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Pseudotachylyte in muscovite-bearing quartzite: Coseismic friction-induced melting and plastic deformation of quartz

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ABSTRACT

Thin (0.5–2 mm thick) pseudotachylyte veins occur within muscovite-bearing (∼10% volume), amphibolite-facies quartzites of the Schneeberg Normal Fault Zone (Austroalpine, Southern Tyrol, Italy). Pseudotachylytes are associated with precursor localized plastic microshear zones (50–150 μm thick) developed sub-parallel to the host-rock foliation and with conjugate sets oriented at a high angle to the foliation. Such microshear zones are characterized by recrystallization to ultrafine-grained (1–2 μm grain size) mosaic aggregates of quartz showing a transition from a host-controlled to a random crystallographic preferred orientation towards the shear zone interior. Subsequent coseismic slip mainly exploited these microshear zones. Microstructural analysis provides evidence of extensive friction-induced melting of the muscovite-bearing quartzite, producing a bimodal melt composition. First, the host-rock muscovite was completely melted and subsequently crystallized, mainly as K-feldspar. Then, about 60% volume of the ultrafine-grained quartz underwent melting and crystallized as spherulitic rims (mostly consisting of quartz ± Ti ± Fe) around melt-corroded quartz clasts. The two melts show immiscibility structures in the major injection veins exploiting microshear zones at high angles to the quartzite foliation. In contrast, they were mechanically mixed during flow along the main fault veins.

1. Introduction

Tectonic pseudotachylytes are solidified friction-induced melts produced along a fault during seismic slip (i.e. at slip rates of 1–3 ms^{-1}) (Sibson, 1986; Spray, 1992; Swanson, 1992; Sibson and Toy, 2006; Lin, 2008; Di Toro et al., 2009 and references within). They have been reported in a large variety of silicate-built rocks including felsic to mafic-ultramafic intrusive rocks and different metamorphic rocks (Sibson and Toy, 2006; Di Toro et al., 2009). However, pseudotachylytes within quartzites have not been reported previously.

Non-equilibrium melting is inferred to be the dominant process during friction-induced melting as indicated by the disappearance, or a decrease in the percentage, of host-rock clasts of low-melting point minerals (e.g. micas and amphiboles) in the pseudotachylyte. Preferential melting of mafic minerals (having relatively low single-phase melting point) results in a more basic composition of the pseudotachylyte melt (or matrix) than the host-rock, whereas the bulk pseudotachylyte composition (clasts + matrix) is identical to that of the host-rock (Allen, 1979; Bossière, 1991; Camacho et al., 1995; Maddock, 1986, 1992; Magloughlin, 1989; Sibson, 1975; Spray, 1992, 1993; Di Toro and Pennacchioni, 2004). In pseudotachylytes from within granitoid rocks: (i) biotite melts completely, (ii) plagioclase (with a melting temperature under dry conditions in the range of 1100–1550 °C) undergoes partial to complete melting in the centre of centimetre thick veins, indicative of superheating of friction-induced melts (Di Toro and Pennacchioni, 2004), and (iii) quartz, having a very high melting temperature (1720 °C under dry conditions; Deer et al., 1992), commonly survives as clast, although embayed shapes have been reported as local evidence of quartz melting (Lin, 2008 and references within). In addition to the high melting point of quartz, the friction-induced melting of this mineral is potentially hindered by the occurrence of extreme fault weakening at high slip rates; this has been experimentally determined in quartzite and related to lubrication by silica gel (Di Toro et al., 2004).

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The maximum temperature achieved during friction-induced melting is an important parameter for estimating the energy budget of an earthquake from exhumed paleoseismic faults (Di Toro et al., 2005). To estimate this temperature, minerals surviving melting have often been used (e.g. Maddock, 1983). The commonly reported range of estimated and inferred friction melt temperatures is 650–1730 °C (Sibson and Toy, 2006). The observation of quartz melting could therefore provide evidence for unusually high thermal peaks (in a dry environment). The amount of quartz involved in melting to form a pseudotachylyte cannot be easily quantified. Spherulitic overgrowth structures around quartz clasts have been described in some pseudotachylytes (e.g. "quartz-nucleus spherulites": Lin, 1994; Di Toro and Pennacchioni, 2004), where inclusion-rich quartz rims surround rounded quartz clasts. However, these features cannot be univocally related to the achievement of single-quartz melting point.

In this study, we report on the occurrence of pseudotachylytes within muscovite-bearing (~10% volume) amphibolite-facies quartzites of the "Schneeberg Normal Fault Zone" (Austroalpine, Southern Tyrol, Italy) clear evidence of extensive frictional melting of quartz. The detailed microstructural and electron microscope analysis (scanning electron microscopy – SEM, electron backscatter diffraction technique – EBSD, and transmission electron microscopy – TEM) show a close spatial association between pseudotachylytes and ultrafine-grained aggregates (grain size in the order of a few microns) delineating microshear zones in the host quartzite close to the fault vein.

2. Methods

2.1. Sample preparation

Optical microscopy (transmitted light) and SEM analysis were carried out on oriented samples. Polished thin-sections were obtained from slabs cut parallel to the mineral lineation (X-axis) and perpendicular to the foliation (XY plane) of the quartzite hosting the pseudotachylyte. The XZ section is also orthogonal to the pseudotachylyte veins. EBSD measurements (Section 5.1.2) have shown that this reference frame also contains the main kinematic axes of the network of microshear zone precursors of seismic slip. For SEM analyses, the thin-sections were chemical polished using a colloidal silica suspension (SYTON) and subsequently carbon coated (coating thickness of ca. 3 nm).

2.2. SEM analysis

SEM analyses were carried out with a ZEISS *CrossBeam* 1540 EsB equipped with a thermo-ionic field emission located at the Department of Material Sciences of the University Erlangen-Nuremberg. The cathodoluminescence (CL) images of Fig. 10d was produced with a TESCAN Vega-XM-U SEM attached with a CL-system.

2.3. EBSD

Full crystallographic orientation data were obtained from automatically indexed EBSD patterns collected in beam scan mode on a 0.2 and 0.3 μm grid (working conditions: working distance 16 mm, 20 kV acceleration voltage, 120 μm aperture and high current mode resulting in ca. 7 nA beam current). The stored EBSD patterns were indexed by using the program CHANNEL 5.09 from Oxford Instruments. The centre of 8 Kikuchi bands was automatically detected using the Hough transform routine (Schmidt et al., 1991; Adams et al., 1993) with a resolution of 120 (internal Hough resolution parameter in the software). The solid angles calculated from the patterns were compared with the mineral specific match unit (muscovite, quartz and/or orthoclase) containing 75 reflectors to index the patterns.

EBSD orientation data are presented as processed orientation maps. Non-indexed points were replaced by the most common neighbouring orientation. The degree of processing required to fill non-indexed data points, without introducing artefacts, was tested carefully by comparing the resulting orientation map with the pattern quality map (Bestmann and Prior, 2003).

2.4. TEM

The TEM foils were examined at 300 kV in a Phillips CM 30 Twin/STEM transmission electron microscope at the Central Facility for High Resolution Electron Microscopy of the University Erlangen-Nuremberg. All diffraction contrast images were produced using bright field (BF) conditions. Geochemical energy-dispersive spectroscopy (EDS) analyses (element mapping and line scans) were carried out in the scanning transmission electron microscopy (STEM) mode with an Oxford Instrument ISIS 300 EDS system, using a Si(Li) detector.

Two different sample preparation methods were applied for the TEM analysis. Samples of 1 inch size were assembled with a 200 μm spaced copper net for conventional ion beam thinning with a BAL-TEC BALZER RES 010 (thinning parameter: inclination angle 11–12°, acceleration voltage 3.5–5 kV). This sample preparation was not appropriate for geochemical area analyses in the TEM because in a polyphase rock, such as the pseudotachylyte, a sample topography could not be excluded. Such small-scale irregularities on the sample surface might cause thickness-dependent artefacts especially in EDS line scans and element mappings. To guarantee plane parallel electron-transparent foils, the focussed ion beam (FIB) technique was applied. This technique allows site specific TEM foils (10–20 μm wide, 5–15 μm high and 100–200 nm thick) to be prepared through Ga-ion beam thinning on standard thin-sections. The TEM foils were prepared using a ZEISS *CrossBeam* 1540 EsB at the Material Science Department at the University Erlangen-Nuremberg.

2.5. Electron microprobe analysis (EMPA)

Compositional data of muscovite and K-feldspar were measured on a Jeol JXA-8200 at the GeoZentrum Nordbayern (University of Erlangen-Nuremberg). Natural silicates were used as standards and a ZAF routine was applied for matrix correction. Measuring conditions using a focussed electron beam were: 15 kV acceleration voltage and 15 nA beam current.

2.6. Image analysis

Image analysis was performed on the quartzite and pseudotachylyte veins in order to estimate the relative amounts of minerals and of the different fabric elements within the pseudotachylyte (i.e. matrix, quartz clasts and spherulitic quartz overgrowth on clasts). Image analysis was carried out with DIAna software (©J. Duyster).

Host-rock volume percentage of quartz, muscovite and K-feldspar were determined from manual drawings from light optical microscope images. The analysis of pseudotachylyte veins was performed automatically on SEM-BSE images using a greyscale range selection option in the DIAna software.

3. Geological setting

The Schneeberg Normal Fault Zone (SNFZ) is developed in the Schneeberg/Monteneve Unit (SMU) which belongs to the composite Austroalpine nappe of the central-Eastern Alps that was