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Apparent activation energy and rate-limiting process estimation from natural shale deformed by pressure solution in shallow subduction zone

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ABSTRACT

Pressure solution is one of the main deformation mechanisms for lithify and stress release in the rocks from shallow subduction zones. We observed temperature-dependent pressure solution development in naturally deformed shale in Shimanto accretionary complex in southwest Japan. The pressure solution develops with shear-dominated or co-axial-dominated deformation. We evaluated apparent activation energy by applying the constitutive equation of pressure solution creep to the temperature-dependent relations. The activation energy of each deformation type was estimated as 18 kJ mol^{-1} for shear-dominated and 45 kJ mol^{-1} for co-axial-dominated shale. The energies enable us to speculate rate-limiting processes of pressure solution i.e. dissolution, diffusion and precipitation, by comparing the energies obtained in this study with energies had been measured by experiments. The lower activation energy estimated here was similar with that of diffusion. The similarity indicates that possible rate-limiting process of shale deformation in shallow subduction zone would be diffusion. The difference of energy between deformation types can be explained by distinctive grain boundary structure.

1. Introduction

While accumulated elastic strain energy in rocks is mainly released by seismic slip, a significant part of the convergence in accretionary prisms of subduction zones is accommodated by aseismic slip. One of the most important mechanisms for aseismic slip is ductile deformation by pressure solution (e.g. Rutter and Mainprice, 1979; Rutter, 1983; Gratier et al., 2003; Tanaka et al., 2007). Pressure solution deformation can be decomposed in three successive basic processes: dissolution, mass transfer and precipitation (Rutter, 1976; Spiers et al., 1990; Shimizu, 1995). As these processes operate sequentially, the total strain rate is controlled by the slowest of these processes, called “rate-limiting process”.

Most flow laws derived from experiments can be expressed, independently of the precise deformation process involved, as $de/dt = a \cdot \exp(-H/RT)$, where e is the strain, t is the duration, a is a constant, H is an activation energy, R is the gas constant and T is the temperature (K). Deformation by pressure solution includes the temperature-dependent flow law and activation energies have been reported from experiments (Rutter, 1983; Gratier and Jenatton, 1984; Schutjents, 1991; Dewers and Hajash, 1995; Niemeijer et al., 2002; Tenthorey and Cox, 2006). The activation energy enables us to estimate rate-limiting process through deformation by comparing with energies, which had been measured by experiments of dissolution, diffusion and precipitation.

Temperature-dependent development of pressure solution has also been suggested in natural rock deformation by investigating the relationship between deformation of sedimentary rock and its burial depth (Tada and Siever, 1989). Recently, we quantitatively evaluated it from natural shales of the Shimanto accretionary complex (Kawabata et al., 2007). We quantified intensity of the deformation using pressure solution seams (PSS) and obtained a positive correlation between the intensity and paleotemperature measured by vitrinite reflectance. After Kawabata et al. (2007), we considered the temperature and duration of PSS development to estimate its corresponding activation energy. Accretion and thermal history of Shimanto accretionary complex have been well studied and was proposed to be a simple thermal structure, which was made mainly by a heating event rather than by the accretion history of sediments (e.g. Sakaguchi, 1999). The simple thermal history allows us to understand the timing and duration of PSS developed in the Shimanto accretionary complex. In this paper we performed an extending study of Kawabata et al. (2007) by compiling the thermal structure and to apply creep law to PSS development for the estimation of activation energies in natural

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shale. Finally, we interpret the phenomenological laws in terms of microscopic mechanisms and discuss the possible rate-limiting process of pressure solution creep.

2. Geologic outline and sampling

The Shimanto belt is an ancient accretionary complex distributed on the Pacific side of southwest Japan, subparallel to the modern Nankai Trough and the Ryukyu Trench (Fig. 1). The belt is divided into two subbelts by the Aki Tectonic Line (ATL), a major thrust separating cretaceous sedimentary rocks in the northern subbelt from tertiary ones in the southern subbelt (Fig. 1) (Taira et al., 1980). The sedimentary sequence within the subbelts trend generally ENE–WSW and dip steeply to the north. The subbelts include coherent, tectonic mélange units and slope-basin deposits. The coherent units consist of trench turbidite and the mélange units consist of a mixture of trench turbidite, hemi-pelagic, pelagic sediments and basalt.

All of the samples used here are composed of shales collected in the eastern coastal area of Shikoku (Fig. 1). In this study, we used two distinct kinds of shale samples, characterized by very different deformation modes: either highly sheared samples from mélange rocks or samples from co-axial-dominated coherent units. In the following the deformation modes are referred as type S for shear-dominated samples from the tectonic mélange and as type C for co-axial dominated samples from the slope-basin deposits.

3. Microstructural observation and analysis of the shales

Microstructural observations indicate that shales are composed of quartz and feldspar grains, clay minerals and small amount of opaque minerals (Fig. 2a and b). In shale of type S larger grains show asymmetric fringes, on the other hand, fringes in type C shales are more symmetrically developed (Fig. 2a and b), suggesting that deformation types are different also at the microstructural scale. However, such large fringes are rather infrequent in both kinds of samples.

PSS are well developed in shale of both types (Fig. 2a and b). PSS are black seams generated as residue during pressure solution deformation (Fig. 2c). PSS density (γ_{PSS}), which we defined as the ratio of PSS-occupied area over the total area in a thin section photograph, can be used as indicator of pressure solution intensity (Kawabata et al., 2007). PSS density is up to 50% for type S and 30% for type C.

Grain size distributions within PSS of two types are shown in Fig. 3. A fractal distribution of grain size is apparent for both types with $N = 0.995d^{-1.89}$, where N is the number of grains and d is the diameter of grain, suggesting fracturing during lithification and/or pressure solution deformation in shales.

Pressure solution mechanism is also known to promote under presence of clay minerals in nature and experiments (e.g. Weyl, 1959; Renard et al., 1997). We carried out X-ray diffraction analysis to determine the composition of clay mineral. The analysis was carried out for shale samples under CuKα at 40 kV and 20 mA (Rigaku RINT2100).

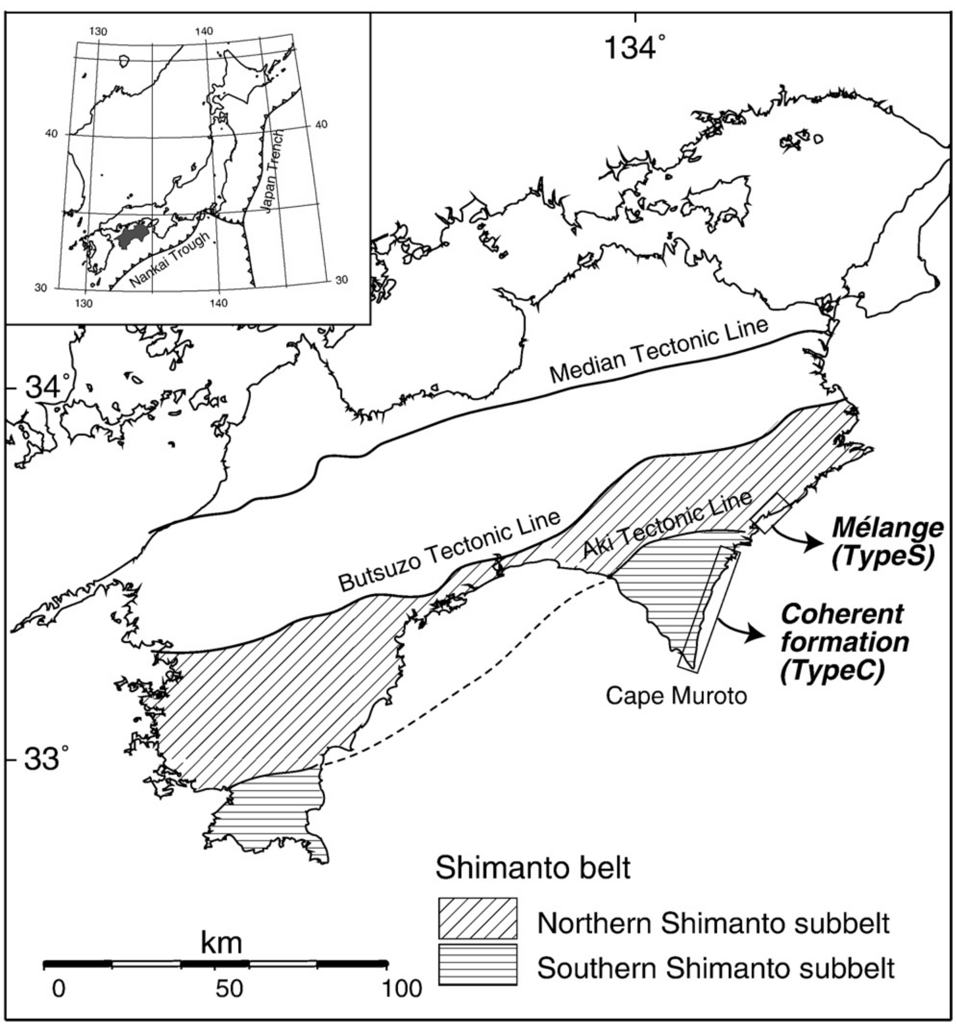

Fig. 1. Geological maps of the Shimanto Belt, southeast Shikoku, Japan. Shimanto belt is divided into northern and southern belts by Aki Tectonic Line.