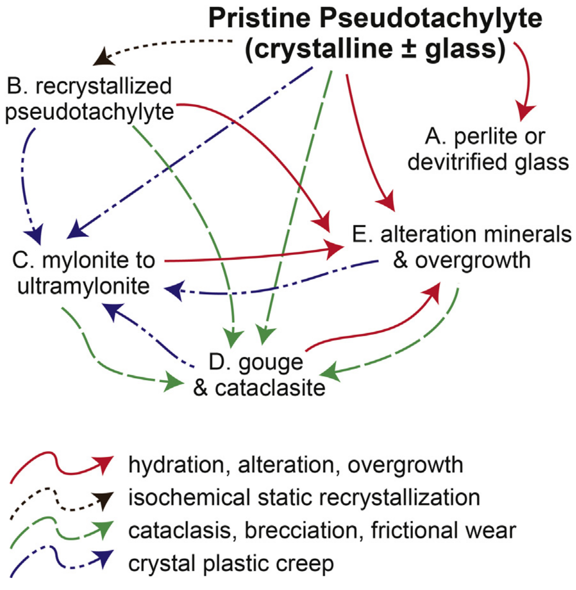

Fig. 6. Conceptual flow chart for evolutionary paths which may destroy the rock record of pseudotachylyte. Simple hydration may form a devitrified material which can still be identified as previously glassy (A). Isochemical static recrystallization may destroy diagnostic microstructures while maintaining suggestive, but not conclusive, macroscopic vein geometries (B). Crystal-plastic deformation (C) may coarsen and recrystallize primary microstructures as well as deforming primary vein geometries (see Price et al., 2012; for a full review of this process). Cataclasis of pseudotachylyte veins (D) may destroy macroscopic structures but diagnostic microstructures within pseudotachylyte clasts may still be observable. Alteration and overgrowth may maintain overall vein geometries but progressively obscure primary microstructure (E). Pseudotachylyte veins subject to multiple phases of deformation or recrystallization become progressively more difficult to identify, e.g. the Pofadder shear zone examples presented in Fig. 5 which have gone through (E) to (C).

Tectonic activity following pseudotachylyte formation may deform pristine veins by either plastic or cataclastic deformation. Plastic deformation localizes in the fine grained matrix of pseudotachylyte veins and causes grain growth, recrystallization and potentially crystallographic preferred orientations in the pristine material. Survivor clasts may also be affected in the manner of porphyroclasts, rotating and elongating in response to viscous deformation and acquiring grain tails. Cataclasis fractures pristine pseudotachylyte veins into smaller fragments, creating fault breccias or cataclasites. Initial textures and vein geometries are disrupted, but little change within vein fragments need occur.

As long as tectonic activity persists, plastic or cataclastic deformation may drive further changes to the pseudotachylyte. For example, brittle overprint of a statically recrystallized, altered or mylonitized pseudotachylyte under retrograde conditions incorporates pseudotachylytes into gouge or cataclasite. Similarly, crystal-plastic deformation of brittlely deformed or altered pseudotachylyte may occur, forming mylonite. Alteration or other metasomatic processes invariably accompanies either of these deformation paths, resulting in a fault rock that may have a vastly different composition to the initial melt phase.

The overall result of each of these pathways is a fault rock that is identified as a cataclasite or mylonite, but which *may* contain remnants of pseudotachylyte primary features. Although pseudotachylytes are susceptible to change, some delicate textures within pseudotachylyte do persist, suggesting that the processes we describe occur very slowly under certain conditions. For example, Precambrian pseudotachylytes exposed at the surface today may contain pristine textures (e.g. Philpotts, 1964; Sherlock et al., 2008). However, pseudotachylytes are generally less stable than both the host rock to the fault and other fault rocks in the same fault, so finding and identifying the indicators of a melt phase is difficult in many cases.

It follows that larger offset faults are more likely to destroy early-formed pseudotachylytes than small offset faults. Pseudotachylyte is far more likely to be preserved if the deformation ceases after it forms. This expectation is consistent with the frequently reported examples of pseudotachylytes along small offset faults inferred to be ‘single-jerk’ melt events (*sensu* Grocott, 1981; Wenk et al., 2000; Di Toro and Pennacchioni, 2005) where pseudotachylytes are not effected by later deformation. In contrast, numerous examples of clasts in gouge from mature faults might be tentatively interpreted as being derived from a melt phase. These clasts no longer retain the exposure or micro-scale characteristics of melt because they formed in a mature fault that experienced further slip. In other words, only the last-formed pseudotachylyte is likely to be pristine, no matter how many earthquakes a fault has experienced.

Progressive deformation over time also changes the physical characteristics in the fault zone changing the likelihood of melting. Wall-rock permeability and availability of water are critical factors controlling the onset of other coseismic processes such as thermal pressurization, which suppresses melting (Rice, 2006; Rempel and Rice, 2006; Bjørnerud, 2010). If the fault conditions change in such a way as to promote other processes over melting, then the deformation will inevitably overprint any earlier-formed pseudotachylytes. In this way, the potential for destruction of pseudotachylyte is inherently related to the likelihood of frictional melting. Pseudotachylytes are much more likely to be preserved in a fault if they form frequently, and conversely not at all preserved if the conditions favor other slip weakening mechanisms than melting.

4.2. Identifying relict veins

In Section 3, we presented examples of pseudotachylytes that no longer show their original, pristine form. These veins underwent deformation and/or metamorphism, yet they can be recognized as derived from a pseudotachylyte. Many of the examples are useful because they are closely associated with clear pseudotachylytes and so have not progressed very far along any evolutionary pathway (Fig. 6). However, the examples presented in Section 3 show that it is possible to recognize pseudotachylyte veins even when the definitive indicators of a quenched melt proposed by Magloughlin and Spray (1992) were overprinted.

We use our observations to develop a set of characteristics for identifying relict pseudotachylyte veins (Table 1). Because deformation and recrystallization processes progressively change a pseudotachylyte, the likelihood of identifying evidence for a melt origin decreases as a pseudotachylyte ages. To reflect this evolution-dependency, we have described the characteristics after small to moderate change and moderate to significant change and suggest that finding characteristics from these categories in fault rocks allows “probable” and “possible” recognition of a melt, and therefore seismic origin, respectively.

It would be impossible to document every conceivable texture resulting from alteration and/or deformation of a pseudotachylyte vein, so Table 1 is representative rather than comprehensive. Identifying melt-origin pseudotachylytes is possible from any pristine cooling textures, but often requires contextual observations of several or more of the other criteria to support a positive identification. We suggest that probable and possible identification are also enhanced with recognition of multiple characteristics. In particular, the matrix and survivor clasts in pseudotachylytes respond differently to deformation and alteration so comparing the matrix and clast textures may be particularly useful. For example, the size distributions of survivor clasts that are indicative of melting (Ray, 2004) may be preserved even when the pristine matrix is completely destroyed by either deformation or alteration (e.g. Fig. 7). Furthermore, with preservation of vein geometry, and secondary microstructure consistent with static recrystallization, devitrification or alteration, relict pseudotachylyte veins may be conclusively recognized (Fig. 6A,B,E). If enclaves of primary microstructure can be found, for example in clasts of pseudotachylyte incorporated in cataclasite, certain identification is also possible (Fig. 6D). Even in cases where pseudotachylytes were affected by multiple processes, the combination of some geometric characteristics and some of the microstructural features may be sufficient for conclusive identification (e.g. Fig. 5G,H).

4.3. *Consequences for interpreting the rock record*

Recognizing pseudotachylytes, even if only as “probable” or “possible” occurrences, is important for assessing the frequency of frictional melting as a coseismic process and for providing indicators of seismic slip in exhumed faults. Pseudotachylytes are readily cannibalized by ongoing deformation and/or metasomatic processes in faults and shear zones, so textures indicative of quenched melts may be relatively rare in exhumed structures. This cannibalization represents perhaps the most significant reason for pseudotachylytes being underreported, and in turn suggests that frictional melts may be produced far more often than is commonly interpreted from the rock record (e.g. Sibson and Toy, 2006). For example, Price et al. (2012) showed by careful mapping of fresh

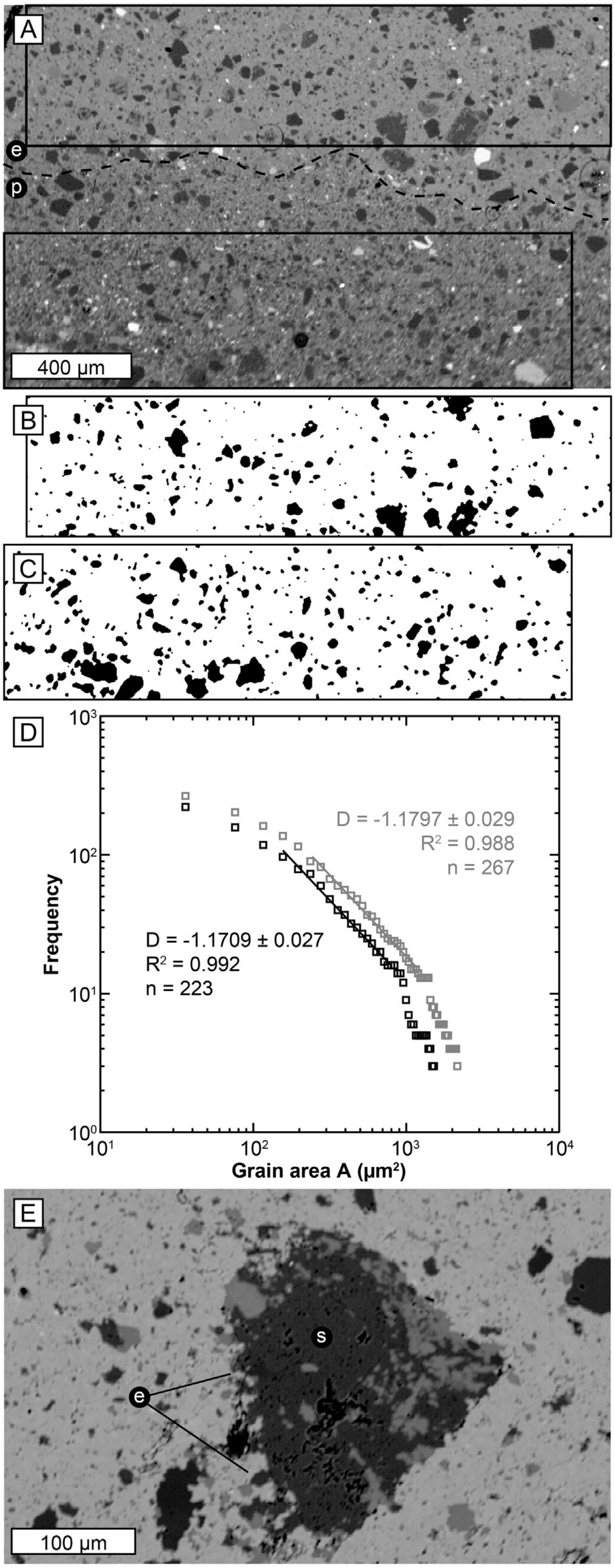

Fig. 7. Comparison of survivor clasts of quartz in a pristine and altered pseudotachylyte vein. A: Back-scattered electron image of part of the pseudotachylyte vein in Fig. 3. The matrix of the upper part of the vein was altered to epidote (e, above dashed line), whereas the lower part is unaltered (p). B and C: Maps of survivor clasts (quartz only) within areas outlined by boxes in A produced from the grayscale values of the clasts using ImageJ. D: Grain-size frequency distributions of the quartz survivor clasts in the upper (black) and lower (grey) maps shown in B and C. The plot shows the frequency of clasts of area A or greater and slopes fitted with a least-squares method to the linear portion of the curve. The slopes are the same, and the populations are statistically indistinguishable. Lateral shift in curves due to different number of clasts in the two maps. E: Backscattered electron image of a lithic survivor clast in the altered part of the vein. The edges of the clast are overgrown with epidote (e) so the clast boundary is extremely tortuous. Consequently, the grain roundnesses may be more sensitive to alteration than the grain-size distribution.

and deformed pseudotachylytes that a lower crustal shear zone may be up to 50% by volume *identifiable* previously melted material. Many previously studied faults contain assemblages of pseudotachylyte, cataclasite, and mylonite from the transitional zone, which if the criteria outlined in Table 1 were applied, would likely be found to contain appreciably more previously melted material than the current inventory of unambiguous pseudotachylyte veins. Possible examples include: the Santa Rosa Shear Zone phyllonites and ultramylonites described by Goodwin and Wenk (1995), the ultramylonites in Sierra Nevada granites studied by McNulty (1995a, b), and the apparently altered (or geochemically segregated) ultramylonite transition described in granites from California and Australia by Tobisch et al. (1991). Furthermore, brittle faults such as the La Grange fault, California, may also be considered to be pseudotachylyte-bearing (Cashman and Cashman, 2006).

The significance of frictional melting as a coseismic process is demonstrated by observations from plate boundary faults. Ancient structures such as the Pasagshak Point thrust subduction décollement, Alaska (Rowe et al., 2005), the Outer Hebrides thrust, Scotland (Sibson, 1975) and Priestley fault, Antarctica (Storti et al., 2001) provide evidence that melting occurs during earthquakes on major faults, probably including great earthquakes. Exhumed portions of active plate boundary faults, such as the Alpine fault, New Zealand (Toy et al., 2011), also contain pseudotachylytes. Furthermore, pseudotachylytes, or at least relict veins, are found in samples of fault rocks from many active faults studied by scientific drilling. Examples include the Nojima fault, Japan, drilled shortly after the Kobe earthquake (Tanaka et al., 2001; Otsuki et al., 2003; Janssen et al., 2013), the Chelungpu fault drilled following the Chi Chi earthquake (Otsuki et al., 2005) and the Median Tectonic Line, Japan (Shigematsu et al., 2012). These faults all have a history of exhumation, so the pseudotachylytes may have formed at greater depths than encountered in the borehole. Fault-drilling projects that targeted faults that do not have the same history of exhumation (e.g. the SAFOD and NanTroSEIZE projects) have not recorded melt-origin pseudotachylytes. In these cases, the fault rock assemblage is representative of the shallow conditions at which the borehole penetrated the fault, so pseudotachylyte formation is unlikely (Fialko and Khazan, 2005).

We emphasize here that a lack of pseudotachylyte in a fault rock assemblage does not imply aseismic slip. New examples of fault rocks that form coseismically have recently been reported (e.g. Han et al., 2010; Ujiie et al., 2011; Niemeijer et al., 2012; Rowe et al., 2012a), demonstrating that the fault rock record is rich in additional lines of evidence of seismic slip rates. We suggest that overall, the geological and seismological observations show that it is more conservative to interpret the fault rock record as predominantly representing seismic processes rather than aseismic processes. Increasing our capability to identify past seismic slip will move the field toward reconciling the frequency of earthquakes on active faults with the apparent rarity of geological evidence for fast slip.

5. Conclusions

The evidence for fault rocks having undergone a melt phase is fragile and often relatively short-lived over geologic time. Recrystallization, hydration and alteration all obliterate the primary textures indicative of quenching from a melt. Concomitant and subsequent deformation by cataclastic and crystal-plastic mechanisms destroy pseudotachylyte veins and re-work them into cataclasites, gouge and mylonites. We show that there are characteristics of disrupted pseudotachylytes that can be used to demonstrate cooling from a melt phase and thereby identify a seismic origin. The preservation potential of pseudotachylytes is not uniform; small-offset faults in the shallow crust are more likely to contain primary melt textures than large offset faults or ductile shear zones. However, pseudotachylytes are found in numerous mature, plate boundary faults, attesting to the significance of frictional melting as a coseismic process. Examples of reworked pseudotachylytes, particularly those that can only be tentatively identified as frictional melts, show that pseudotachylytes are formed more often than is currently appreciated.

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References

Andersen, T.B., Mair, K., Austrheim, H., Podladchikov, Y.Y., Vrijmoed, J.C., 2008. Stress release in exhumed intermediate and deep earthquakes determined from ultramafic pseudotachylyte. Geology 36, 995–998.

Bestmann, M., Pennacchioni, G., Nielsen, S., Göken, M., de Wall, H., 2012. Deformation and ultrafine dynamic recrystallization of quartz in pseudotachylyte-bearing brittle faults: a matter of a few seconds. Journal of Structural Geology 38, 21–38.

Bjørnerud, M., 2010. Rethinking conditions necessary for pseudotachylyte formation: observations from the Otago schists, South Island, New Zealand. Tectonophysics 490, 69–80.

Brodsky, E.E., Rowe, C.D., Meneghini, F., Moore, J.C., 2009. A geological fingerprint of extremely low viscosity fault fluids mobilized during an earthquake. Journal of Geophysical Research 114, 14. http://dx.doi.org/10.1029/2008JB005633.

Camacho, A., Vernon, R.H., Fitzgerald, J.D., 1995. Large volumes of anhydrous pseudotachylyte in the Woodroffe Thrust, eastern Musgrove Ranges, Australia. Journal of Structural Geology 17, 371–383.

Cashman, S.M., Cashman, K.V., 2006. Cataclastic textures in La Grange fault rocks, Klamath Mountains, California. Geological Society of America, Special Paper 410, 433–450.

Chattopadhyay, A., Khasdeo, L., Holdsworth, R.E., Smith, S.A.F., 2008. Fault reactivation and pseudotachylite generation in the semi-brittle and brittle regimes: examples from the Gavilgarh-Tan Shear Zone, central India. Geological Magazine 145, 766–777.

Chu, H.T., Hwang, S.L., Shen, P., Yui, T.F., 2012. Pseudotachylyte in the Tananao metamorphic complex, Taiwan: occurrence and dynamic phase changes of fossil earthquakes. Tectonophysics 581, 62–75.

Cosca, M.A., Caby, R., Bussy, F., 2005. Geochemistry and ^{40}Ar/^{39}Ar geochronology of pseudotachylyte associated with UHP whiteschists from the Dora Maira massif, Italy. Tectonophysics 402, 93–110.

Cowan, D.S., 1999. Do faults preserve a record of seismic slip? a field geologist's opinion. Journal of Structural Geology 21, 995–1001.

Di Toro, G., Nielsen, S., Pennacchioni, G., 2005. Earthquake rupture dynamics frozen in exhumed ancient faults. Nature 446, 1009–1012.

Di Toro, G., Pennacchioni, G., 2004. Superheated friction-induced melts in zoned pseudotachylytes within the Adamello tonalites (Italian Southern Alps). Journal of Structural Geology 26, 1783–1801.

Di Toro, G., Pennacchioni, G., 2005. Fault plane processes and mesoscopic structure of a strong-type seismogenic fault in tonalites (Adamello batholith, Southern Alps). Tectonophysics 402, 55–80.

Fabbri, O., Lin, A., Tokushige, H., 2000. Coeval formation of cataclasite and pseudotachylyte in a Miocene forearc granodiorite, southern Kyushu, Japan. Journal of Structural Geology 22, 1015–1025.

Fialko, Y., Khazan, Y., 2005. Fusion by earthquake fault friction: stick or slip? Journal of Geophysical Research 110 (B12), 407–415.

Friedman, I., Smith, R.L., Long, W.D., 1966. Hydration of natural glass and formation of perlite. Geological Society of America Bulletin 77, 323–328.

Goodwin, L.B., Wenk, H.R., 1995. Development of phyllonite from granodiorite: mechanisms of grain-size reduction in the Santa Rosa mylonite zone, California. Journal of Structural Geology 17, 689–707.

Griffith, W.A., Nielsen, S., Di Toro, G., Smith, S.A.F., 2010. Rough faults, distributed weakening, and off fault deformation. Journal of Geophysical Research 115. http://dx.doi.org/10.1029/2009JB006925.

Grocott, J., 1981. Fracture geometry of pseudotachylyte generation zones: a study of shear fractures formed during seismic events. Journal of Structural Geology 3, 169–178.

Han, R., Hirose, T., Shimamoto, T., 2010. Strong velocity weakening and powder lubrication of simulated carbonate faults at seismic slip rates. Journal of Geophysical Research 115. http://dx.doi.org/10.1029/2008JB006136.

Hayashi, N., Tsutsumi, A., 2010. Deformation textures and mechanical behavior of a hydrated amorphous silica formed along an experimentally produced fault in chert. Geophysical Research Letters 37. http://dx.doi.org/10.1029//2010GL042943.

Hetzel, R., Altenberger, U., Strecker, M.R., 1996. Structural and chemical evolution of pseudotachylytes during seismic events. Mineralogy and Petrology 58, 33–50.

Hirose, T., Mizoguchi, K., Shimamoto, T., 2012. Wear processes in rocks at slow to high slip rates. Journal of Structural Geology 38, 102–116.

Hobbs, B.E., Ord, A., Teyssier, C., 1986. Earthquakes in the ductile regime? Pure and Applied Geophysics 124, 309–336.

Janssen, C., Wirth, R., Lin, A., Dresen, G., 2013. Tem microstructural analysis in a fault gouge sample of the nojima fault zone, Japan. Tectonophysics 583, 101–104.

Janssen, C., Wirth, R., Rybacki, E., Naumann, R., Kemnitz, H., Wenk, H., Dresen, G., 2010. Amorphous material in safod core samples (San Andreas fault): evidence for crush-origin pseudotachylytes? Geophysical Research Letters 37, L01303.

John, T., Schenk, V., 2006. Interrelations between intermediate-depth earthquakes and fluid flow within subducting oceanic plates: constraints from eclogite facies pseudotachylytes. Geology 34, 557–560.

Kirkpatrick, J.D., Dobson, K.J., Mark, D.F., Shipton, Z.K., Brodsky, E.E., Stuart, F.M., 2012. The depth of pseudotachylyte formation from detailed thermochronology and constraints on coseismic stress drop variability. Journal of Geophysical Research 117. http://dx.doi.org/10.1029/2011JB008846.

Kirkpatrick, J.D., Shipton, Z.K., 2009. Geologic evidence for multiple slip weakening mechanisms during seismic slip in crystalline rock. Journal of Geophysical Research 114. http://dx.doi.org/10.1029/2008JB006037.

Kirkpatrick, J.D., Shipton, Z.K., Persano, C., 2009. Pseudotachylytes: rarely generated, rarely preserved or rarely reported? Bulletin of the Seismological Society of America 99, 382–388 http://dx.doi.org/10.1785/0120080114.

Kisters, A.F.M., Belcher, R.W., Scheepers, R., Rozendaal, A., Jordaan, L.S., Armstrong, R.A., 2002. Timing and kinematics of the Colenso Fault: the early Paleozoic shift from collisional to extensional tectonics in the Pan-African Saldania Belt, South Africa. South African Journal of Geology 105, 257–270.

Kuo, L.W., Song, S.R., Yeh, E.C., Chen, H.F., 2009. Clay mineral anomalies in the fault zone of the Chelungpu Fault, Taiwan, and their implications. Geophysical Research Letters 36. http://dx.doi.org/10.1029/2009GL039269.

Lin, A., 1994. Glassy pseudotachylyte veins from the Fuyun fault zone, northwest China. Journal of Structural Geology 16, 71–83.

Lin, A., 1997. Fluidization and rapid injection of crushed fine-grained materials in fault zones during episodes of seismic faulting. In: Zheng (Ed.), Proceedings of the 30th International Congress, vol. 14, pp. 27–40.

Lin, A., 1999. Roundness of clasts in pseudotachylytes and cataclastic rocks as an indicator of frictional melting. Journal of Structural Geology 21, 473–478.

Lin, A., 2008a. Fossil Earthquakes: the Formation and Preservation of Pseudotachylytes. Lecture Notes in Earth Sciences, vol. 111. Springer.

Lin, A., 2008b. Seismic slip in the lower crust inferred from granulite-related pseudotachylyte in the Woodroffe Thrust, central Australia. Pure and Applied Geophysics 165, 215–233.

Lin, A., Maruyama, T., Aaron, S., Michibayashi, K., Camacho, A., Kano, K.i., 2005. Propagation of seismic slip from brittle to ductile crust: evidence from pseudotachylyte of the Woodroffe thrust, central Australia. Tectonophysics 402, 21–35.

Lofgren, G., 1970. Experimental devitrification rate of rhyolite glass. Geological Society of America Bulletin 81, 553–560.

Lund, M.G., Austrheim, H., 2003. High-pressure metamorphism and deep-crustal seismicity: evidence from contemporaneous formation of pseudotachylytes and eclogite facies coronas. Tectonophysics 372, 59–83.

Macaudière, J., Brown, W.L., 1982. Transcrystalline shear fracturing and pseudotachylyte generation in a meta-anorthosite (Harris, Scotland). Journal of Structural Geology 4, 395–406.

Maddock, R.H., 1983. Melt origin of fault-generated pseudotachylytes demonstrated by textures. Geology 11, 105–108.

Maddock, R.H., 1986. Frictional melting in landslide-generated frictionites (hyalomylonites) and fault-generated pseudotachylytes – discussion. Tectonophysics 128, 151–153.

Maddock, R.H., 1992. Effects of lithology, cataclasis and melting on the composition of fault-generated pseudotachylytes in Lewisian gneiss, Scotland. Tectonophysics 204, 261–278.

Magloughlin, J.F., 1989. The nature and significance of pseudotachylyte from the Nason terrane, North Cascade Mountains, Washington. Journal of Structural Geology 11, 907–917.

Magloughlin, J.F., 1992. Microstructural and chemical changes associated with cataclasis and frictional melting at shallow crustal levels: the cataclasite-pseudotachylyte connection. Tectonophysics 204, 243–260.

Magloughlin, J.F., 2011. Bubble collapse structure: a microstructural record of fluids, bubble formation and collapse, and mineralization in pseudotachylyte. Journal of Geology 119, 351–371.

Magloughlin, J.F., Spray, J.G., 1992. Frictional melting processes and products in geologic materials: introduction and discussion. Tectonophysics 204, 197–206.

Mambane, P.W., Hein, K.A.A., Twemlow, S.G., Manzi, M.S., 2011. Pseudotachylyte in the South Boundary fault at the Cooke shaft, Witwatersrand basin, South Africa. South African Journal of Geology 75, 109–120.

McNulty, B.A., 1995a. Pseudotachylyte generated in the semi-brittle and brittle regimes, Bench Canyon shear zone, central Sierra Nevada. Journal of Structural Geology 17, 1507–1521.

McNulty, B.A., 1995b. Shear zone development during magmatic arc construction: the Bench Canyon shear zone, central Sierra Nevada, California. Geological Society of America Bulletin 107, 1094–1107.

Meneghini, F., Di Toro, G., Rowe, C.D., Moore, J.C., Tsutsumi, A., Yamaguchi, A., 2010. Record of mega-earthquakes in subduction thrusts: the black fault rocks of Pasagshak Point (Kodiak Island, Alaska). Geological Society of America Bulletin 122, 1280–1297. http://dx.doi.org/10.1030/B30049.1.

Mitchell, T., Sibson, R., Renner, J., Toy, V., di Toro, G., Smith, S., 2010. Experimental fault reactivation on favourably and unfavourably oriented faults. Eos Transactions AGU. Fall Meeting Supplement, Abstract, vol. 1. p. 2113.

Mittempergher, S., Pennacchioni, G., Toro, G.D., 2009. The effects of fault orientation and fluid infiltration on fault rock assemblages at seismogenic depths. Journal of Structural Geology 31, 1511–1524.

Moecher, D.P., Brearley, A.J., 2004. Mineralogy and petrology of a mullite-bearing pseudotachylyte: constraints on the temperature of coseismic frictional fusion. American Mineralogist 89, 1486–1495.

Moecher, D.P., Steltenpohl, M.G., 2009. Direct calculation of rupture depth for an exhumed paleoseismogenic fault from mylonitic pseudotachylyte. Geology 37, 999–1002.

Nielsen, S., Toro, G., Griffith, W., 2010. Friction and roughness of a melting rock surface. Geophysical Journal International 182, 299–310.

Niemeijer, A., Di Toro, G., Griffith, W.A., Bistacchi, A., Smith, S.A.F., Nielsen, S., 2012. Inferring earthquake physics and chemistry using an integrated field and laboratory approach. Journal of Structural Geology 39, 2–36.

Obata, M., Shun-Ichiro, Karato, 1995. Ultramafic pseudotachylite from the Balmuccia peridotite, Ivrea–Verbano zone, northern Italy. Tectonophysics 242, 313–328.

O'Hara, K., 1992. Major- and trace element constraints on the petrogenesis of a fault-related pseudotachylyte, western Blue Ridge province, North Carolina. Tectonophysics 204, 279–288.

Otsuki, K., Monzawa, N., Nagase, T., 2003. Fluidization and melting of fault gouge during seismic slip: identification in the Nojima fault zone and implications for focal earthquake mechanisms. Journal of Geophysical Research 108, 18. http://dx.doi.org/10.1029/2001JB001711.

Otsuki, K., Uduki, T., Monzawa, N., Tanaka, H., 2005. Clayey injection veins and pseudotachylyte from two boreholes penetrating the Chelungpu Fault, Taiwan: their implications for the contrastive seismic slip behaviors during the 1999 Chi–Chi earthquake. The Island Arc 14, 22–36.

Ozawa, K., Takizawa, S., 2007. Amorphous material formed by the mechanochemical effect in natural pseudotachylyte of crushing origin: a case study of the Iida-Matsukawa Fault, Nagano Prefecture, Central Japan. Journal of Structural Geology 29, 1855–1869.

Passchier, C.W., 1982. Pseudotachylyte and the development of ultramylonite bands in the Saint-Barthélemy Massif, French Pyrenees. Journal of Structural Geology 4, 69–79.

Passchier, C.W., Trouw, R.A.J., 2005. Microtectonics, second ed. Springer.

Pec, M., Stünitz, H., Heilbronner, R., Drury, M., de Capitani, C., 2012. Origin of pseudotachylites in slow creep experiments. Earth and Planetary Science Letters 355, 299–310.

Philpotts, A.R., 1964. Origin of pseudotachylytes. American Journal of Science 262, 1008–1035.

Pittarello, L., Di Toro, G., Bizzarri, A., Pennacchioni, G., Hadizadeh, J., Cocco, M., 2008. Energy partitioning during seismic slip in pseudotachylyte-bearing faults (Gole Larghe Fault, Adamello, Italy). Earth and Planetary Science Letters 269, 131–139.

Pittarello, L., Pennacchioni, G., Di Toro, G., 2012. Amphibolite-facies pseudotachylytes in Premosello metagabbro and felsic mylonites (Ivrea Zone, Italy). Tectonophysics 580 (C), 43–57.

Price, N.A., Johnson, S.E., Gerbi, C.C., David, P., West, J., 2012. Identifying deformed pseudotachylyte and its influence on the strength and evolution of a crustal shear zone at the base of the seismogenic zone. Tectonophysics 518–521, 63–83.

Rabinowitz, H., Skemer, P.A., Mitchell, T.M., Di Toro, G., 2011. Experimental reactivation of pseudotachylite-bearing faulted rocks. Eos Transactions AGU. Fall Meeting Supplement, Abstract, vol. 1. p. 2341.

Ray, S.K., 2004. Melt-clast interaction and power-law size distribution of clasts in pseudotachylytes. Journal of Structural Geology 26, 1831–1843.

Rempel, A.W., Rice, J.R., 2006. Thermal pressurization and onset of melting in fault zones. Journal of Geophysical Research 111. http://dx.doi.org/10.1029/2006JB004314.

Rice, J.R., 2006. Heating and weakening of faults during earthquake slip. Journal of Geophysical Research 111, B05311.

Rowe, C.D., Fagereng, A., Miller, J.A., Mapani, B., 2012a. Signature of coseismic decarbonation in dolomite fault rocks of the Naukluft Thrust, Namibia. Earth & Planetary Science Letters 333–334, 200–210.

Rowe, C.D., Kirkpatrick, J.D., Brodsky, E.E., 2012b. Fault rock injections record paleo-earthquakes. Earth & Planetary Science Letters 335–336, 154–166.

Rowe, C.D., Meneghini, F., Moore, J.C., 2011. Textural record of the seismic cycle: strain rate variation in an ancient subduction thrust, in: geology of the Earthquake Source: a Volume in Honour of Richard Sibson. Journal of the Geological Society Special Publication 359, 77–95.

Rowe, C.D., Moore, J.C., Meneghini, F., McKiernan, A.W., 2005. Large-scale pseudotachylytes and fluidized cataclasites from an ancient subduction thrust fault. Geology 33, 937–940.

Shand, S.J., 1916. The pseudotachylyte of Parijs (Orange Free State) and its relation to 'trop-shotten gneiss' and 'flinty crush-rock'. Quarterly Journal of the Geological Society 72, 198–221.

Sherlock, S.C., Jones, K.A., Park, R.G., 2008. Grenville-age pseudotachylyte in the Lewisian: laserprobe ^{40}Ar/^{39}Ar ages from the Gairloch region of Scotland (UK). Journal of the Geological Society, London 165, 73–78.

Shigematsu, N., Fujimoto, K., Tanaka, N., Furuya, N., Mori, H., Wallis, S., 2012. Internal structure of the Median Tectonic Line fault zone, SW Japan, revealed by borehole analysis. Tectonophysics 532–535, 103–108.

Sibson, R.H., 1975. Generation of pseudotachylyte by ancient seismic faulting. The Geophysical Journal of the Royal Astronomical Society 43, 775–794.

Sibson, R.H., 1989. Earthquake faulting as a structural process. Journal of Structural Geology 11, 1–14.

Sibson, R.H., Toy, V.G., 2006. The habitat of fault-generated pseudotachylyte: presence vs. absence of friction-melt. In: Abercrombie, R., McGarr, A., Kanamori, H., Di Toro, G. (Eds.), Earthquakes: Radiated Energy and the Physics of Faulting. Geophysical Monograph, vol. 170. American Geophysical Union, pp. 153–166.

Spray, J.G., 2010. Frictional melting processes in planetary materials: from hypervelocity impacts to earthquakes. Annual Review of Earth and Planetary Sciences 38, 221–254. http://dx.doi.org/10.1146/annurev.earth.031208.100045.

Storti, F., Rossetti, F., Salvini, F., 2001. Structural architecture and displacement accommodation mechanisms at the termination of the Priestley Fault, northern Victoria Land, Antarctica. Tectonophysics 341, 141–161.

Takagi, H., Goto, K., Shigematsu, N., 2000. Ultramylonite bands derived from cataclasite and pseudotachylyte in granites, northeast Japan. Journal of Structural Geology 22, 1325–1339.

Tanaka, H., Fujimoto, K., Ohtani, T., Ito, H., 2001. Structural and chemical characterization of shear zones in the freshly activated Nojima fault, Awaji Island, southwest Japan. Journal of Geophysical Research 106, 8789–8810.

Techmer, K.S., Ahrendt, H., Weber, K., 1992. The development of pseudotachylyte in the Ivrea-Verbano Zone of the Italian Alps. Tectonophysics 204, 307–322.

Tobisch, O.T., Barton, M.D., Vernon, R.H., Paterson, S.R., 1991. Fluid-enhanced deformation: transformation of granitoids to banded mylonites, western Sierra Nevada, California, and southeastern Australia. Journal of Structural Geology 13, 1137–1156.

Toy, V.G., Ritchie, S., Sibson, R.H., 2011. Diverse habitats of pseudotachylytes in the Alpine fault zone and relationships to current seismicity. In: Fagereng, A., Toy, V.G., Rowland, J.V. (Eds.), Geology of the Earthquake Source: a Volume in Honour of Rick Sibson. Geological Society of London, Special Publications, vol.359, pp. 115–133.

Ueda, T., Obata, M., Di Toro, G., Kanagawa, K., Ozawa, K., 2008. Mantle earthquakes frozen in mylonitized ultramafic pseudotachylytes of spinel-lherzolite facies. Geology 36, 607–610.

Ujiie, K., Tsutsumi, A., Kameda, J., 2011. Reproduction of thermal pressurization and fluidization of clay-rich fault gouges by high-velocity friction experiments and implications for seismic slip in natural faults. In: Fagereng, A., Toy, V.G., Rowland, J.V. (Eds.), Geology of the Earthquake Source: A Volume in Honour of Rick Sibson. Geological Society, London, Special Publications, vol. 359, pp. 267–285.

Uysal, I.T., Mutlu, H., Altunel, E., Karabacak, V., Golding, S.D., 2006. Clay mineralogical and isotopic (K–Ar, δ^{18}O, δD) constraints on the evolution of the North Anatolian fault zone, Turkey. Earth and Planetary Science Letters 243, 181–194.

Viti, C., 2011. Exploring fault rocks at the nanoscale. Journal of Structural Geology 33, 1715–1727.

Wenk, H.R., 1978. Are pseudotachylites products of fracture or fusion? Geology 6, 507–511.

Wenk, H.R., Johnson, L.R., Ratschbacher, L., 2000. Pseudotachylytes in the eastern peninsular ranges of California. Tectonophysics 321, 253–277.

White, J.C., 2012. Paradoxical pseudotachylyte – fault melt outside the seismogenic zone. Journal of Structural Geology 38, 11–20.

Yund, R., Blanpied, M., Tullis, T., Weeks, J., 1990. Amorphous material in high strain experimental fault gouges. Journal of Geophysical Research 95, 15589–15615.