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Deformation processes at the down-dip limit of the seismogenic zone: The example of Shimanto accretionary complex

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ABSTRACT

In order to constrain deformation processes close to the brittle-ductile transition in seismogenic zone, we have carried out a microstructural study in the Shimanto accretionary complex (Japan), the fossil equivalent of modern Nankai accretionary prisms. The Hyuga Tectonic Mélange was sheared along the plate interface at mean temperatures of 245 °C ± 30 °C, as estimated by Raman spectroscopy of carbonaceous material (RSCM). It contains strongly elongated quartz ribbons, characterized by very high fluid inclusions density, as well as micro-veins of quartz. Both fluid inclusion planes and micro-veins are preferentially developed orthogonal to the stretching direction. Furthermore, crystallographic preferred orientation (CPO) of quartz *c*-axes in the ribbons has maxima parallel to the stretching direction. Recrystallization to a small grain size is restricted to rare deformation bands cutting across the ribbons. In such recrystallized quartz domains, CPO of quartz *c*-axes are orthogonal to foliation plane. The evolution of deformation micro-processes with increasing temperature can be further analyzed using the Foliated Morotsuka, a slightly higher-grade metamorphic unit (342 ± 30 °C by RSCM) from the Shimanto accretionary complex. In this unit, in contrast to Hyuga Tectonic Mélange, recrystallization of quartz veins is penetrative. CPO of quartz *c*-axes is concentrated perpendicularly to foliation plane. These variations in microstructures and quartz crystallographic fabric reflect a change in the dominant deformation mechanism with increasing temperatures: above ~300 °C, dislocation creep is dominant and results in intense quartz dynamic recrystallization. In contrast, below ~300 °C, quartz plasticity is not totally activated and pressure solution is the major deformation process responsible for quartz ribbons growth. In addition, the geometry of the quartz ribbons with respect to the phyllosilicate-rich shear zones shows that bulk rheology is controlled by quartz behavior. Consequently, below 300 °C, the application of quartz pressure-solution laws, based on realistic geometry derived from Hyuga microstructures, results in strongly lowering the overall strength of the plate interface with respect to the classical brittle envelop.

1. Introduction

As illustrated by the rheological envelopes model (e.g. Evans and Mackwell, 1995; Stöckhert and Gerya, 2005; Burov, 2011), crustal deformation is usually accounted for brittle/plastic deformation in its upper/lower part. The transition from dominant cataclastic flow to dislocation creep, often referred to as the brittle-ductile transition (Rutter, 1986; Chester, 1995) is promoted by increasing depth and temperature.

This transition is generally associated to the temperature of ~350 °C corresponding to the limit for the onset of quartz plasticity (Tse and Rice, 1986; Hyndman et al., 1997) in quartzo-feldspatic rocks (e.g. Tullis and Yund, 1977, 1980; Blanpied et al., 1991). As observed in deformed rocks of the upper crust (Ramsay, 1967; Durney, 1972; Kerrich et al., 1977; Gratier and Gamond, 1990; Becker, 1995) above the brittle/ductile transition and in the presence of abundant intergranular fluid phase (e.g. Gratier, 1987) cataclastic flow is accompanied by the contribution of another process, pressure solution creep (PSC). PSC has been defined as a non-equilibrium process (Spiers et al., 2004; Gratier et al., 2009) involving dissolution of material at high stressed regions (e.g. grain contacts), diffusion through a grain boundary fluid phase and precipitation on grain interfaces under low normal stress (Rutter and Elliott, 1976; Raj, 1982; Spiers et al., 1990; Shimizu, 1995). The importance of PSC is also recognized at high metamorphic

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conditions such as blueschist and amphibolite facies (Bell and Cuff, 1989; Wintsch and Yi, 2002), e.g. in the development of crenulation cleavage if stresses are not high enough for the activation of plastic deformation (Brander et al., 2012). The most common microstructures suggesting the operation of pressure solution are stylolite, micro-fractures, mineral shadows or fringes and dissolution cleavages (Evans, 1988; Goodwin and Wenk, 1990). In contrast with cataclasis which requires high differential stresses and act at high strain rates, pressure solution is most characteristic of slow creeping processes which take place in the upper crust at very low differential stress (Cox and Etheridge, 1989; Gratier and Gamond, 1990). Pressure solution contributes significantly to the overall strain (Ramsay, 1967; Durney, 1972; Kerrich et al., 1977; Cox and Etheridge, 1983; Gratier, 1993; den Brok, 1998; Spiers et al., 2004): the estimations of bulk volume loss due to this process can range from 30 to 80% for slaty cleavage in low metamorphic grade rocks (Wright and Henderson, 1992; Wright and Platt, 1982; Cox and Etheridge, 1983, 1989; Chester, 1995; Goldstein et al., 1995, 1998; Kawabata et al., 2007).

In the light of these considerations, the “two end-members” model describing crust rheology in terms of brittle/plastic behavior needs to be reconsidered by the integration of pressure solution creep at the transition from brittle to ductile regime (Chester, 1988, 1995; Scholz, 1988; Kirby, 1983).

The role of pressure solution is presumably highest in subduction zones, where subducted sediments deformed along the plate interface carry along a large quantity in water (Rutter and Elliott, 1976). In such setting, in order to analyze the deformation processes active near the brittle-ductile transition and the potential contribution of pressure-solution, we performed microstructural and Electron Back-Scattered diffraction (EBSD) analysis on low-grade quartz-rich metasediments from the Shimanto accretionary complex (Japan). The Hyuga Tectonic Mélange is a good example for deformation at plate interface at conditions close to the brittle/ductile transition. We describe microstructural evidences of quartz deformation principally by pressure solution and crack-seal at relatively low temperatures (~250 °C) in the Hyuga Tectonic Mélange, while quartz plastic behavior is very limited. The temperature effect on the activation of quartz plasticity is then studied observing quartz microstructures from the Foliated Morotsuka, deformed at slightly higher temperatures (~340 °C). Finally, using the pressure solution creep law revisited by Gratier et al. (2009) and the geometry of naturally deformed metasediments, we discuss the implication that pressure solution creep may have for bulk rock rheology and subduction interface strength.

2. Geological framework

2.1. General structure

The Shimanto accretionary complex, exposed on-land along the Honshu, Kyushu and Shikoku islands (Fig. 1a), is recognized as an ancient accretionary prism (e.g. Taira et al., 1982, 1988). The whole complex, trending parallel to the modern trench axis of the Nankai Trough, is composed of several superposed coherent sedimentary units and tectonic mélanges, younging toward the south-east and separated from the Chichibu belt by the Butsuzu Tectonic Line (BTL).

Our study focuses on the basal part of the Morotsuka Group, the Foliated Morotsuka (Raimbourg et al., 2014) and the upper part of the Hyuga Group, known as Hyuga Tectonic Mélange. The two units are juxtaposed by the Nobeoka Tectonic Line (NTL), a large-scale, low-dipping thrust fault with movement toward southeast (Murata, 1991, 1997, 1998; Saito, 1996).

2.2. Tectonic features

2.2.1. Hyuga Tectonic Mélange

The Hyuga Tectonic Mélange, also known as Mikado Unit (Teraoka et al., 1981; Saito, 1996), is the upper member of the Hyuga group and is exposed in the footwall of the Nobeoka Tectonic Line (Fig. 1). Microfossil assemblages indicate ages from Middle Eocene to Early Oligocene (Sakai et al., 1984; Nishi, 1988). At the outcrop scale, the Hyuga Tectonic Mélange is characterized by a typical block-in-matrix structure (e.g. Festa et al., 2010a): the coherent stratigraphic succession is disrupted and the rock is made of blocks of sandstone, siltstone breccia with minor amounts of basalt, red shales and cherts, embedded in a dark, pelitic matrix (Saito, 2008).

Estimation of the mineral composition by relative XRD peak intensity ratio of constituent minerals (Fukuchi et al., 2014) shows that quartz constitutes from 60 to 80% of the rocks of the unit, while phyllosilicates (typically chlorite and white mica) form most of the rest. A peculiar feature of the mélange rocks is the abundance of domains of precipitated quartz, on the form of veins cutting across boudinaged sandstone blocks, but also as elongated bodies within the pelitic matrix. The alignment of the broken and boudinaged sandstone blocks and quartz veins (Figs. 2 and 3) defines the foliation, which dips gently to the north-northwest (Raimbourg et al., 2014). A penetrative network of centimeter- to meter-long shear zones (Figs. 2 and 3) cut across the pre-existing foliation. Shear zones carry a lineation orientated NW-SE defined by elongated blocks and phyllosilicates. Their kinematics has systematically top-to-the-SE sense of shear.

From petrological analysis of basalts blocks, the syn-deformational metamorphic conditions are within the prehnite-pumpellyite facies (Imai et al., 1971; Toriumi and Teruya, 1988). Peak temperatures estimated with illite crystallinity (Hara and Kimura, 2008; Mukoyoshi et al., 2009) and vitrinite reflectance (Kondo et al., 2005; Mukoyoshi et al., 2009) range between ~250–280 °C. Raimbourg et al. (2015) find similar temperatures by microthermometry on fluid inclusions.

2.2.2. Foliated Morotsuka

The Foliated Morotsuka corresponds to the basal portion of the Morotsuka Group and form the hanging wall of the NTL along most of its length (Fig. 1). Ages, estimated by microfossil assemblages, indicate depositional lapse in the Cenomanian to Campanian/Maastrichian (Teraoka and Okumura, 1992).

The Foliated Morotsuka has sometimes been described as a tectonic mélange characterized by sandstone blocks and pillow basalts embedded in pelitic matrix (Teraoka and Okumura, 1992; Saito, 1996), but in most areas blocks are rare and the unit is composed simply of fine alternations of quartz-rich and phyllosilicate-rich layers defining a metamorphic foliation (Fig. 4).

In the studied area, the metamorphic foliation gently dips to the NW. On the foliation planes, the well-developed lineation is marked by the alignment of white mica and chlorite crystals. Deformation kinematic is principally vertical shortening associated with coaxial stretching to the NNW-SSE, with a minor contribution of top-to-the-NNW shear zones (Fabbri et al., 1990; Raimbourg et al., 2014). Centimeter-to-meter long quartz veins (Fig. 4) are distributed throughout the whole unit and flattened in the foliation.

Metamorphic conditions have been estimated to prehnite-pumpellyite to greenschist facies (Toriumi and Teruya, 1988), in agreement with paleotemperatures derived from illite crystallinity (300–310 °C) (Hara and Kimura, 2008) and vitrinite reflectance (320 °C) (Kondo et al., 2005).

2.3. Tectonic interpretation of the deformation

A general scheme of evolution of the Shimanto accretionary complex is developed in detail in (Raimbourg et al., 2014). We recall here the principal results regarding the tectonic interpretations of the deformation recorded in the two units considered here. (1) The foliation of the base of the Morotsuka Group developed at Eocene time after it had already been accreted to the hanging wall of the plate interface. It occurred near the plate interface as a result of an event of prism collapse and horizontal extension (Fig. 1b).