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Grain-size-sensitive deformation of upper greenschist- to lower amphibolite-facies metacherts from a low-*P*/high-*T* metamorphic belt

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ABSTRACT

To identify the dominant deformation mechanism in continental middle crust at an arc–trench system, we used an SEM-EBSD system to measure the lattice-preferred orientations of quartz grains in fine-grained metachert from the low-grade (chlorite and chlorite–biotite zones) part of the low-*P*/high-*T* Ryoke metamorphic belt, SW Japan. Quartz *c*-axis fabrics show no distinct patterns related to dislocation creep, although the strain magnitudes estimated based on deformed radiolarian fossils are high enough that a distinct fabric might be expected to have formed during deformation. Fabric intensities are very low, indicating a random distribution of quartz *c*-axes. Quartz grains are equant in shape and polygonal, and free of intracrystalline plasticity. These observations suggest that the dominant deformation mechanism in the metacherts was grain-size-sensitive flow (diffusion creep accompanied by grain-boundary sliding) rather than dislocation creep, possibly reflecting the relatively low strain rate or low flow stress compared with that in high-strain zones. The development of grain-size-sensitive flow in metamorphic tectonites at mid-crustal conditions would result in a significant decrease of the rocks strength of the continental middle crust.

1. Introduction

The dominant deformation mechanism within metamorphic tectonites is the most important factor in understanding the rheological behavior of the crust and mantle, as the effective viscosity is markedly different for rocks deformed by dislocation creep or grain-size-sensitive flow (diffusion creep accompanied by grain-boundary sliding or diffusion-accommodated grain-boundary sliding). In dislocation creep, the strain rate is independent of grain size but has a strong non-linear dependence on flow stress. In grain-size-sensitive creep, in contrast, strain rate has a linear dependence on stress but a non-linear dependence on grain size. Grain size appears to be the main parameter in determining whether an aggregate deforms by dislocation creep or by grain-size-sensitive creep associated with diffusive mass transfer within crystals or along grain boundaries (e.g. Schmid et al., 1977; Etheridge and Wilkie, 1979; Behrmann, 1983). Small grain size favors grain-size-sensitive creep, as diffusion paths are relatively short. The presence of a second mineral phase can enhance this process because it inhibits syn-deformation grain growth keeping the grains small enough so that grain-size-sensitive creep can be active (e.g. Herwegh and Jenni, 2001; Krabbendam et al., 2003; Herwegh and Berger, 2004; Song and Ree, 2007).

The flow laws for grain-boundary diffusion creep (Coble creep) and diffusion-accommodated grain-boundary sliding have a similar dependence on flow stress (stress exponent ~1) and grain size (grain-size exponent ~3) so the mechanisms cannot be distinguished from these exponents alone (e.g. Etheridge and Wilkie, 1979). In this study, Coble creep will be used to describe grain-size-sensitive creep. According to Passchier and Trouw (2005; p. 65), for a quartz aggregate, the flow law for bulk diffusion-controlled dislocation creep can be expressed by

$$\dot{\varepsilon} = \frac{\mu b D_L}{kT} \cdot (\sigma/\mu)^3 \cdot e^{(-H_L/RT)}, \tag{1}$$

and the flow law for Coble creep is

$$\dot{\varepsilon} = \frac{A_C \mu V D_G W}{RTd^3} \cdot (\sigma/\mu) \cdot e^{(-H_G/RT)}, \tag{2}$$

where $\dot{\varepsilon}$ is strain rate [s^{-1}]; σ is flow stress [Pa]; T is temperature [K]; b is the Burgers vector [m]; A_C is a numerical factor for Coble creep, which depends on grain shape and boundary conditions (141); H_L and D_L are molar activation enthalpy (243 kJ/mol) and pre-exponential factor (2.9×10^{-5} m^2/s) for oxygen self-diffusion used in the flow law for dislocation creep (Farver and Yund, 1991); H_G and D_G are molar activation enthalpy (137 kJ/mol) and pre-exponential factor (3.7×10^{-10} m^2/s) for silicon bulk diffusion in the presence of water for diffusion creep (Farver and Yund, 2000); W is grain-boundary thickness (10^{-7} m); V is the molar volume of quartz (2.6×10^{-5} m^3/mol); μ is the shear modulus of quartz (42×10^9 Pa); d is grain size [m]; R is a

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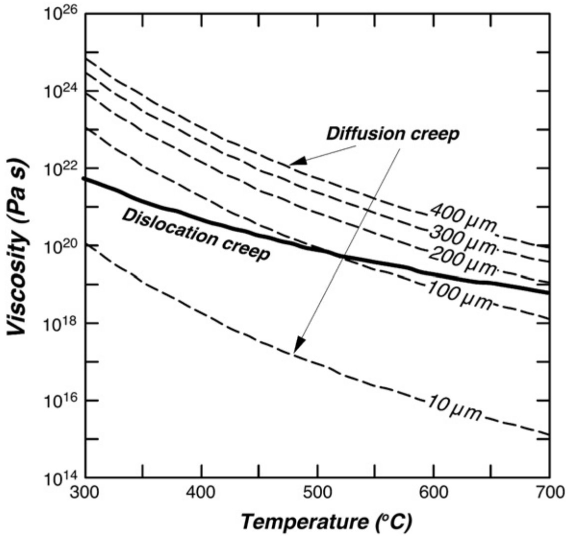

Fig. 1. Variations in effective viscosity with temperature, for dislocation creep and diffusion creep for various grain sizes. Viscosity was calculated for a strain rate of 10^{-14} s^{-1}.

gas constant (8.3143 J/mol/K); and k is the Boltzmann constant (1.38062×10^{-23} J/mol/K). The effective viscosity η, that is calculated using Eqs. (1) and (2), the relationship $\eta = \sigma / \dot{\varepsilon}$ and assuming $\dot{\varepsilon} = 10^{-14}$ s^{-1}, of a quartz aggregate deforming by dislocation creep at 500 °C is approximately three orders of magnitude higher than that of an aggregate (grain size, 10 μm) deforming by diffusion creep (Fig. 1).

Previous studies have reported the deformation of various rock types (e.g. marbles, peridotites and granitic mylonites) by grain-size-sensitive flow (e.g. Schmid et al., 1977; Lisle, 1985a; Behrmann and Mainprice, 1987; Stünitz and Fitz Gerald, 1993; Rutter et al., 1994; Fliervoet et al., 1997; Kruse and Stünitz, 1999; Jiang et al., 2000; Bestmann and Prior, 2003; Herwegh and Berger, 2004; Storey and Prior, 2005; Warren and Hirth, 2006). In contrast, although a few papers reported grain-size-sensitive flow in quartz aggregates (e.g., Krabbendam et al., 2003; Wightman et al., 2006; Song and Ree, 2007), almost all quartzose rocks (e.g. quartzites and quartz mylonites) are considered to deform by dislocation creep, even in ultrafine-grained rocks (Fliervoet and White, 1995; Rutter and Brodie, 2004; Fitz Gerald et al., 2006; Ishii et al., 2007).

The low-*P*/high-*T* metamorphic rocks of the Cretaceous Ryoke metamorphic belt, SW Japan, are considered to be derived from the Jurassic Mino–Tamba accretionary complex (e.g. Okudaira et al., 2009). Because accretionary complexes form at a subduction zone and low-*P*/high-*T* metamorphic belts form near a volcanic arc, the deformation history of metamorphosed accretionary complexes (e.g. the Ryoke metamorphic belt) represents a key to understanding the nature of geodynamic processes in continental middle crust.

In studies of low-grade (chlorite–biotite and biotite zones) metacherts of the Ryoke metamorphic belt, Toriumi et al. (1986) and Toriumi (1989) reported microstructures that could not have originated by dislocation glide. Although their microstructural and textural analyses were not sufficient, they suggested that the rocks deformed by diffusive mass transfer, including pressure solution, under low flow stress or a low strain rate. On the other hand, it has been suggested that in high-grade (cordierite, sillimanite and garnet–cordierite zones) metacherts dislocation creep is the dominant deformation mechanism (Hara, 1962; Okudaira et al., 1995).

In the present study, we used a scanning electron microscope (SEM) equipped with electron backscatter diffraction (EBSD) to analyze the lattice-preferred orientations (LPOs) of quartz grains in very-fine-grained metacherts from the Ryoke metamorphic belt, with the aim of clarifying the effects of physical parameters on the development of grain-size-sensitive creep within fine-grained metamorphic tectonites.

2. Methods and results

2.1. Samples

In the Wazuka–Kasagi district, SW Japan, weakly-metamorphosed sedimentary rocks of the Mino–Tamba accretionary complex show a gradual transition to Ryoke metamorphic rocks (Fig. 2). The metamorphic rocks are divided into the following four mineral zones (in order of increasing metamorphic grade): chlorite zone, chlorite–biotite zone, biotite zone, and sillimanite zone (Ozaki et al., 2000). The chlorite and chlorite–biotite zones are of upper greenschist to lower amphibolite facies; the metamorphic temperature of the chlorite–biotite zone in this area has been estimated to be ≤490 °C, based on the occurrence of fully ordered graphite in the highest-grade rocks of this zone (Nakamura, 1995). The samples of metachert analyzed in the present study were collected from the chlorite zone (sample 080429-04) and chlorite–biotite zone (sample 070523-12). The samples exhibit banding structures defined by alternating thick (several centimeters) chert layers and thin (several millimeters) pelitic layers oriented parallel/subparallel to lithologic boundaries. Numerous deformed radiolarian fossils (average diameter ~200 μm) are observed; the fossils can be recognized based on their ellipsoidal and rounded shapes. The long axes of the fossils are aligned to define a weak tectonic foliation (Fig. 3a). The fossils are filled with quartz grains larger than the matrix ones. Quartz grains within the fossils are polygonal, with no shape-preferred orientation. A schistosity develops within thin pelitic layers that also include deformed radiolarian fossils. A weak stretching lineation is observed upon the schistosity. The metacherts are not folded mesoscopically. For strain and fabric analyses, thin sections were prepared normal to the schistosity and parallel to the stretching lineation (*XZ*-sections), normal to both the schistosity and the lineation (*YZ*-sections), and parallel to the schistosity (*XY*-sections).

2.2. Microstructures

The chlorite zone sample consists mainly of quartz, with minor muscovite, chlorite, graphite, pyrrhotite and ilmenite. The chlorite–biotite zone sample consists of quartz, with minor muscovite, chlorite, biotite, graphite, pyrrhotite and ilmenite. Quartz grains in the matrix are largely equigranular in both samples and exhibit foam-like microstructure (Fig. 3b, c), although some are elongated subparallel to the lineation, defining a weak tectonic foliation. There are no microstructures indicative of dynamic recrystallization (e.g. undulose extinction or grain-boundary bulging). The minor sheet silicates are not clustered, and they commonly occur along quartz grain boundaries, having a strong preferred orientation with the basal planes parallel to the tectonic foliation. They exhibit no chemical heterogeneity within each crystal.

The grain sizes and modal percentages of quartz grains were estimated by image analysis using the software NIH image. Grain sizes were calculated as the equivalent diameter of a spherical grain. Table 1 lists the average grain sizes and modal percentages of

Fig. 2. (a) Distribution of the Ryoke metamorphic belt, SW Japan and (b) geology of the Wazuka–Kasagi district (Ozaki et al., 2000; Okudaira et al., 2009). Sample localities are also shown. Inset: lower-hemisphere equal-area projection showing the orientations of the stretching lineation observed upon the schistosity within metacherts (open circles) and metapelites (open squares).