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Coupled micro-faulting and pressure solution creep overprinted on quartz schist deformed by intracrystalline plasticity during exhumation of the Sambagawa metamorphic rocks, southwest Japan

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ABSTRACT

In the Sambagawa schist, southwest Japan, while ductile deformation pervasively occurred at D_1 phase during exhumation, low-angle normal faulting was locally intensive at D_2 phase under the conditions of frictional–viscous transition of quartz (*c.* 300 °C) during further exhumation into the upper crustal level. Accordingly, the formation of D_2 shear bands was overprinted on type I crossed girdle quartz *c*-axis fabrics and microstructures formed by intracrystalline plasticity at D_1 phase in some quartz schists. The quartz *c*-axis fabrics became weak and finally random with increasing shear, accompanied by the decreasing degree of undulation of recrystallized quartz grain boundaries, which resulted from the increasing portion of straight grain boundaries coinciding with the interfaces between newly precipitated quartz and mica. We interpreted these facts as caused by increasing activity of pressure solution: the quartz grains were dissolved mostly at platy quartz–mica interface, and precipitated with random orientation and pinned by mica, thus having led to the obliteration of existing quartz *c*-axis fabrics. In the sheared quartz schist, the strength became reduced by the enhanced pressure solution creep not only due to the reduction of diffusion path length caused by increasing number of shear bands, but also to enhanced dissolution at the interphase boundaries.

1. Introduction

Rheology in rocks is important to understand dynamics in the earth. The rheology in the upper crust has been modeled with the brittle upper part deforming by frictional faulting, and ductile lower part rate-controlled by power-law creep in quartz or feldspar (e.g. Kohlstedt et al., 1995). Such modeling of upper crustal rheology seems to be relevant, because it can predict the lower-limit depth of hypocenters of inland earthquakes based on the depth of frictional–viscous transition (e.g. Stewart et al., 2000), which is consistent with the naturally observed depth of 15–20 km in mobile belts (e.g. Duebendorfer et al., 1988). On the other hand, this strength profile has been criticized, because such high differential stresses, say a few hundreds of megapascal at the depth of seismogenic zones, have been never reported from natural fault zones, e.g. the San Andreas Fault zone, where a differential stress of 20 MPa is inferred from heat flow data (Lachenbruch and Sass, 1992). Another question on the strong upper crust comes from the modeling of exhumation of metamorphic rocks. Beaumont et al. (2004) conducted numerical modeling of channel flows for the Himalayan metamorphic rocks, and showed that channeling mid-crustal rocks (i.e. metamorphic rocks) are never able to be extruded along brittle faults in the upper crust, unless the coefficient of internal friction is much less than the experimental ones, say by one-third. The fact suggests that the coefficient of internal friction on natural faults was indeed decreased by some softening mechanisms during exhumation of metamorphic rocks.

In natural deformation, in particular at frictional–viscous transition conditions, we know that both micro-faulting shown by formation of shear bands along which mica was precipitated (e.g. Schrank et al., 2008), and pressure solution creep (e.g. Hippertt, 1994; Takeshita and Hara, 1998; Stöckhert, 2002) are important deformation mechanisms. In fact, Bos and Spiers (2002) and Niemeijer and Spiers (2005) theoretically showed that at most of the depth range (ca. 5–20 km) in the upper part of the crust, frictional sliding in mica accommodated by pressure solution of quartz controls the rheology, the strength of which is less than one third of that predicted by the Byerlee (1978)'s law. However, as Bos and Spiers (2002) admitted,

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the numerical modeling of frictional–viscous deformation is still in infancy, because material constants, in particular, grain boundary friction and diffusion coefficients at high pressure conditions, which greatly affect the final results, are still uncertain. Furthermore, some predictions on pressure solution creep in quartz give an unrealistically high rate of pressure-solution creep, c. 10^{-7}–10^{-11}/s at $T = 350\,^{\circ}$C and $\sigma = 100$ MPa compared to natural ones, also because diffusion coefficients at high pressure conditions are not well constrained (Nakashima, 1995; Shimizu, 1995). Therefore, considering the limitation of numerical modeling at current stages, natural observation of pressure solution creep of quartzite is important to constrain its flow law.

In this paper, we describe the penetrative development of both deformation microstructures in quartz schist samples from the Sambagawa metamorphic rocks, southwest Japan: micro-faults (i.e. shear bands) indicative of frictional sliding, and grain microstructures and quartz *c*-axis fabrics indicative of pervasive pressure solution creep. These microstructures were formed during the final exhumation into upper crustal levels at the frictional–viscous transition conditions, which was called D_2 phase in the previous studies (Osozawa and Pavlis, 2007; El-Fakharani and Takeshita, 2008). Then, we will interpret how the microstructures were developed with increasing strain (i.e. deformation histories). Based on these observations and interpretations, we will discuss a model of large strain deformation, and the possible large degree of strain softening due to frictional sliding accommodated by pressure solution creep in quartz–mica aggregates deformed at frictional–viscous transition regions.

2. Geological setting

The Sambagawa belt is a high-*P*/*T* type metamorphic belt that extends from eastern Kyushu to the Kanto mountains, north-west of Tokyo, over 700–800 km, throughout south-west Japan (Fig. 1a). It is widely exposed in central Shikoku, where the maximum width is ca. 30 km. To the north this belt is separated from the low-*P*/*T* type Ryoke metamorphic belt by the Median Tectonic Line (MTL). Miyashiro (1961) originally suggested that the low- and high-*P*/*T* type paired Ryoke and Sambagawa metamorphic belts were formed under a volcanic arc and at a subduction zone, respectively with a 100–200 km separation distance. However, recent studies have suggested that they originated from an accretionary prism at places far from each other along a common subduction zone to the Pacific Ocean, which were later juxtaposed as a result of Cretaceous left-lateral transcurrent faulting along the MTL oblique to the arc (Taira et al., 1989; Brown, 1998; Sakashima et al., 2003).

The Sambagawa metamorphic rocks are inferred to have originated from Jurassic accretionary complexes based on radiolarian fossils (e.g. Isozaki and Itaya, 1990; Faure et al., 1991), which consist of pelitic, psammitic, mafic and quartz schists with rare serpentinite and metagabbro. Okamoto et al. (2004) have reported SHRIMP U–Pb zircon ages, varying between 132 and 112 Ma for quartz-bearing eclogites, which are interpreted as the age of peak-metamorphism. Amphibole and phengite yielded K–Ar (or ^{40}Ar/^{39}Ar) ages ranging from 94 to 65 Ma (e.g. Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990), probably indicating the ages of exhumation.

Based on the appearance of index minerals in pelitic schists, the Sambagawa metamorphic rocks can be divided into four zones (Fig. 1b), starting with the lowest metamorphic grade: chlorite zone (300–360 °C, 5.5–6.5 kbar), garnet zone (440 ± 15 °C, 7–8.5 kbar), albite–biotite zone (520 ± 25 °C, 8–9.5 kbar), and oligoclase–biotite zone (610 ± 20 °C, 10–11 kbar), respectively (e.g. Higashino, 1990; Enami et al., 1994). The metamorphic zonal sequence is inverted in the lower structural level from the chlorite to oligoclase–biotite zone, while it is normal in the upper structural level from the albite–biotite to garnet zone (Fig. 1c). This structure has been interpreted either as a large-scale recumbent fold (Banno et al., 1978; Wallis et al., 1992) or as thrust sheets (Hara et al., 1977; Faure, 1985; Higashino, 1990) formed after the peak metamorphism.

Based on field observations and structural studies, we can conclude that deformation structures of Sambagawa metamorphic belt were formed at three distinct deformation phases (D_1, D_2 and D_3) under retrograde conditions during the exhumation stages (e.g. Hara et al., 1977; Faure, 1983; Wallis, 1990). The D_1 phase is characterized by ductile flow in an east–west direction, and during this phase of deformation the main foliation and lineation were formed. The lineation is defined by the shape-preferred orientation (SPO) of matrix amphiboles, which grew under retrograde conditions (Hara et al., 1990, 1992; Wallis et al., 1992; Nakamura and Enami, 1994; Wintsch et al., 1999; Banno, 2000; Yagi and Takeshita, 2002; Okamoto and Toriumi, 2004, 2005), and by elongated quartz (Takeshita and Yagi, 2004), whereas the shape-preferred orientation of phengite and flattened quartz define the foliation.

D_2 phase in the chlorite zone is characterized by south-vergent overturned folds with crenulation cleavages (Hara et al., 1977; Faure, 1983). On the other hand, the D_2 folds in the high grade zones are characterized by recumbent folds (e.g. Wallis, 1990). Both Osozawa and Pavlis (2007) and El-Fakharani and Takeshita (2008) have recently reported dominant activity of D_2 low-angle north-dipping normal faults in the high grade zones, which accompany north-vergent recumbent folds.

D_3 folds are open upright folds with E–W to WNW–ESE trending horizontal axes. The D_3 folds are interpreted to have been formed after exhumation (Banno and Sakai, 1989), in relation to left-lateral displacement along MTL (Hara et al., 1977; Shiota et al., 1993).

3. Post-D_1 deformations in the Niihama area and sample localities

The Sambagawa metamorphic rocks in the Niihama area mostly belong to the albite–biotite zone of the upper structural level, while some of them belong to the oligoclase–biotite and garnet zones (Higashino, 1990, Fig. 1). The map-scale distribution of the Sambagawa metamorphic rocks in central Shikoku are mostly controlled by the major D_3 folds. In the Asemi river-Kamio river section (I–I′ section in Fig. 1), the Yakushi antiform to the north and Tsuneyama synform to the south are easily identified, where these metamorphic rocks strike E–W to NW–SE and dip either N or S. These map-scale D_3 folds could be extended from the Asemi and Kamio river areas to the Niihama area in the WNW direction with decreasing the layer thickness, as mentioned below.

In the Niihama area, the thickness of the whole metamorphic sequence from the chlorite zone in the lower structural level to the garnet zone in the upper structural level is much thinner than that in the Asemi river area, based on the exposed width 5 km versus 10 km in each area, respectively. This fact could be attributed to the difference in the displacement of late-stage D_2 normal faulting at both areas. In fact, in the Niihama area the rocks are much more severely faulted than in the Asemi river area, and Hara et al. (1992) called the zone between the MTL and the upper boundary of the thick mafic schist distributed in the SE corner of the study area (Fig. 2) the Ojoin mélange zone. Both Fukunari and Wallis (2007) and El-Fakharani and Takeshita (2008) analyzed the fault systems in this area, and concluded that most of these are low-angle normal faults dipping NNW, which can be correlated with those in the Asemi river area (Takeshita and Yagi, 2004). Although the metamorphic layers (D_1 foliation) are clearly cut by these normal faults, these are significantly dragged, indicating the semi-brittle nature