AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL090020

Pseudotachylyte Alteration and the Rapid Fade of Earthquake Scars From the Geological Record

M. Fondriest[1,2,3], J. Mecklenburgh[1], F. X. Passelegue[4], G. Artioli[2], F. Nestola[2], E. Spagnuolo[5], M. Rempe[6], and G. Di Toro[2,5]

[1]Department of Earth and Environmental Sciences (DEES), University of Manchester, Manchester, UK, [2]Dipartimento di Geoscienze, Università degli Studi di Padova, Padova, Italy, [3]Now at Institut des Sciences de la Terre (ISTerre), Université Grenoble Alpes, Grenoble, France, [4]École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, [5]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy, [6]Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum, Bochum, Germany

Key Points:

- We investigated the preservation of pseudotachylytes in the presence of fluids with long-lasting (18–35 days) hydrothermal experiments
- After the experiments, pseudotachylytes were heavily altered with dissolution of the matrix and neo-formation of clay aggregates
- Hydrothermal alteration can determine the rapid (days to months) fade of pseudotachylytes from the geological record

Supporting Information:

- Supporting Information S1

Correspondence to:

M. Fondriest,
michele.fondriest@univ-grenoble-alpes.fr

Citation:

Fondriest, M., Mecklenburgh, J., Passelegue, F. X., Artioli, G., Nestola, F., Spagnuolo, E., et al. (2020). Pseudotachylyte alteration and the rapid fade of earthquake scars from the geological record. *Geophysical Research Letters*, *47*, e2020GL090020. https://doi.org/10.1029/2020GL090020

Received 28 JUL 2020
Accepted 31 OCT 2020
Accepted article online 4 NOV 2020

Author Contributions:

Conceptualization: M. Fondriest, J. Mecklenburgh, F. X. Passelegue, G. Di Toro
Data curation: M. Fondriest, G. Artioli, F. Nestola
Formal analysis: M. Fondriest, F. Nestola
Investigation: M. Fondriest, E. Spagnuolo
Supervision: J. Mecklenburgh
Validation: M. Rempe, G. Di Toro
Writing - original draft: M. Fondriest
Writing – review & editing: M. Fondriest, J. Mecklenburgh, F. X. Passelegue, G. Artioli, F. Nestola, E. Spagnuolo, M. Rempe, G. Di Toro

Abstract Tectonic pseudotachylytes are solidified frictional melts produced on faults during earthquakes and are robust markers of seismic slip events. Nonetheless, pseudotachylytes are apparently uncommon fault rocks, because they are either rarely produced or are easily lost from the geological record. To solve this conundrum, long-lasting (18–35 days) hydrothermal alteration tests were performed on fresh pseudotachylytes produced by sliding solid rock samples at seismic slip rates in the laboratory. After all tests, the pseudotachylytes were heavily altered with dissolution of the matrix and neo-formation of clay aggregates. Post-alteration products closely resemble natural altered pseudotachylytes and associated ultracataclasites (i.e., fault rocks affected by fracturing in the absence of melting), demonstrating that the preservation potential of original pseudotachylyte microstructures is very short, days to months, in the presence of hydrothermal fluids. As a consequence, pseudotachylytes might be significantly underrepresented in the geological record, and on-fault frictional melting during earthquakes is likely to occur more commonly than generally believed.

Plain Language Summary Tectonic pseudotachylytes are solidified melts produced by rapid sliding of faults during earthquakes. A long-lasting unsolved dispute in earthquake physics regards the abundance of pseudotachylytes in nature and the relevance of frictional melting as a seismic-related process. Although experimental and theoretical arguments indicate that frictional melts are easily generated at seismic deformation conditions, pseudotachylytes are apparently rare in the geological record and are often related to specific structural settings (i.e., water-deficient environments and high shear stresses). Such a discrepancy poses the problem whether pseudotachylytes are rarely generated or only rarely preserved in a recognizable form. Here we investigated the preservation potential of pseudotachylytes in the presence of fluids, by performing long-lasting (18–35 days) hydrothermal tests on fresh pseudotachylytes produced in the laboratory. After all tests, the pseudotachylytes were heavily altered with the generation of microstructures resembling those of very common fault rocks called cataclasites, which are unrelated to frictional melting. We suggest that pseudotachylytes are easily produced during earthquakes but they fade from the geological record in few weeks at most, in the presence of altering fluids percolating along the faults. This implies that frictional melting is a relevant process occurring on faults during earthquakes rupturing crystalline basement rocks.

1. Introduction

Tectonic pseudotachylytes are solidified friction-induced melts produced along faults by seismic slip associated to the propagation of earthquake ruptures (Sibson, 1975). They consist of dark aphanitic material forming irregular fault parallel veins or off-fault injections with a range of thicknesses that rarely exceed few centimeters (Sibson, 1975; Sibson & Toy, 2006; Swanson, 1989) (Figures 1a). Despite their mesoscale intrusive geometry, the original melt state of pseudotachylytes is only revealed by a combination of key microstructures such as embayed clasts that survived melting, chilled margins, flow banding, vesicles/amygdules, microlites/spherulites, or preserved glass in the matrix (Lin, 2007; Magloughlin & Spray, 1992). To date, pseudotachylytes represent the most robust and established marker of seismic slip in the geological record (Rowe & Griffith, 2015). For this reason, they have been

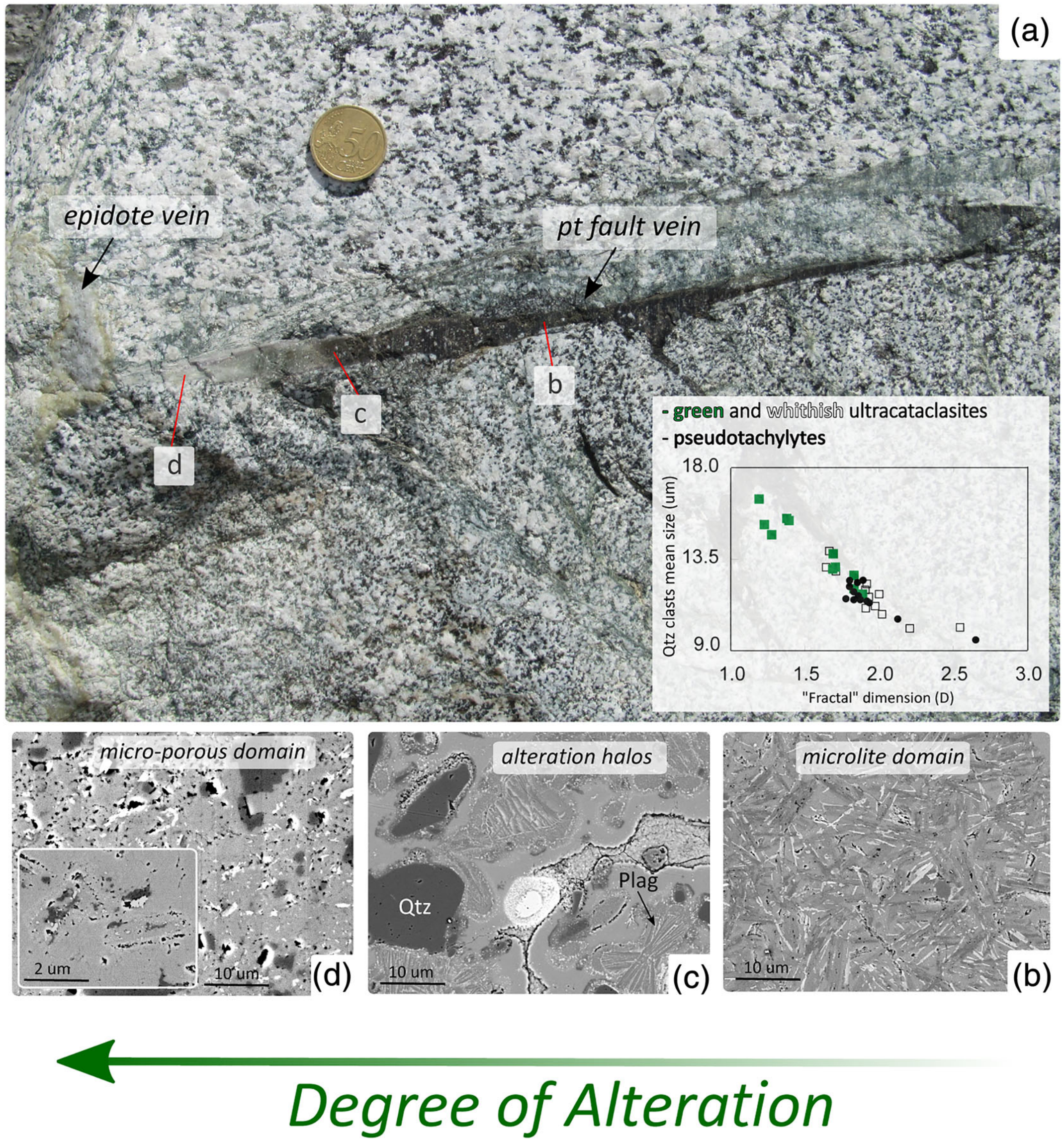

Figure 1. Pseudotachylyte alteration in nature. (a) Pseudotachylyte fault vein cutting tonalites from the Gole Larghe Fault Zone (Southern Alps of Italy) (Di Toro & Pennacchioni, 2005). Moving from right to left in the photograph, the blackish fresh pseudotachylyte vein, associated to lateral injection, fades into a greenish-grayish chlorite and epidote enriched fault rock layer. The epidote vein (left side of the photograph) cuts through the pseudotachylyte vein and controls its progressive alteration. Inset plot in panel (a) reports published data (Di Toro & Pennacchioni, 2005) comparing the quartz clast size distributions (CSDs) of fresh pseudotachylytes veins (black circles) and associated greenish (chlorite-epidote enriched) to whitish (K-feldspar enriched) apparently ultracataclastic layers (green and whitish squares respectively; see Figure S1for more details). Data are reported as "fractal" dimension (i.e., slope of each CSD in logarithmic plots) in abscissa against mean clasts size of each distribution in the ordinate. The fact that some CSDs of apparently cataclastic layers overlap with those of fresh pseudotachylytes suggests that some greenish to whitish fault rock layers may represent intensely altered pseudotachylytes. (b–d) Microstructural domains representative of an increasing alteration degree in natural pseudotachylytes of the Gole Larghe Fault Zone (BSE-SEM images). The fresh black domain in (b) is characterized by a felt of plagioclase and less frequently biotite microlites immersed into a microcrystalline to cryptocrystalline biotite dominated matrix. With increasing alteration degree in (c), peculiar porous and dark alteration halos develop around quartz clasts and matrix starts to be progressively dissolved and replaced by chlorite plus epidote. At more intense alteration stages (d), the matrix is affected by significant microporosity and consists of chlorite plus epidote micrograins. Skeletons of original microlites are only locally recognizable (see the inset in panel d).

extensively studied to determine their abundance within fault zones and to constrain earthquake source parameters (Di Toro et al., 2005, 2006; Sibson, 1975). Theoretical arguments (Jeffreys, 1942; McKenzie & Brune, 1972) and experimental evidence (Niemejier et al., 2011; Violay et al., 2014) suggest that frictional melting of solid rocks or gouges should occur after few millimeters of slip during an earthquake and, as a consequence, pseudotachylytes should be widespread along seismic fault zones. However, the report of pseudotachylytes in the geological record is relatively rare, especially when compared with the frequency of earthquakes in the crystalline basement (~150 per year with magnitude ≥6, each potentially associated with a pseudotachylyte fault vein ≥2–7 mm thick) (Di Toro et al., 2006; Kirkpatrick & Rowe, 2013; Sibson, 1975; Sibson & Toy, 2006). Such a discrepancy poses the problem whether pseudotachylytes are rarely generated or only rarely preserved in a recognizable form (Kirkpatrick & Rowe, 2013). Indeed, there are lines of evidence suggesting that well-preserved (i.e., poorly altered) pseudotachylytes are typical of fluid-deficient tectonic settings or are produced at fault asperities sustaining very high shear stresses (Austrheim & Andersen, 2004; Pennacchioni et al., 2020; Scambelluri et al., 2017; Sibson & Toy, 2006). However, pseudotachylytes with variable degree of alteration have been increasingly reported within "wet" to fluid-rich tectonic settings (Boullier et al., 2001; Magloughlin, 2011; Meneghini et al., 2010; Phillips et al., 2019; Rowe et al., 2005; Uijie et al., 2007) and were experimentally produced both in dry, water-dampened and water-pressurized conditions (Violay et al., 2014). Assessing the preservation potential of pseudotachylytes after their formation is thus fundamental to determine the effective relevance of frictional melting as a widespread mechanism of fault lubrication during earthquakes (Di Toro et al., 2011). Indeed, the dominance of frictional melting rather than other dynamic fault weakening mechanisms activated at lower temperatures (e.g., thermal pressurization) potentially has significant implications in earthquake mechanics (e.g., earthquake energy budgets, rapid and pronounced coseismic healing, and postseismic fault strength recovery due to melt cooling, solidification, and fault welding; Brantut & Mitchell, 2018; Kanamori & Heaton, 2000; Mitchell et al., 2016; Proctor & Lockner, 2016; Violay et al., 2019).

Here we investigate the preservation potential of pseudotachylytes in the presence of hydrothermal fluids, a condition typical of many fault zones in the seismogenic crust, without considering the effect of any brittle to viscous overprinting which can further contribute to obliterate pseudotachylyte primary features (Sibson & Toy, 2006). We performed long-lasting (18–35 days) hydrothermal tests on "fresh" pseudotachylytes produced in the laboratory under seismic deformation conditions with rotary shear experiments. Artificial pseudotachylytes obtained from tonalite and two types of gabbros were maintained at temperatures of 300–600°C under confining and water pore pressure of 150–200 MPa. After all tests, the pseudotachylytes were heavily altered showing (i) the generation of clastic-like microstructures (i.e., matrix dissolution with porosity enhancement) and (ii) the neoformation of clay aggregates. The experimentally altered products closely resemble some of the natural altered pseudotachylytes and associated ultracataclasites (a fault rock produced by rock fragmentation in the absence of melting) of the Gole Larghe fault zone (a 30 Ma old exhumed seismogenic fault) (Di Toro & Pennacchioni, 2005). This study demonstrates that the preservation potential of the original pseudotachylytes microstructures is very short, days to months, in the presence of hydrothermal fluids and increases only within very dry tectonic settings, thus suggesting that the generation of frictional melts in natural fault zones is likely to be more common than generally believed.

2. Altered Pseudotachylytes of the Gole Larghe Fault Zone

The Gole Larghe fault zone is an exhumed paleoseismic fault crosscutting the Adamello tonalites in the Italian Southern Alps (Di Toro & Pennacchioni, 2004). Ambient conditions of faulting were at 9–11 km depth and 250–300°C and the fault zone accommodated ~1.1 km of dextral strike slip over a fault thickness of ~600 m. Ancient seismicity is attested by the widespread occurrence of pseudotachylytes associated with green chlorite-epidote bearing cataclasites to ultracataclastites (Di Toro & Pennacchioni, 2005) (Figures 1a and S1 in the supporting information). Black "fresh"-looking pseudotachylyte veins with well-preserved primary microstructures (e.g., microlites-spherulites) and injections are abundant within the fault damage zone, while pseudotachylytes become rarer within an ~200 m-thick central altered propylitic zone delimited by two ultracataclastic fault cores (~2 m thick) affected by higher intensity of healed and sealed microfractures (Rempe et al., 2018; Smith et al., 2013). Mineralogical and isotopic studies revealed the ingression of metamorphic fluids at the time of seismic faulting which were focused within the central portion of the fault zone (Mittempergher et al., 2014; Smith et al., 2013). However, when looking carefully at the mesoscale and microscale, even the "fresh"-looking pseudotachylytes within the fault damage zone are frequently associated to few millimeters thick dark green to purple chlorite- and epidote-rich or whitish K-feldspar-rich ultracataclastic layers (Di Toro & Pennacchioni, 2005) (Figures 1a and S1). These thin layers are characterized by quartz clasts size distributions comparable with those of fresh-looking pseudotachylytes and might thus represent the product of intense alteration of original pseudotachylytes (Di Toro & Pennacchioni, 2005) (inset in Figure 1a; Figure S1). In addition, pseudotachylyte fault veins show evidence of incipient alteration where they are cut by chlorite- and epidote-bearing veins (Figure 1a). Moving from the black (less altered) to the grayish (more altered) portions of the pseudotachylytes, the pristine melt-derived matrix, made by a felt of plagioclase and biotite microlites (Figure 1b), developed porous alteration halos around quartz clasts (Figure 1c) and is progressively substituted by chlorite plus epidote micrograins (Figure 1d).

3. Hydrothermal Alteration of Experimentally Produced Pseudotachylytes

Experimental pseudotachylytes were produced with the rotary shear apparatus SHIVA at the Istituto Nazionale di Geofisica e Vulcanologia in Rome (Di Toro et al., 2010) (Figure S2). Couples of solid rock cylinders (diameter 50 mm) of tonalite (from the Gole Larghe Fault), quartz-microgabbro (from the Bushveld igneous complex) and gabbro (from the Balmuccia ultramafic suite) were sheared at slip rates of 2.5–5 m s^{-1} (i.e., on-fault seismic slip rates) and normal stresses of 10–20.5 MPa for 3–9 s under vacuum (10^{-3}–10^{-4} mbar) to produce a frictional melt layer sufficiently thick to weld the samples together (see Text S1 and Figure S3 for details). The melt-welded rock samples were cored along the fault interface to obtain smaller (diameter 10 mm) rock cylinders with the experimental pseudotachylyte oriented parallel to the long axis (Figure S3). These samples were finally cooked with water as pore fluid at confining (*Pc*) and pore pressure (*Pp*) of 150–200 MPa and temperatures (*T*) of 300–600°C for 18–35 days using two high-temperature fluid-confined triaxial apparatus at the Rock Deformation Laboratory of the University of Manchester (Rutter et al., 1985) (see Text S1 and Figure S4). The experimental conditions were chosen to be representative of the pressures and temperatures of the host rocks at the time of pseudotachylyte formation (Di Toro & Pennacchioni, 2004; Obata & Karato, 1995). Here below, we focus on the description of the tonalite-derived samples, cooked at $Pc = Pp = 150$ MPa and $T = 300$°C, for which we have well-constrained natural comparisons (Figure 1).

Under the scanning electron microscope (SEM), the pseudotachylyte produced from tonalites with SHIVA is an ~1 mm-thick layer with clasts of quartz and plagioclase up to 150 μm in size immersed in a glassy to cryptocrystalline matrix with virtual no porosity (Figures 2a and 2b). The chemical composition of the matrix (determined through energy dispersive spectroscopy, EDS) is andesitic, biotite clasts are almost absent due to their selective melting (Shand, 1916; Spray, 2010) (see text S2 and Figure S5), and <5 μm-long plagioclase microlites locally formed (inset in Figure 2b). Quartz and less frequently plagioclase survivor clasts have cuspate-lobate shapes possibly due clast-melt interaction (Figure 2b). The cumulative size distribution of survivor quartz clasts measured in two dimensions over a clast size range of 2–70 μm displayed a slope D ~ 1.6 in logarithmic plot, while average clast circularity was ~0.5, where circularity is a morphometric index in the range 0–1 describing the roundness of an object (e.g., the circularity of a circle is 1; see Text S3 and Figures S6 and S7).

The experimental pseudotachylyte recovered after the hydrothermal test (35 days at 300°C and $Pc = Pp = 150$ MPa) consisted of a grayish fine-grained layer macroscopically distinct from the original black pseudotachylyte (Figure 2c). Relative to the fresh pseudotachylyte, the experimentally altered one showed a significant increase in porosity coupled with a decrease in the number of quartz and plagioclase clasts (Figure S6). Moreover, the fine-grained clast fraction (D ~ 2.1 in the size range 4–40 μm for quartz clasts; Figure S6) and clasts circularity (~0.6–0.7 for quartz; see Figure S7) increased, while clasts <4 μm in size were no longer detected. The occurrence of few relics of less-altered pseudotachylyte helped us to track the progress of alteration through space and time (Figures 2c and 3a). Alteration is observed to start primarily along fractures (probably because of permeation by hydrothermal fluids) and around quartz clasts (Figures 2 and 3). In particular, the matrix around quartz clasts developed dark-gray halos that appear to

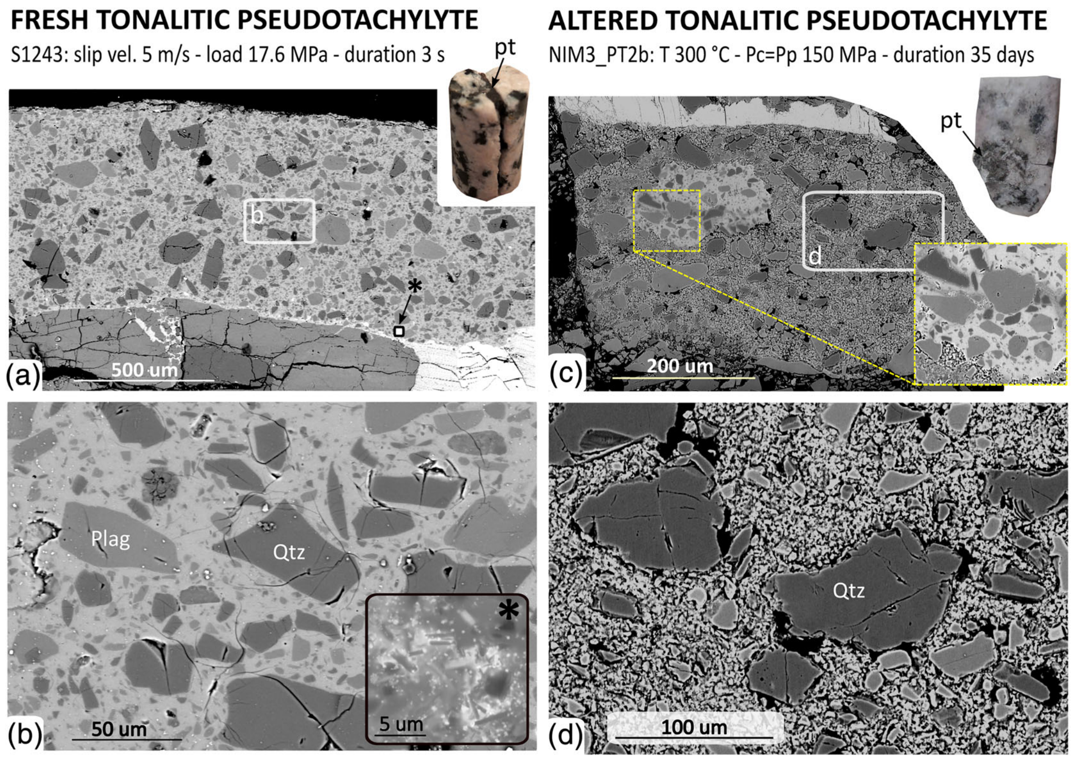

Figure 2. Pseudotachylyte alteration in experiments. (a, b) Fresh experimental pseudotachylyte vein; see the up-right inset in (a) for a macroscopic view of the sample. Pseudotachylyte produced through a high-velocity rotary shear experiment with SHIVA starting from a tonalite from the Adamello batholith (host rock of the Gole Larghe Fault Zone). The experimental pseudotachylyte vein consists of quartz and plagioclase clasts immersed into a glassy to cryptocrystalline matrix with andesitic composition (see Figure S5) and a negligible amount of porosity in the form of cooling microcracks (BSE-SEM images). Embayed quartz and plagioclase clasts (also with cuspate-lobate borders) indicate progressive melting, while biotite is almost absent as clast due to selective melting (b). Locally, few micrometers in size plagioclase microlites crystallized from the melt (inset in b). (c, d) Experimental pseudotachylyte (a, b) after long term (35 days) hydrothermal test ($Pc = Pp = 150$ MPa, $T = 300$°C). The up-right inset in (c) shows that the altered pseudotachylyte turned into a grayish layers macroscopically different from the original black one. The altered pseudotachylyte vein consists of a clastic layer characterized by a striking increase of porosity with respect to the original one in panel (a). Quartz and plagioclase clasts are subrounded and are immersed in a microgranular matrix (c, d) (BSE-SEM images). Relics of fresh pseudotachylyte are still preserved (see down-right inset with yellow border in panel c) and allowed to track the evolution of the alteration process. Incipient alteration produced peculiar dark porous halos which resemble the ones observed in the altered pseudotachylytes of the Gole Larghe Fault Zone.

have evolved into progressively more porous regions (in SEM backscatter electron images; Figures 2 and 3). Energy dispersive spectroscopy (EDS) analyses performed in the pseudotachylyte matrix both outside and within the halos and along transect through quartz clasts show a significant depletion of alkali (especially K) within the alteration halos. The variation of other elements like Si and Al is within the measurements error (Figure 3). The portions of the pseudotachylyte affected by more intense alteration (i.e., the more porous regions) were characterized by the growth of few micrometers in size aggregates of platy minerals within the pores (Figure 4). Single crystal microdiffraction performed on a fragment of the altered pseudotachylyte ~100 μm in size in conjunction with EDS spot analyses indicates that the newly formed mineral phase is a Ca- and Mg-smectite clay (see Text S4, Figures 4 and S8, and Table S1). A characteristic single phase diffraction peak of the smectite clay (d = 14.85 Å) was associated with a continuous diffraction ring (i.e., no single diffraction spots) indicative of the nanocrystalline nature of this phase (estimated average crystallite size ~19 nm; see Text S4 for details) (Figure 4). In the case of the altered pseudotachylytes produced from the Bushveld quartz-microgabbro ($Pc = Pp = 200$ MPa, $T = 500$°C, duration = 18 days) and Balmuccia gabbro ($Pc = Pp = 200$ MPa, $T = 600$°C, duration = 24 days), similar clastic microstructures again associated with the growth of platy minerals in the newly formed porosity were reported (see Figure S9 for microstructural details).

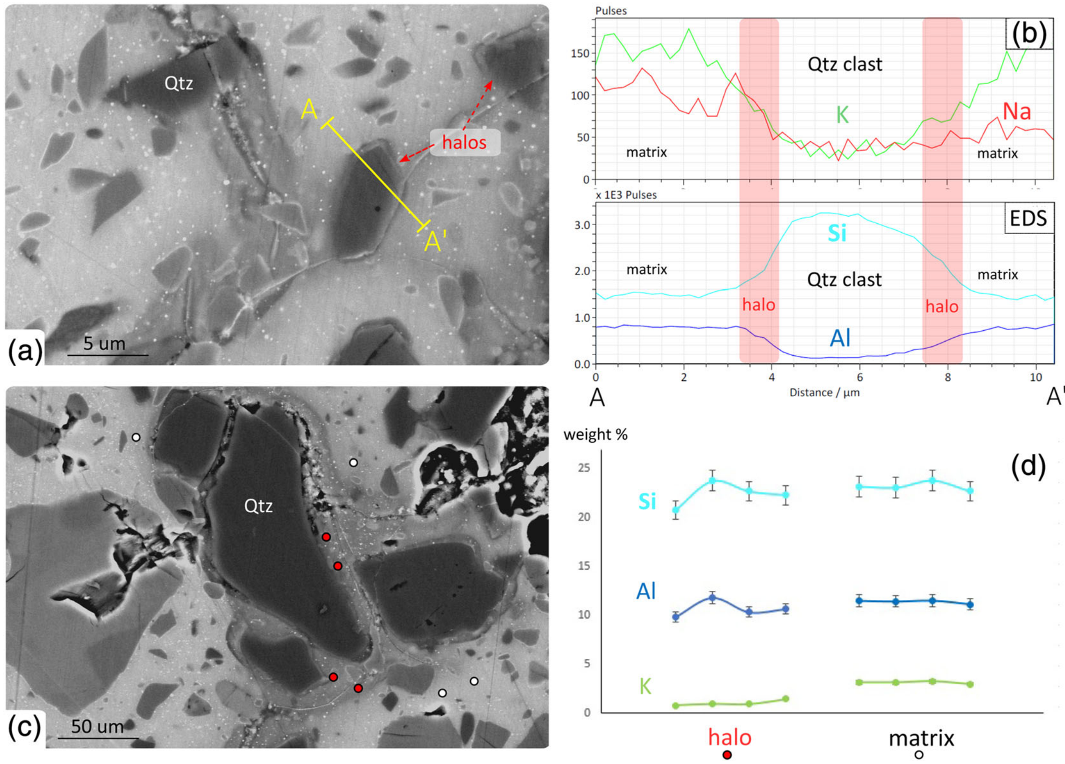

Figure 3. The onset of pseudotachylyte alteration under hydrothermal conditions. (a) Detail (BSE-SEM image) of a fragment of fresh pseudotachylyte affected by incipient alteration. Alteration starts along fractures (see the vertical fracture in image a) and in the matrix around quartz clasts where dark porous halos develop. (b) Energy dispersive spectroscopy profile analyses across a quartz clast, the alteration halo, and the surrounding matrix. The halo is depleted in alkali (especially K) with respect to the matrix; instead, major elements such as Si and Al show a regular gradient between the matrix and the clast. (c, d) Multiple alteration halos around quartz clasts merge to form progressively more porous regions. Spot EDS analyses within the halos (red circles) and within the unaltered matrix (white circles). Again, only alkalis are depleted within the halos with respect to the surrounding matrix; no significant difference is detectable for major elements like Si and Al, given the error associated to the EDS analyses.

4. Discussion and Conclusions

4.1. The Rapid Alteration of Pseudotachylytes and Implications for Natural Fault Zones

The present experimental study documents the rapid alteration (days to months, a negligible time duration compared to geological or even earthquake recurrence timescales) of the typical pseudotachylytes microstructures under hydrothermal conditions. In the case of the tonalite-derived pseudotachylyte, the alteration conditions ($T = 300°$C and $Pc = Pp = 150$ MPa with water as pore fluid) correspond to those estimated for the pseudotachylytes and the chlorite-epidote bearing cataclasites of the Gole Larghe fault zone that was, at least locally, infiltrated by water-rich fluids (Di Toro & Pennacchioni, 2004) (Figure 1a). This structural setting corresponds to that of a seismogenic fault zone in the crystalline basement, which is ruptured during an earthquake associated with on-fault frictional melting and pseudotachylyte generation (Figure S10a). The early postseismic infiltration of metamorphic fluids occurs from the wall rocks to the fault slip zone through the coseismically activated fault and fracture network (Sibson et al., 1975) and leads to the inception of fluid-mediated alteration of the fault rock assemblages (Figure S10b).

After hydrothermal alteration, the originally black experimental pseudotachylyte turned into a fine-grained grayish material similar to some of the intensely altered pseudotachylytes of the Gole Larghe fault zone (compare area "d" in Figure 1a with Figure 2c). More importantly, the dark halos which formed in the glassy matrix around the quartz clasts during the first stages of the experimental alteration (Figure 2c) are a common microstructure of the pseudotachylytes affected by incipient alteration in the Gole Larghe fault zone (Di Toro & Pennacchioni, 2004) (Figure 1c). However, in our experiment, the more altered portions of pseudotachylyte turned into a microporous microstructure due to extensive dissolution of the glassy matrix and, to a

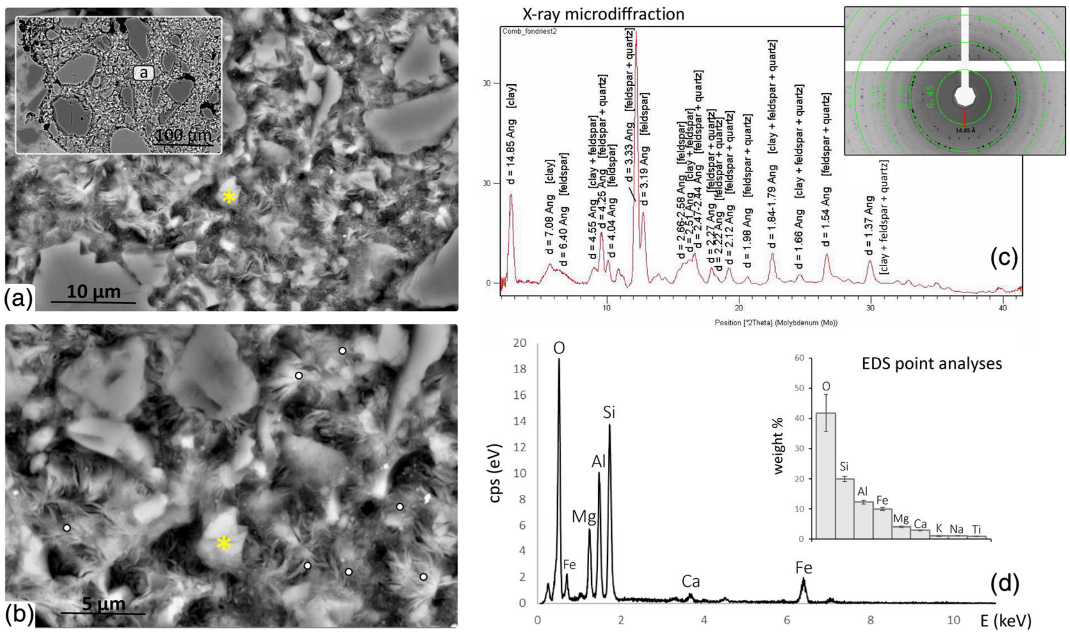

Figure 4. Advanced pseudotachylyte alteration and secondary phase nucleation. (a, b) Detail of the microporous matrix within the areas affected by more intense dissolution after hydrothermal alteration. See inset in (a) for the location of images (a) and (b). The microporous matrix consists of micrometer to submicrometer quartz and plagioclase rounded clasts and stacks of a new platy mineral phase. (c) X-ray microdiffraction has been performed on a 100 μm in size fragment of altered pseudotachylyte matrix. The resulting diffractogram is shown is (c) and was interpreted by cross-checking diffraction data with elemental EDS analyses (see d). The diffraction analysis reveals the occurrence of a smectite clay. The characteristic peak of this phase is at $d = 14{,}85$ Å (positioned at $2\theta = 2.71°$) and is not associated to single diffraction spots (as it is the case for all the other peaks dominated by the occurrence of quartz and feldspar clasts in the analyzed fragment), but to diffraction rings, thus suggesting the polycrystalline nature of this newly formed phase. (d) Elemental EDS spot analyses of the neo-formed smectite. The selected spectrum is a representative one of the seven spot analyses performed on the sample (white circles in (b) whose elemental composition (weight % of each element) is summarized in the histogram in (d). The joined diffraction and elemental analyses suggest that the new phase is a (Ca and Mg) smectite with estimated crystallite size $d = 19$ nm (see Text S4 for more details).

less extent, of the survivor clasts. This advanced stage of alteration was accompanied by the neo-formation of nanocrystalline Ca-Mg smectite clay. Previous tests investigating the dissolution of basaltic and rhyolitic glasses up to hydrothermal conditions ($T \leq 400°C$, $Pc = Pp \leq 90$ MPa, and water as pore fluid with varying pH, ion concentration, and fluid to rock ratios) describe an initial rapid far from equilibrium congruent dissolution stage responsible for the break of the glass silicate network (i.e., Si-O bonds, due to proton exchange reactions) (Oelkers & Gislason, 2001) and the liberation of cations in the fluid (Declerq et al., 2013; Gislason & Oelker, 2003). Over longer timescales, as the solution approaches chemical equilibrium with the glass, the dissolution rate reduces, and the formation of a secondary mineral phases occurs (Frugier et al., 2008; Giorgetti et al., 2006; Rani et al., 2012; Seyfried & Mottl, 1982); this is also the case for smectite as observed in our experiment. The naturally altered pseudotachylytes of the Gole Larghe fault zone, instead, are sealed by chlorite and epidote due to the ingression of water-rich fluids of metamorphic origin enriched in large-ion lithophile elements (K, Rb, Sr, Cs, and Ba) (Di Toro & Pennacchioni, 2004; Mittempergher et al., 2014), rather than pure water as in our experiment. Therefore, smectite clays probably never formed at the depths and temperatures typical of the Gole Larghe Fault zone. Moreover, the fragile porous fabric, which formed with $Pc = Pp$ in our experiment (Figure 2c), likely would not sustain the differential stresses of natural fault zones and is therefore expected to collapse, possibly resulting in a more cataclastic microstructure. Therefore, some of the thin grayish to whitish layers previously interpreted in the field as ultracataclasites (i.e., fault rocks produced in the absence of frictional melting and perhaps not associated to seismic faulting) might instead be the result of intense alteration of original pseudotachylytes. Consequently, only the maintenance of injection-like features (see Figures S1 and S10) or clast size distributions of apparent "cataclasites" resembling those typical of fresh looking pseudotachylytes (see inset in Figure 1a) may help us to recognize intensely altered pseudotachylytes.

The current study proves that the preservation potential of pseudotachylytes in the presence of hot pore water is very scarce, especially for the thinner millimetric to submillimetric fault veins (see also the communication of Hayward et al., 2015). The alteration rate will then vary with factors such as: composition of the pseudotachylyte glass and the fluid, fluid-rock ratio, temperature and pore pressure, and surface area (i.e., fluid infiltration through fractures). The alteration of pseudotachylytes driven by hydrothermal fluids is consistent with earthquake faulting being responsible for the rapid infiltration and redistribution of large volumes of fluids both in the upper and lower crust and the generation of hydrothermal mineralizations and country rocks metasomatism (e.g., Jamtveit et al., 2018; Sibson et al., 1975).

Many pseudotachylytes are intrinsically difficult to be identified in fault zones by untrained eyes, because they are ultrafine-grained dark colored rocks, often very thin, and spatially associated or overprinted by other macroscopically similar fault products such as ultracataclasites and ultramylonites (Kirkpatrick & Rowe, 2013). This issue is then hampered by the fact that pseudotachytes are rapidly altered by hydrothermal fluids percolating along faults after earthquakes, as we showed in this study. As a consequence, pseudotachylytes may be largely overlooked in the geological record, and therefore, frictional melting represents a relevant on-fault coseismic process which is likely to occur more often than previously thought during earthquakes.

Conflict of Interest

The authors declare that they have no competing interests.

Data Availability Statement

All data needed to evaluate the conclusions of the study are presented in the paper and in the supporting information. Other data, image analysis and further EDS analyses, can be found at the repository Fondriest_et_GRL_2020 (https://figshare.com/s/c00d55b703277650491e). The article is based on original data; CSD data in Figure 1 are from Di Toro and Pennacchioni (2005), as it is stated in the figure caption.

Acknowledgments

The authors thank Heath Bagshaw and Andrea Cavallo for microanalytical support; Leonardo Tauro and Marco Favero for thin sections production and samples polishing; Nicola Michelon and Stefano Castelli for high-resolution scans; Francesco Gosio, Alessia Modesti, and Luca Del Rio for support in acquiring and analyzing SEM images. The authors also thank the excellent technical support of Steve May and Lee Paul at the Rock Deformation Laboratory of the University of Manchester. M. F. thanks Ernie Rutter for fruitful discussions. M. F. and G. D. T. acknowledge the European Research Consolidator Grant (No. 614705) NOFEAR; M. F. acknowledges the MSCA-IF DAMAGE (No. 839880); and M. R. acknowledges DFG grant (No. 403438118).

References

Austrheim, H., & Andersen, T. B. (2004). Pseudotachylytes from Corsica: Fossil earthquakes from a subduction complex. *Terra Nova*, *16*(4), 193–197.

Boullier, A.-M., Ohtani, T., Fujimoto, K., Ito, H., & Dubois, M. (2001). Fluid inclusions in pseudotachylytes from the Nojima fault, Japan. *Journal of Geophysical Research*, *106*, 965–977.

Brantut, N., & Mitchell, T. M. (2018). Assessing the efficiency of thermal pressurization using natural pseudotachylyte-bearing rocks. *Geophysical Research Letters*, *45*, 9533–9541. https://doi.org/10.1029/2018gl078649

Declerq, J., Diedrich, T., Perrot, M., Gislason, S. R., & Oelkers, E. H. (2013). Experimental determination of rhyolitic glass dissolution rates at 40–200°C and 2 < pH < 10.1. *Geochimica et Cosmochimica Acta*, *100*, 251–263.

Di Toro, G., Han, R., Hirose, T., Paola, N. D., Nielsen, S., Mizoguchi, K., et al. (2011). Fault lubrication during earthquakes. *Nature*, *471*(7339), 494–498. https://doi.org/10.1038/nature09838

Di Toro, G., Hirose, T., Nielsen, S., Pennacchioni, G., & Shimamoto, T. (2006). Natural and experimental evidence of melt lubrication of faults during earthquakes. *Science*, *311*(5761), 647–649. https://doi.org/10.1126/science.1121012

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

Di Toro, G., Niemeijer, A., Tripoli, A., Nielsen, S., Di Felice, F., Scarlato, P., et al. (2010). From field geology to earthquake simulation: A new state-of-the-art tool to investigate rock friction during the seismic cycle (SHIVA). *Rendiconti Lincei*, *21*, 95–114.

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.

Frugier, P., Gin, S., Minet, Y., Chave, T., Bonin, B., Godon, N., et al. (2008). SON68 nuclear glass dissolution kinetics: Current state of knowledge and basis of the new GRAAL model. *Journal of Nuclear Materials*, *380*, 8–21.

Giorgetti, G., Monecke, T., Kleeberg, R., & Hannington, M. G. (2006). Low-temperature hydrothermal alteration of silicic glass at the Pacmanus hydrothermal vent field, Manus basin: An XRD, SEM and AEM-TEM study. *Clays and Clay Minerals*, *54*, 240–251.

Gislason, S. R., & Oelker, E. H. (2003). Mechanism, rates, and consequences of basaltic glass dissolution: II. An experimental study of the dissolution rates of basaltic glass as a function of pH and temperature. *Geochimica et Cosmochimica Acta*, *67*, 3817–3832.

Hayward, K. S., Cox, S. F., & Fitz Gerald, J. (2015). How common are pseudotachylytes? Experimental insights into formation and preservation of frictional melt on quartz fault interfaces. *Geotectonic Research*, *97*, 44–45.

Jamtveit, B., Ben-Zion, Y., Renard, F., & Austrheim, H. (2018). Earthquake-induced transformation of the lower crust. *Nature*, *556*(7702), 487–491. https://doi.org/10.1038/s41586-018-0045-y

Jeffreys, H. (1942). On the mechanics of faulting. *Geological Magazine*, *79*, 291–295.

Kanamori, H., & Heaton, T. H. (2000). Microscopic and macroscopic physics of earthquakes. *GeoComplexity and the Physics of Earthquakes - Monograph-American Geophysical Union*, *120*, 147–164.

Kirkpatrick, J. D., & Rowe, C. D. (2013). Disappearing ink: How pseudotachylytes are lost from the rock record. *Journal of Structural Geology*, *52*, 183–198.

Lin, A. (2007). Terminology and Origin of Pseudotachylyte. In *Fossil earthquakes: The formation and preservation of pseudotachylytes* (Vol. 111, pp. 5–15). Berlin, Heidelberg: Springer.

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

Magloughlin, J. F., & Spray, J. G. (1992). Frictional melting processes and products in geological materials: Introduction and discussion. *Tectonophysics*, *204*, 197–204.

McKenzie, D., & Brune, J. N. (1972). Melting on fault planes during large earthquakes. *Geophysical Journal International*, *29*, 65–78.

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*(7/8), 1280–1297.

Mitchell, T. M., Toy, V., Di Toro, G., Renner, J., & Sibson, R. H. (2016). Fault welding by pseudotachylyte formation. *Geology*, *44*, 1059–1062.

Mittempergher, S., Dallai, L., Pennacchioni, G., Renard, F., & Di Toro, G. (2014). Origin of hydrous fluids at seismogenic depth: Constraints from natural and experimental fault rocks. *Earth and Planetary Science Letters*, *385*, 97–109.

Niemejier, A., Di Toro, G., Nielsen, S., & Di Felice, F. (2011). Frictional melting of gabbro under extreme experimental conditions of normal stress, acceleration, and sliding velocity. *Journal of Geophysical Research*, *116*, B07404. https://doi.org/10.1029/2010JB008181

Obata, M., & Karato, S. (1995). Ultramafic pseudotachylite from the Balmuccia peridotite, Ivrea-Verbano zone, northern Italy. *Tectonophysics*, *242*, 313–328.

Oelkers, E. H., & Gislason, S. R. (2001). The mechanism, rates and consequences of basaltic glass dissolution: I. An experimental study of the dissolution rates of basaltic glass as a function of aqueous Al, Si and oxalic acid concentration at 25°C and pH = 3 and 11. *Geochimica et Cosmochimica Acta*, *65*, 3671–3681.

Pennacchioni, G., Scambelluri, M., Bestmann, M., Notini, L., Nimis, P., Plümper, O., et al. (2020). Record of intermediate-depth subduction seismicity in a dry slab from an exhumed ophiolite. *Earth and Planetary Science Letters*, *548*, 116490.

Phillips, N. J., Rowe, C. D., & Ujiie, K. (2019). For how long are pseudotachylytes strong? Rapid alteration of basalt-hosted pseudotachylytes from a shallow subduction complex. *Earth and Planetary Science Letters*, *518*, 108–115.

Proctor, B., & Lockner, D. A. (2016). Pseudotachylyte increases the post-slip strength of faults. *Geology*, *44*, 1003–1006.

Rani, N., Shrivastava, J. P., & Bajpai, R. K. (2012). Near hydrothermal alteration of obsidian glass: Implications for long term performance assessments. *Journal of the Geological Society of India*, *79*, 376–382.

Rempe, M., Mitchell, T. M., Renner, J., Smith, S. A. F., Bistacchi, A., & Di Toro, G. (2018). The relationship between microfracture damage and the physical properties of fault-related rocks: The Gole Larghe Fault Zone, Italian Southern Alps. *Journal of Geophysical Research: Solid Earth*, *123*, 7661–7687. https://doi.org/10.1029/2018JB015900

Rowe, C. D., & Griffith, A. W. (2015). Do faults preserve a record of seismic slip: A second opinion. *Journal of Structural Geology*, *78*, 1–26.

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*(12), 937–940.

Rutter, E. H., Peach, C. J., White, S. H., & Johnston, D. (1985). Experimental "syntectonic" hydration of basalt. *Journal of Structural Geology*, *7*, 251–266.

Scambelluri, M., Pennacchioni, G., Gilio, M., Bestmann, M., Plümper, O., & Nestola, F. (2017). Fossil intermediate-depth earthquakes in subducting slab mantle linked to differential stress release. *Nature Geoscience*, *10*, 960–966.

Seyfried, W. E., & Mottl, M. J. (1982). Hydrothermal alteration of basalt by seawater under seawater-dominated conditions. *Geochimica et Cosmochimica Acta*, *46*, 985–1002.

Shand, S. J. (1916). The pseudotachylyte of Parijs (Orange Free State), and its relation to "Trap-Shotten Gneiss" and "Flinty Crush-rock". *Quarterly Journal of the Geological Society*, *72*, 198–221.

Sibson, R. H. (1975). Generation of pseudotachylyte by ancient seismic faulting. *Geophysical Journal of the Royal Astronomical Society*, *43*, 775–794. https://doi.org/10.1111/j.1365-246X.1975.tb06195.x

Sibson, R. H., Moore, J. M. M., & Rankin, A. H. (1975). Seismic pumping—A hydrothermal fluid transport mechanism. *Journal of the Geological Society*, *131*, 653–659.

Sibson, R. H., & Toy, V. G. (2006). The habitat of fault-generated pseudotachylyte: Presence vs. absence of friction-melt. *Geophysical Monograph-American Geophysical Union*, *170*, 153–166.

Smith, S. A. F., Bistacchi, A., Mitchell, T. M., Mittempergher, S., & Di Toro, G. (2013). The structure of an exhumed intraplate seismogenic fault in crystalline basement. *Tectonophysics*, *599*, 29–44.

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.

Swanson, M. T. (1989). Side wall ripouts in strike-slip faults. *Journal of Structural Geology*, *11*, 933–948.

Uijie, K., Yamaguchi, H., Sakaguchi, A., & Toh, S. (2007). Pseudotachylytes in an ancient accretionary complex and implications for melt lubrication during subduction zone earthquakes. *Journal of Structural Geology*, *29*, 599–613.

Violay, M., Nielsen, S., Gibert, B., Spagnuolo, E., Cavallo, A., Azais, P., et al. (2014). Effect of water on the frictional behavior of cohesive rocks during earthquakes. *Geology*, *42*, 27–30.

Violay, M., Passelègue, F., Spagnuolo, E., Di Toro, G., & Cornelio, C. (2019). Effect of water and rock composition on re-strengthening of cohesive faults during the deceleration phase of seismic slip pulses. *Earth and Planetary Science Letters*, *522*, 55–64.

References From the Supporting Information

Marone, C., & Scholz, C. H. (1989). Particle-size distribution and microstructures within simulate fault gouge. *Journal of Structural Geology*, *11*, 799–814.

Nestola, F., Burnham, A. D., Peruzzo, L., Tauro, L., Alvaro, M., Walter, M. J., et al. (2016). Tetragonal Almandine-Pyrope Phase, TAPP: Finally a name for it, the new mineral jeffbenite. *Mining Magazine*, *80*, 1219–1232.

Turcotte, D. L. (1986). Fractals and fragmentation. *Journal of Geophysical Research*, *91*, 1921–1926.