Supplementary Material

1. Experimental Methods

Our conventional triaxial test arrangement consists of a confining-fluid system with a servo-hydraulically controlled pressure intensifier. Pore-fluid pressure was not applied. We conducted constant-rate axial loading experiments using a servo-hydraulically controlled rig with 500 ton loading capacity. Rubber jackets enclosed the cylindrical samples. Axial load was measured with a load cell (accuracy 0.01 %) and axial displacement with a coupled pair of displacement transducers (accuracy 0.2 %). The axial piston advanced at a constant velocity of 0.1 mm/min corresponding to a nominal axial strain rate of $\sim 2 \times 10^{-5}$ s$^{-1}$. 
Supplementary Figure DR1

Schematic illustration of the triaxial experimental apparatus

2. Sampling

Cores of 30 mm diameter and 70 mm length ground to strict tolerances (± 0.01 mm) as to the squareness of their edges were prepared with pre-existing PST veins, saw cuts, or foliation planes were oriented at 30° to the sample long axis (Figure 2). Samples were oven dried at 60 °C before the triaxial experiments.
Supplementary Figure DR2

(a) Handspecimen of Alpine Fault Zone mylonite bearing PST, illustrating the cored area (dashed line).

(b) Cores of Alpine Fault Zone rock before deformation. (c) Cores of the Gole Larghe Fault Zone tonalite before deformation. All cores are 70 x 30 mm.
3. Microstructures of the natural PST bearing samples

3.1 Alpine Fault zone mylonitic host rock

The mylonite is derived from a quartzo-feldspathic Alpine Schist, resulting from amphibolite-facies metamorphism of a metasedimentary protolith (part of the Aspiring Lithologic Association of the Torlesse Terrane; Norris and Craw (2013). Its mineralogy by volume is ~40% quartz, ~35% oligoclase feldspar, ~15% mica (biotite + muscovite) and 10% accessory minerals, notably garnet, calcite, and amphibole. In places (commonly planar zones but also more pervasively), the biotite shows retrogression to a green Ti-deficient end member, or is altered to chlorite. Feldspar is slightly sericitised but generally retained its oligoclase composition. The main fabric is a planar and penetrative foliation defined by aligned phyllosilicates and rare mm-thick pure quartz or mixed quartz-feldspar bands. In general, the phases are well mixed. A lineation is not strongly developed in the polyphase rocks but is visible on the surfaces of thicker quartz bands (Toy et al., 2013).

3.2 Alpine Fault Zone pseudotachylyte

The PSTs are planar fault veins (in the sense of Sibson, (1975) with thicknesses of typically a mm or less, but some veins thicken up to a cm in lenses associated with fault plane irregularities. Injection structures at high angles to the fault are not common; where present they only extend to less than 1 mm off the fault vein. More commonly, associated fractures extend off the fault veins in Riedel shear orientations; these commonly bound wedge-shaped injection structures. These PSTs contain about 30% clasts, dominantly quartz and feldspar, in matrices composed of very fine grained phyllosilicates in which grain-long axes subtend obliquely (angles of 30°) to the vein boundaries. These matrices may have directly crystallised from a melt or may be a devitrification product. Foliation parallel PSTs and cataclasites are intimately associated and mostly cannot be confidently differentiated in the outcrops. In some cases,
blobs of PST occur within ultracataclasite veins. Cataclasites and PSTs commonly connect along fractures with Riedel shear orientations (Fig. 3a).

3.3 Gole Larghe Fault Zone tonalitic host rock

The Gole Larghe Fault Zone cuts across hornblende-free, generally homogenous fine- to medium-grained tonalites (< 1 cm in grain size) belonging to the Avio intrusion of the composite Adamello batholith (Bianchi et al., 1970). The Avio tonalite is part of a calc-alkaline series intruded the crystalline basement and covers of the Italian Southern Alps 34-32 Ma ago (Del Moro et al., 1983) to a depth of 9-11 km (see Di Toro and Pennacchioni 2004 for discussion). The tonalite is composed of plagioclase (andesine, 45–50 % in volume), quartz (25–30 %), biotite (15–20 %) and K-feldspar (1–5 %) (Di Toro and Pennacchioni, 2004). Greenschist to sub-greenschist alteration of tonalites occurs in limited volumes (typically less than few mm thick) bordering magmatic cooling joints (Di Toro and Pennacchioni, 2005; Pennacchioni et al., 2006).

3.4 Gole Larghe Fault Zone pseudotachylyte

Planar fault veins range up to 1 cm thickness and commonly overprint cataclasite, an epidote-cemented layer preserved parallel to the PST (Di Toro and Pennacchioni, 2005). Injection veins are common, comprising both veins that extend up to 20 cm off the slip surface at high but erratic angles, and more chaotic injection structures (Di Toro et al., 2005). The PST contains <20 % clasts of quartz and feldspar (the minor component), in an extensively devitrified and altered matrix now commonly composed of fine (< 10 μm) grains of epidote and chlorite (Di Toro and Pennacchioni, 2004).
4. Brittle microstructures generated in re-shear experiments

AFZ samples: During triaxial deformation experiments, two to three sub-parallel brittle fractures formed parallel to the foliation and the existing PST layer in the two tested samples and accommodated 400 μm of total displacement comprising co-seismic slip and post-stress drop stable sliding. Total co-seismic slip during the stress drop is not known. These fracture planes do not coincide with the PST layers but are localised around a quartz-rich lamination within the host rock. The fractures are wavy and display anastomosing linkages with one another. Although they appear open in thin sections they were filled with a gouge at the end of the experiment that was lost in thin-section preparation.

GLFZ samples: During triaxial deformation experiments, a single through-going fault formed within the Adamello tonalite host rock (main text Fig. 3b). The fault is wavy with an amplitude of 20 mm and a 15 mm wavelength. The fractures dilated as confining pressure was released so are open in the thin sections, but in places some cataclasites are preserved. The primary fault cuts across (main text Fig. 3b), displaces, and even cataclastically reworks injection structures from the original PST but without a clear relationship that indicates the pre-existing PST played a role in determining the locus of failure.

5. Calculations of cooling of pseudotachylyte veins:

Temperature distributions in and around PST veins were modelled envisioning cooling of a thin, infinite sheet by conduction perpendicular to its margins (Carslaw and Jaeger, 1959). The temperature, \( T \), on a profile perpendicular to the vein plane is given by:

\[
T = T_h + \frac{T_i-T_h}{2} \left[ \text{erf}\left(\frac{0.5l-z}{\sqrt{4kt}}\right) + \text{erf}\left(\frac{0.5l+z}{\sqrt{4kt}}\right) \right] \tag{1}
\]
where

\[ l \] is the thickness of the PST vein,

\[ T_i \] is initial temperature of the PST vein, approximated as 1450 °C for GLFZ and 1200 °C for the AFZ (Di Toro & Pennacchioni, 2004; Toy et al., 2011),

\[ T_h \] is the initial host rock temperature, taken as 350 °C for the AFZ, 250 °C for GLFZ (Di Toro and Pennacchioni, 2004; Toy et al., 2011),

\[ \kappa \] is thermal diffusivity of both gouge and host rock, taken as \(0.7 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}\) according to Di Toro & Pennacchioni, (2004),

\[ z \] is distance from the centre of the vein (average widths of 0.7 mm for the AFZ, 5.0 mm for GLFZ as illustrated in Fig. 2), and

\[ t \] is time.

The model predicts that the wall rock of the thin Alpine Fault PSTs (0.35 mm from the centres of the veins) cool below their solidus (assuming this is ca. 800 °C for the wall rock and the frictional melt) in \(<<1\) s and the vein centres in 0.2 s (supplementary Figure 3a). The GLFZ PSTs (2.5 mm from the centre of the vein) and the vein centre would have cooled below solidus in \(~5\) and \(~10\) s, respectively (supplementary Figure 2b).
**Supplementary Figure DR3**

(a) Temperature distribution during cooling of 0.7 mm thick Alpine fault PSTs calculated from Eq. 1. (b) Temperature distribution during cooling of 5 mm thick GLFZ PSTs.

**References**


