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Deep-seated pseudotachylytes from the Ivrea Zone metagabbros (Southern Alps, Italy)

L. Pittarello[1*], G. Pennacchioni[2, 3] and G. Di Toro[2, 3]

[1]*Department of Lithospheric Research, Center for Earth Sciences, University of Vienna, Althanstrasse, 14 - 1090 Vienna, Austria.*

[2]*Università degli Studi di Padova, Dipartimento di Geoscienze, via G. Gradenigo, 6, 35131 Padova, Italy.*

[3]*Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605, 00143 Roma, Italy.*

[*]*e-mail: lidia.pittarello@univie.ac.at*

Abstract: Pseudotachylytes associated with localized ultramlylonites occur in the Premosello granulite-amphibolite metagabbros of the Ivrea Zone. Petrographic and microstructural data show that the pseudotachylyte developed under similar amphibolite facies metamorphic conditions as the ultramylonites. Our observations lend support to the model of several cycles of alternating pseudotachylytes and ultramylonites occurring in a dry middle-lower crust during the pre-Alpine exhumation. These pseudotachylytes might retain information on earthquake mechanics below the "normal" depth of the brittle-plastic transition in the crust.

Keywords: pseudotachylyte, mylonite, metagabbro, Ivrea Zone.

Pseudotachylytes are solidified melts produced by coseismic frictional sliding in faults within silicate-built rock (Sibson, 1975). Studying pseudotachylytes in exhumed faults might give information on several aspects of earthquake mechanics (Sibson, 1975; Di Toro *et al.*, 2005; Pittarello *et al.*, 2008) complementary to seismological information. Though pseudotachylytes are mostly generated in the upper brittle crust, they have also been reported from the ductile field developing in association with mylonites. Pseudotachylyte overprinted by low grade mylonites can be expected in the high differential stress region close to the plastic-brittle transition in the crust as result of plastic instabilities (Hobbs *et al.*, 1986), but pseudotachylytes have also been described at higher metamorphic grades up to granulite facies conditions (Sibson, 1980; Passchier, 1982; Clarke and Norman, 1993; Austrheim and Boundy, 1994; White, 1996; Pennacchioni and Cesare, 1997; Lin *et al.*, 2005). Different mechanisms have been proposed to explain production of pseudotachylytes in the middle and lower crust: plastic instability during creep (Hobbs *et al.*, 1986, White, 1996; Handy and Brun, 2004), downward propagation of seismic ruptures from the upper brittle crust (Tse and Rice, 1986; Scholz, 1988), and shear heating (Sibson, 1980; Kelemen and Hirth, 2007).

Here we describe pseudotachylytes associated with localized amphibolite facies mylonites within granulitic metagabbros of the Ivrea Zone. These metagabbros were formed by underplating at the base of the pre-Alpine continental crust and were exhumed during Permian lithospheric stretching without later strong involvement in Alpine metamorphism (Handy *et al.*, 1999). Therefore, these pseudotachylytes must have developed under high-grade conditions during the pre-Alpine exhumation path. The study of this type of deep-seated pseudotachylyte may discriminate between the different mechanism described above which has potential strong implications on the interpretation of the rheology of the continental crust as, for example, on the cut-off depth of propagation of seismic ruptures from the upper brittle crust (see Handy and Brun, 2004).

Geological setting

Samples of the studied pseudotachylytes were collected in the Premosello metagabbros of the Ivrea Zone (Italian Southern Alps) (Fig. 1). The Ivrea Zone consists of pre-Alpine continental lower crust and lithospheric mantle involved in Permo-Mesozoic extension, thinning and high temperature metamorphism (Giese, 1968; Brodie and Rutter, 1987; Zingg *et al.*, 1990). The metagabbros were emplaced by magmatic underplating about 299±5 Ma ago (Vavra *et al.*, 1999; Handy *et al.*, 1999) at the base of the crust and were pervasively deformed along high-temperature shear zones (280-270 Ma old). These shear zones developed either during prograde isobaric heating from amphibolite to granulite facies, according to some authors (Brodie, 1981; Brodie and Rutter 1985; Handy *et al.*, 1999), or might be related to isothermal decompression (Choudhuri and Silva, 2000).

Between 230 and 180 Ma localized mylonites developed in metagabbros during retrograde amphibolite facies conditions associated with extensional tectonics (Brodie and Rutter, 1987; Handy *et al.*, 1999). Alpine (50-20 Ma) faulting and folding affected the metagabbros, without a significant metamorphic overprint (Handy *et al.*, 1999).

Methods

Metagabbros and the crosscutting fault rocks were investigated with an optical microscope, scanning electron microscope (SEM), field-emission scanning electron microscope (FE-SEM) and electron probe microanalyzer (EPMA). Image analysis was performed with Adobe Photoshop and Image SXM (implemented by S. Barrett, see references). Geothermobarometry was conducted using the GTB software (Spear and Kohn, see references) and Thermocalc (Holland and Powell, 1998).

Results

The Premosello metagabbros consist of garnet (37% vol.) (Alm_{47}, Pyr_{34}, Gro_{15}, And_3, Spe_2; a list of mineral abbreviations is reported in Appendix 1), An_{85-54} plagioclase (31%), clino- and orthopyroxene (23%) (En_{37} Fs_{29} Wo_{28} diopside and En_{63} orthopyroxene), magnetite-ilmenite and apatite. Metagabbros are locally deformed to flaser gabbros with a foliation outlined by ribbons of dynamically recrystallized aggregates (grain size of 10-50 μm) of An_{50} plagioclase, by elongate domains of cataclastic garnet and pyroxene and thin layers of ilmenite-magnetite. Garnet and pyroxene commonly show rims of An_{85} plagioclase-orthopyrox-

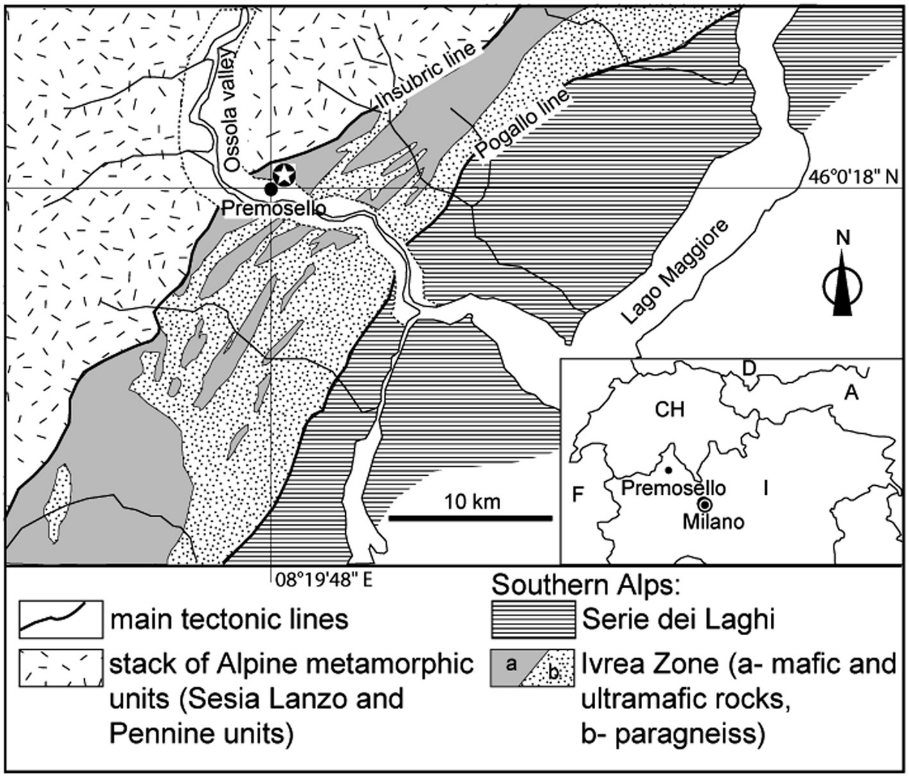

Figure 1. Simplified regional tectonic lower Ossola Valley (northwestern Italian Alps), modified from Handy *et al.* (1999). The studied samples were collected in the Premosello metagabbros (location is indicated by a star) of the mafic complex of the Ivrea Zone.

ene-magnetite kelyphite and symplectite (clinopyroxene/amphibole, magnetite/ilmenite and rare quartz), respectively, formed at 800-900 °C and 0.7-0.8 GPa (Zingg, 1990; Handy *et al.*, 1999).

The metagabbros and the flaser gabbros are cut by sharply bounded ultramylonites and pseudotachylytes. Ultramylonite (a few millimeters to centimeters thick) consists of a matrix (grain size of 1-5 µm) of An_{54} plagioclase, hornblende and magnetite/ilmenite including rounded clasts of plagioclase, pyroxene and garnet. Plagioclase-hornblende pairs from the matrix yield temperatures of 600-650 °C using the calibration of Holland and Blundy (1994).

Pseudotachylytes (Figs. 2a and 2b) are rather common and consist of a granoblastic matrix aggregate (grain size of 1-10 µm) of plagioclase, a mafic phase (EPMA analyses show a wide scatter in composition indicating a cryptocrystalline intergrowth of different minerals, though not visible under the FE-SEM), ilmenite/magnetite and rare idioblastic garnet (Alm_{64}, Gro_{12}, Pyr_{11}, And_{8}, Spe_{5}) (Figs. 2b, 2c and 2d). The garnet is poikilitic with small (~1-2 µm) inclusions of matrix minerals. Locally (mainly in injection veins), plagioclase (An_{47}) shows microlite crystal shapes typical of pseudotachylyte (Fig. 2f). The pseudotachylyte matrix includes clasts of the host rock plagioclase (most common), pyroxene and apatite. Garnet is almost absent among clasts.

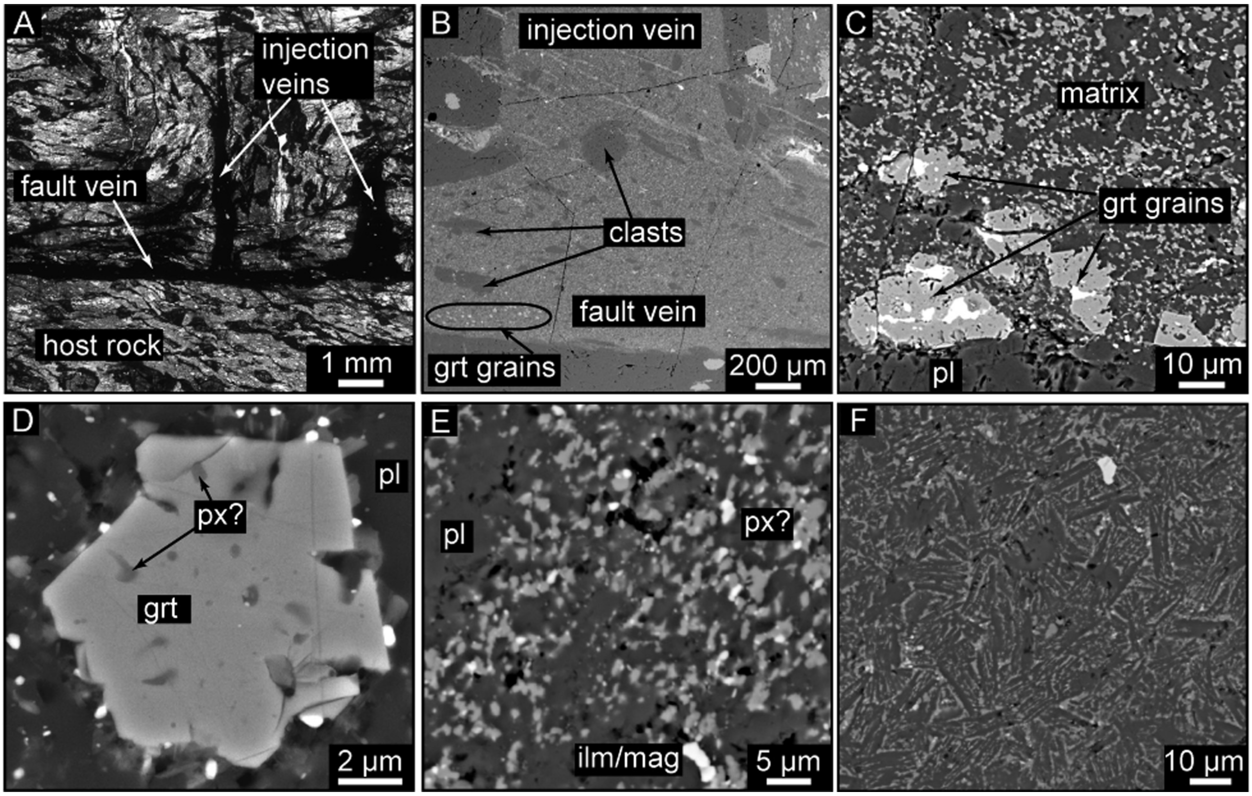

Figure 2. Microstructures of the Premosello pseudotachylyte. (A) Photo of a thin section under optical microscope showing pseudotachylyte veins in plane polarized light. Pseudotachylyte fault vein (E-W black layer) with two injection veins within flaser gabbros. Both the fault and injection veins cut the foliation of the host rock discordantly. (B) Back-scattered SEM image showing the detail of the intersection between the fault vein and central injection vein in (A). The pseudotachylyte fine grain of the matrix includes elongate plagioclase clasts (dark gray) defining a foliation in the fault vein, slightly oblique to the vein boundary, that disappears in the injection vein. In the lower left side of the fault vein a cluster of small idioblastic garnets (grt) is present. (C) Back-scattered SEM image of garnet grains in (B). Garnets have idioblastic shape and show inclusions of ilmenite/magnetite aligned with the matrix foliation. (D) Back-scattered FE-SEM image of poikilitic single idioblastic garnet in the pseudotachylyte with small inclusions of pyroxene (px?). (E) Matrix in the pseudotachylyte fault vein consisting of plagioclase (pl; dark gray), a femic mineral phase (px?; light gray) and small bright grains (white) of ilmenite/magnetite. (F) Plagioclase microlites in the injection vein. Microlites are decorated along the edges by small bright grains of oxides. Both (E) and (F) are backscattered SEM images.

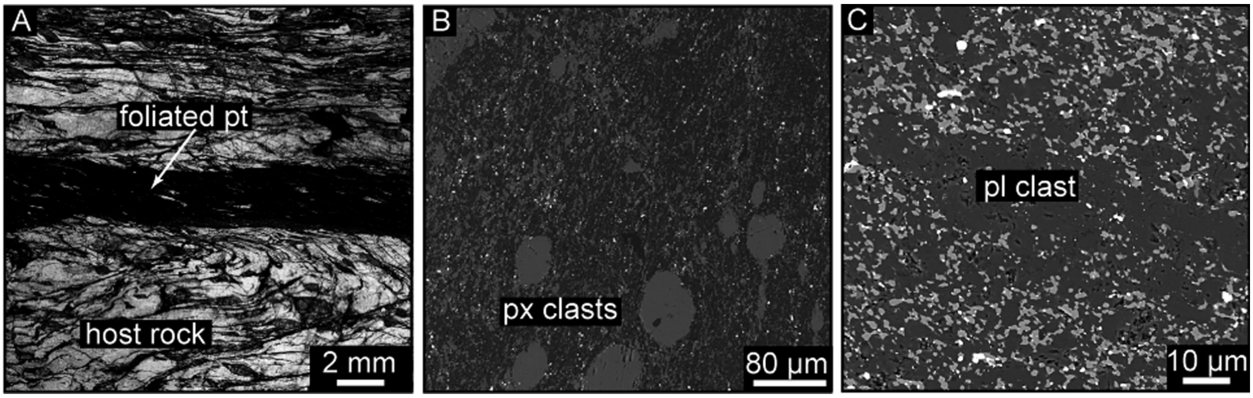

Figure 3. Foliated pseudotachylyte. (A) Optical micrograph showing the foliation in a pseudotachylyte (pt) fault vein highlighted by elongated white ribbons of plagioclase derived from shearing of former clasts. (B) Backscattered SEM image of clasts of host pyroxene (px) within the foliated matrix of a sheared pseudotachylyte. (C) Backscattered SEM image of elongated clast of plagioclase (pl; dark gray) in the recrystallized matrix of a sheared pseudotachylyte consisting of plagioclase, pyroxene/amphibole (?) and ilmenite/magnetite.

Some pseudotachylytes show a crystal-plastic overprint with development of a foliation (Figs. 3a and 3b), outlined by elongated and recrystallized plagioclase clasts (Fig. 3c). Some typical localized ultramylonites in the metagabbros also preserve a non-foliated portion of the matrix, including angular clasts and showing cataclastic relationships with the host metagabbros in embayment in the host rock (Fig. 4).

Discussion and conclusions

The fine grain size and the mixed composition of the mafic component of the pseudotachylyte matrix did not allow a precise estimate of the temperature of formation of the frictional melts in the Premosello metagabbros. However, the presence of a crystal-plastic overprint of pseudotachylyte, the dynamic recrystallization of an An-rich (An_{47}) plagioclase and the growth of garnet on the pseudotachylyte matrix suggest amphibolite facies ambient conditions for the pseudotachylyte development. Pseudotachylytes have already been described in the Ivrea gabbros by Brodie and Rutter (1987) and by Zingg *et al.* (1990), but they were interpreted as having formed during the low temperature Alpine history. Our new observations indicate that a part of these pseudotachylytes must be referred to as pre-Alpine consistently with the assumption of Handy and Brun (2004).

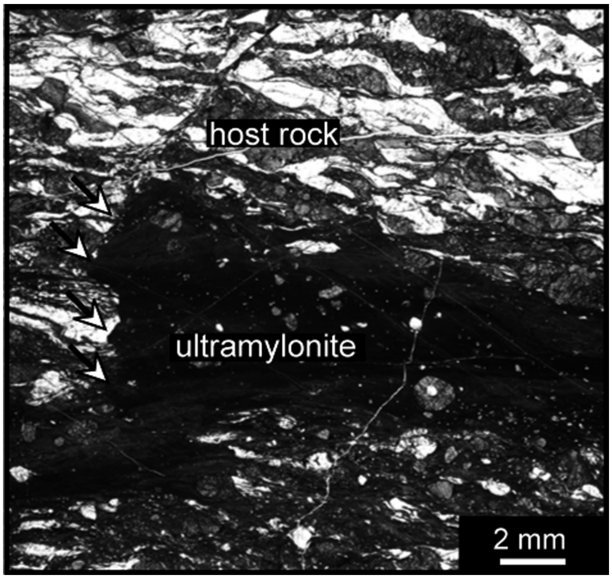

Figure 4. Localized ultramylonite. Optical micrograph of the localized ultramylonite showing a portion of the ultramylonite (marked by arrows) in an embayment in the host metagabbro, with angular fragments and cataclastic relationships with the host rock.

The widespread production of frictional melts, at temperatures under which metagabbros should be capable of ductile flow and well below the typical plastic-brittle transition of crustal rocks, is consistent with different processes including downward propagation of seismic ruptures from the upper brittle crust (Tse and Rice, 1986; Scholz, 1988), plastic instabilities (Hobbs *et al.*, 1986; White, 1996; Handy and Brun, 2004) and shear heating (Sibson, 1980; Kelemen and Hirth, 2007).

The relatively high ambient temperature of generation of pseudotachylytes has been associated with relatively dry conditions in the middle-lower crust (Pennacchioni and Cesare, 1997) affecting the temperature of the brittle-plastic transition. There is not a straightforward criterion to discriminate between the above listed mechanics actually responsible for generation of deep-seated pseudotachylytes although some microstructural observations apparently lend support to the concept of a relatively strong middle-lower crust due to the presence of water-deficient rocks (Mancktelow and Pennacchioni, 2004; Fitz Gerald *et al.*, 2006). Discriminating between these processes is of paramount importance in the understanding of the rheology of the continental crust and will be the topic of a forthcoming work.

The association between very localized ultramylonite and pseudotachylyte of similar thickness and orientation, the presence of an amphibolite facies overprint of some mylonites and the relict cataclastic features preserved in some domains of ultramylonites suggest that pseudotachylyte may have acted as structural heterogeneities for the nucleation and localization of some mylonitic deformation after post-seismic stress relaxation. The primary role of pre-existing structural and compositional heterogeneities in the nucleation of ductile shear zones is well established in several metamorphic environments (e.g. Mancktelow and Pennacchioni, 2005; Pennacchioni and Mancktelow, 2007).

Appendix 1. List of mineral symbols

These abbreviations are used in the text for mineral names: Alm: almandine; And: andradite; An: anorthite; En: enstatite; Fs: ferrosillite; Gro: grossular; Pyr: pyrope; Spe: spessartine and Wo: wollastonite.

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