STUDY OF EXHUMED PALAEO-SEISMIC FAULTS AS A GAUGE TO ESTIMATE EARTHQUAKE SOURCE PARAMETERS

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ABSTRACT

Exhumed faults decorated by pseudotachylyte (*i.e.*, solidified friction induced melt recording a seismic rupture) might give information about the earthquake source. Two cases, representative of different seismogenic environments have been investigated: the pseudodotachylyte-mylonite association in the middle-lower crust, in the Ivrea Zone metagabbros and kinzigite-mylonites, and the "upper crust" pseudotachylytes in the Tertiary Adamello granitoid batholith.

In the metagabbro and kinzigite-mylonites, a cyclical and coeval production of frictional melts and localized ultramylonites, under amphibolite facies metamorphic conditions, has been documented.

From a selected pseudotachylyte-bearing fault hosted in the Adamello batholith the earthquake energy budget was estimated, concluding that most energy was dissipated as frictional heat. The thermal evolution of a frictional melt and of included clasts has been modeled, demonstrating that the pristine cataclastic structure used to estimate the surface energy can be locally preserved.

INTRODUCTION

Pseudotachylytes are fault rocks made of solidified melts including relict clasts of the host rock and produced by coseismic frictional sliding within silicate-built rock (Sibson, 1975). Pseudotachylytes allow the estimate of mechanical parameters of the seismogenic source, *e.g.* the depth of the seismic rupture, the dynamic fault strength, the energy budget of an earthquake (*e.g.*, Di Toro *et al.*, 2006; Zechmeister *et. al.*, 2007), which sometimes cannot be estimated by seismological data.

This work investigated pseudotachylytes produced at different crustal levels, choosing two cases representative of the middle-lower and of the upper crust, respectively. Besides field and lab-analysis the frictional melt production and the following thermal evolution have been studied and modeled.

METHODS

Pseudotachylytes were studied in the field, collecting samples and structural data. Microstructures were investigated with optical microscope, scanning electron microscope (SEM), electron backscatter diffraction (EBSD) and field emission scanning electron microscope (FE-SEM). Quantitative microstructural analysis was performed with Adobe Photoshop, Adobe Illustrator, and Image SXM (Barrett, 2008). Chemical compositions were estimated with the energy dispersive spectroscopy (EDS) connected to the SEM, the electron probe micro analyzer (EPMA) and X-ray powder diffraction (XRPD). The Rietveld refinement has been also applied to the XRPD data for a quantitative estimate of the mineralogical composition. Geothermobarometry was conducted using the software GTB (Kohn & Spear, 2001), hb-plag.1.sea (Holland & Blundy, 1994), and Thermocalc (Holland & Powell, 1998).

DEEP-SEATED PSEUDOTACHYLYTES IN IVREA ZONE METAGABBRO AND KINZIGITE-MYLONITES

Pseudotachylytes associated with localized ultramylonites occur inside the Premosello granulite metagabbros and the adjacent kinzigite-mylonites of the Premosello area (Ossola Valley) in the Ivrea Zone. The Ivrea Zone represents a slice of the pre-Alpine continental lower crust and lithospheric mantle tectonically exhumed and exposed in the Italian Southern Alps (Giese, 1986; Brodie & Rutter, 1987; Zingg *et al.*, 1990). Pseudotachylytes are mostly generated in the brittle upper crust (Scholz, 1988), but they are also reported from the middle to lower crust, where rocks usually deform by crystal-plastic processes at the normal tectonic strain rate, in association with mylonites (Sibson, 1980; Passchier, 1982; Clarke & Norman, 1993; Camacho *et al.*, 1995; Pennacchioni & Cesare, 1997; John & Schenk, 2006; Andersen & Austrheim, 2006). Pseudotachylytes formed in high temperature conditions might retain information on earthquake mechanics below the “normal” depth of the brittle-plastic (elasto-frictional/viscous-plastic) transition in the crust.

Petrographic and microstructural data and geothermobarometry indicate that the studied pseudotachylytes and localized ultramylonites developed coevally under the same metamorphic conditions (temperature higher than 550°C). In particular, the development of poikilitic and dendritic garnet over the recrystallized matrix of pseudotachylytes (Fig. 1) allows us to constrain the frictional melt solidification temperature.

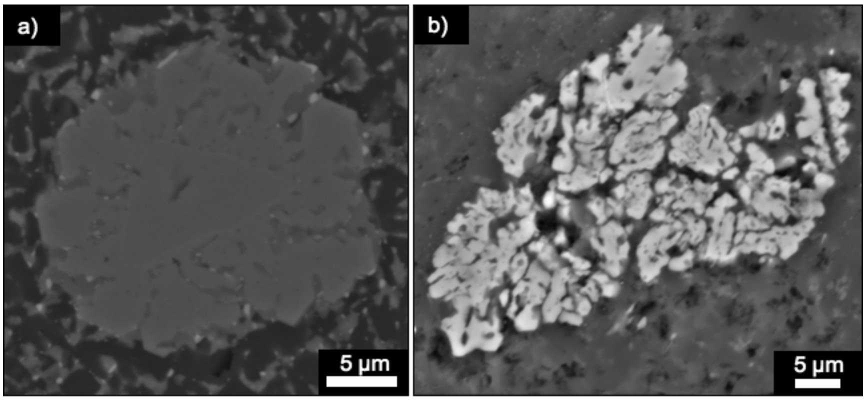

Fig. 1 - New garnet in the pseudotachylyte matrix. a) Dendritic overgrowth of new garnet around a small clast of granulitic garnet within the pseudotachylytes inside metagabbro. The pseudotachylytes matrix is composed by labradorite-bytwonite plagioclase (77.5%), orthopyroxene (11.8%) and dispersed ore mineral. BSE-SEM image. b) Dendritic garnet in the pseudotachylytes within the kinzigite-mylonites. The matrix is composed by quartz, oligoclase, K-feldspar and biotite. BSE-SEM image.

The mutual overprinting relationships between pseudotachylytes and ultramylonites, the presence of foliated pseudotachylytes and the association of ultramylonites with a cataclastic deformation of the host rock suggest: (i) cyclical production of frictional melts during high temperature conditions (Handy & Brun, 2004) in a dry middle-lower crust (see, *e.g.*, Pennacchioni & Cesare, 1997) during the pre-Alpine exhumation, and (ii) that pseudotachylytes form the brittle precursor for nucleation and localization of viscous-plastic shearing (Mancktelow & Pennacchioni, 2005).

THE ENERGY BUDGET OF AN EARTHQUAKE AT 10 KM DEPTH

The determination of the earthquake energy budget remains a challenging issue for Earth scientists, as understanding the partitioning of energy is a key towards the understanding the physics of earthquakes. The partitioning of the mechanical work density into heat and surface energy was estimated for a selected fault segment of a strike-slip fault zone crosscutting the Adamello batholith. This fault has recorded a single seismic rupture, as demonstrated by field and microstructural analyses on the filling pseudotachylyte, and was exhumed from a depth of 10 km.

The frictional heat was estimated by the volume of pseudotachylyte along the fault, according to the method of Di Toro *et al.* (2005) and it yields ~ 27 MJ m^{-2}. The surface energy, the energy required to create new surface by fracturing, was estimated from the microcrack density inside clasts of the host rock preserved by melting within the pseudotachylytes. In particular, the characteristic internal fragmentation of plagioclase clasts (Fig. 2), referable to the coseismic slip, was considered and yields a value less than

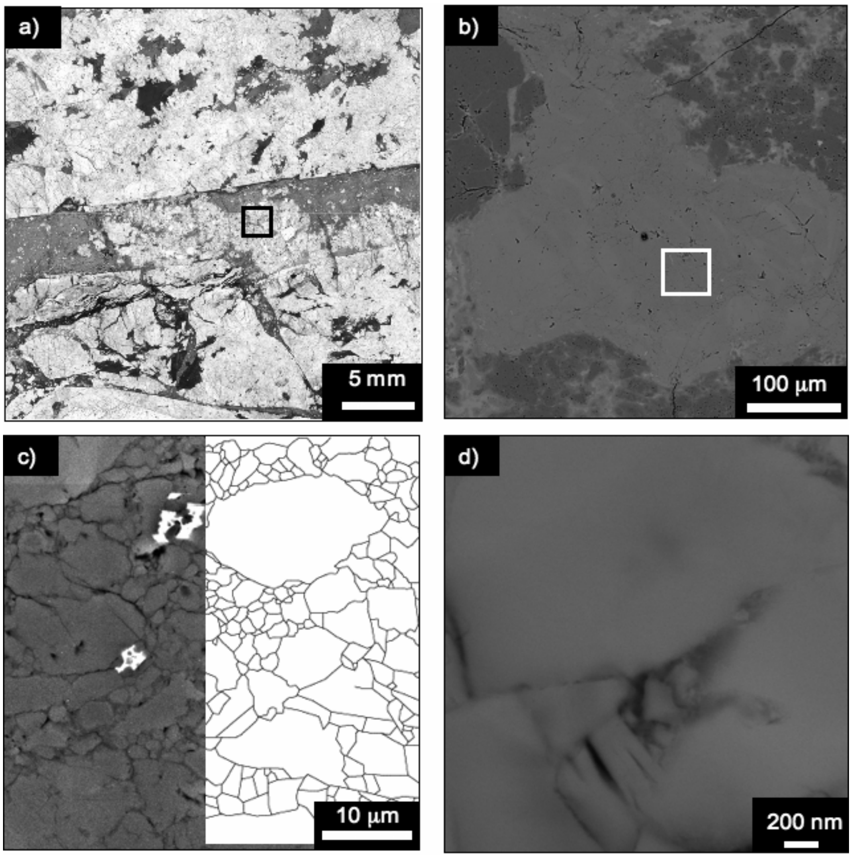

Fig. 2 - Fragmentation of plagioclase clasts. a) Pseudodachylyte vein containing white clasts of plagioclase and quartz suspended in a glassy-like matrix. Optical microscope, polarized light. The box indicates the location of the microstructure shown in (b). b) Clasts of plagioclase (light grey) and quartz (dark grey). BSE-SEM image. The white box indicates the location of the microstructure shown in (c). c) Internal fragmentation of plagioclase clasts: BSE FE-SEM image on the left and drawing of the network of fragment boundaries on the right. d) Enlargement of an area in (c) showing the smallest fragments. BSE FE-SEM image.

0.85 MJ m^{-2}. Therefore in the case of the studied seismic faulting most (97%) of the energy budge was dissipated as heat on the fault plane (for details, see Pittarello *et al.*, 2008).

THERMAL EVOLUTION OF A FRICTIONAL MELT

The estimate the surface energy produced during an earthquake along the Adamello pseudotachylyte-bearing fault was based on the assumption that the microstructural fragmentation within the plagioclase clasts escaped any alteration after their formation. Although the fragments used for the estimate of the surface energy do not show evidence for melt-fragment interaction, other clasts fragments show reverse zoning likely developed during the high temperature stages of cooling of the frictional melt. Therefore this process may have obliterated the pristine fragment size distribution.

To determine the potential of preservation of the original clast internal microstructure, the thermal evolution of the pseudotachylyte and of the plagioclase clast have been modeled under different conditions (position of the clast in the vein, the clast size, the initial thermal conditions and the vein thickness). The methods used for modeling are the theoretical analysis (Carslaw & Jaeger, 1959) and numerical FEM modeling (Comsol Multiphysics). The results of the modeling indicate that, under particular conditions (clast radius larger than a critical size and position of the clast near the vein margins), the diffusion and the growth within plagioclase clast are negligible and the pristine microstructure may be preserved.

CONCLUSIONS

The study of tectonic pseudotachylytes allows the estimate of different earthquake source parameters and is complementary to the seismological approach. In this work, the metamorphic conditions for the coeval formation of pseudotachylytes and related ultramylonites in Ivrea Zone metagabbros and kinzigite-mylonites have been estimated by microstructural analyses. The determined metamorphic conditions are in agreement with earthquake nucleation in a "brittle" dry middle-lower crust. The field and microstructural analysis of a selected pseudotachylyte from the Adamello batholith allows the estimate of the energy budget for an earthquake nucleated at 10 km depth: under those conditions most energy is spent as heat. Furthermore, the thermal evolution of such pseudotachylyte has been modeled, allowing the constrain of the conditions for preservation of the pristine microstructures.

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