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Origin of hydrous fluids at seismogenic depth: Constraints from natural and experimental fault rocks

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ABSTRACT

Fluids control the mechanical behavior of fault zones during the seismic cycle. We used geochemical, mineralogical, microstructural, hydrogen isotope compositions and Fourier Transform Infrared (FTIR) investigations to characterize the origin of hydrous fluids involved in ductile and brittle shear zones at the bottom of the seismogenic crust. Natural samples were collected from exhumed mylonitic shear zones and cataclasite–pseudotachylyte bearing faults in the northern Adamello (Italian Southern Alps), which were active at 9–11 km depth. Pseudotachylytes, solidified coseismic friction-induced melts, testify to ancient seismogenic behavior of the faults. Natural pseudotachylytes were compared with artificial pseudotachylytes produced in high velocity friction experiments simulating seismic slip.

Mylonites have mineralogical, elemental and hydrogen isotope compositions ($-80‰ < \delta D < -78‰$) similar to the host tonalite ($-77‰ < \delta D < -73‰$), within the analytical error of $\pm 5‰$. Cataclasites have instead mineralogical (chlorite, epidote, K-feldspar, no biotite), major and trace elements (enrichment in K_2O, Ba, Rb; depletion in CaO, Na_2O, SiO_2) and hydrogen isotope ($-69‰ < \delta D < -60‰$) compositions suggesting interactions with a crustal metamorphic fluid. Pseudotachylytes are composed of high temperature minerals (plagioclase, biotite, dmisteinbergite, cordierite, and scapolite) and have elemental compositions resulting from mixing of tonalite and cataclasite. Pseudotachylytes have complex microstructures, including: (i) microlitic domains, with well crystallized micrometric biotite, which have hydrogen isotope composition ($-81‰ < \delta D < -59‰$) similar to cataclasites and tonalite; and (ii) cryptocrystalline domains, with poorly crystallized biotite, which have very high water content, release water upon heating at $T > 50\,^\circ C$ and have low δD value ($-93‰$). The hydrogen isotope composition of bulk samples is dominated by the composition of cryptocrystalline domains ($-103‰ < \delta D < -88‰$), where most of the water is hosted. Their hydrogen isotope composition is compatible with adsorption of present day rainfall water ($\delta D = -95‰$). Artificial pseudotachylytes have the same hydrogen isotope compositions of the starting tonalite ($-76‰ < \delta D < -74‰$) or cataclasite ($-68‰ < \delta D < -62‰$), with a slight decrease of the δD values in some samples ($-85‰ < \delta D < -81‰$).

The first ingression of a crustal metamorphic fluid occurred in cataclastic faults. Natural pseudotachylytes, when not contaminated by present day rainfall water, have a hydrogen isotope composition similar to tonalite and cataclasite, as reproduced in dry high velocity friction experiments. The fluids dissolved in coseismic melts are most likely derived from the breakdown of hydrous minerals of cataclasite and tonalite undergone melting, and we could not identify the infiltration of an external fluid during earthquakes.

1. Introduction

Faults are important conduits for fluid flow in the lithosphere (e.g., Kerrich, 1986; Caine et al., 1996; McCaig, 1997), and fluids are linked to the chemical and mechanical processes controlling fault mechanics during the seismic cycle (e.g., Etheridge et al., 1984; Reynolds and Lister, 1987; Hickman et al., 1995).

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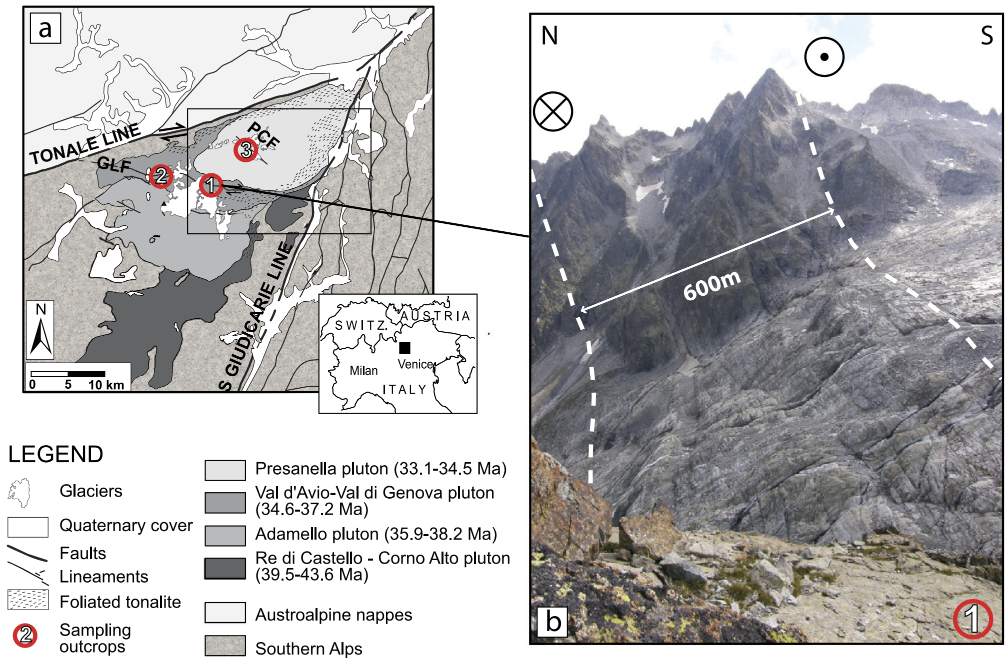

Fig. 1. Geological setting. (a) Simplified geological sketch of the Adamello batholith, with the main faults of the area (GLFZ = Gole Larghe Fault Zone; PCFZ = Passo Cercen Fault Zone) and the sampled outcrops (1: Lobbia glacier; 2: Avio Valley; 3: Cercen Pass). The ages of the plutons are U–Pb zircon LA-ICP MS dating from Skopelitis et al. (2012). (b) View of outcrop 1 at the front of the Lobbia glacier (to the South) along the Gole Larghe Fault Zone. The fault zone is composed of hundreds of sub-parallel fault strands oriented approximately E–W. The deep gullies oriented N–S are preferentially exploited by mylonites and late stage zeolite bearing faults.

Variations in fluid pressure might trigger seismicity by lowering the effective stresses and facilitating earthquake nucleation (Sibson, 1973, 1974; Beeler et al., 2000; Cocco and Rice, 2002; Miller et al., 2004). Long term fluid–rock interactions during the interseismic period promote mass transfer processes and mineral reactions, which gradually modify the composition and texture of fault rocks, controlling their mechanical properties, and accommodating aseismic creep (e.g., Sibson, 1977; Wintsch et al., 1995; Collettini et al., 2009; Gratier et al., 2011). Fault rocks include deformation structures formed in the various phases of the seismic cycle, and a combined textural and geochemical analysis of fault rocks has given insights on the origin of fluids in different geological environments (e.g., Lin et al., 2003; Ghisetti et al., 2001; Vannucchi et al., 2010).

At depth of nucleation of many crustal earthquakes, between 7 and 15 km (Scholz, 2002), faults in silicate rocks commonly contain cataclasites and, sometimes, pseudotachylytes (Sibson, 1977; Scholz, 2002). Cataclasites are cohesive fault rocks composed of wall rock fragments (Sibson, 1977), cemented by a mineral assemblage which is generally more hydrated than the wall rock (e.g., Magloughlin, 1992). Pseudotachylytes are solidified friction-induced melts which form during fault slip at seismic rates ($\sim$1 $m\,s^{-1}$) (Sibson, 1975) and are thought to form in the absence of pore fluids (e.g., Sibson and Toy, 2006). During seismic slip, it is expected that any fluid in the slipping zone would be pressurized because of frictional heating, causing total release of stresses and inhibiting melting (Sibson, 1973; Rice, 2006). However, pseudotachylytes often post-date hydrothermally cemented cataclasites (Magloughlin, 1992; Fabbri et al., 2000), thereby implying that pseudotachylytes can actually form in a fluid infiltrated fault. Importantly, formation of friction melts in the presence of fluids during earthquakes is supported by evidence from faults hosted in cohesive silicate-bearing rocks and from experiments, including: (1) the coexistence, in the same slipping zone, of pseudotachylytes in compressional jogs and vein fillings (precipitated from fluids) in dilatational jogs (Kirkpatrick and Shipton, 2009; Griffith et al., 2010); (2) the presence of vesicles, amygdales, and fluid inclusions in some pseudotachylytes (e.g., Maddock et al., 1987; Boullier et al., 2001; Magloughlin, 2011); (3) the formation of friction melts in experiments reproducing seismic deformation conditions in the presence of pore water (Violay et al., 2013). As a consequence, frictional melts are likely to dissolve any fluid impregnating the fault rocks or derived from melting of the hydrated minerals inside and close to the slipping zone.

Hydrogen and oxygen stable isotopes have been extensively used as tracers for the origin of hydrous fluids which interacted with silicate rocks in different geological processes (Taylor, 1974, 1977), including fault mechanics (e.g., Wickham and Taylor, 1985; McCaig, 1997). Previous studies demonstrated that the oxygen isotope compositions of pseudotachylytes are often buffered by the oxygen of the melted minerals, implying that only a small proportion, if any, of an external hydrous fluid was dissolved in the melt (O'Hara and Sharp, 2001; Moecher and Sharp, 2004). Hydrogen isotope compositions are more sensitive to the ingression of small quantities of water, or to fractionation due to chemical or physical processes (e.g., Sharp, 2007). Moecher and Sharp (2004) found variations in hydrogen isotope compositions of pseudotachylytes, likely due to hydrogen fractionation during muscovite crystallization in pseudotachylyte matrix during devitrification. Thus it was not possible to identify a source of fluids other than the hydrous host rock minerals undergone melting. The pseudotachylytes analyzed in their study were not associated with cataclasites, and do not show coherent traces of interaction with any external fluid.

We investigated the origin of fluids in mylonites, cataclasites and pseudotachylytes exhumed from 9–11 km depth in the Adamello batholith. Artificial pseudotachylytes produced in experiments simulating seismic slip (slip rate of $\sim$1 $m\,s^{-1}$, slip of few meters) on the Adamello's tonalites and cataclasites were used to investigate the volatile behavior during frictional melting. Natural and artificial samples were characterized by microstructural, mineralogical, geochemical and hydrogen isotope analyses. The natural cataclasites record the ingression of an external fluid, with hydrogen isotope composition compatible with crustal metamorphic origin. The natural pseudotachylytes include cryptocrystalline