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Low-grade metamorphism around the down-dip limit of seismogenic subduction zones: Example from an ancient accretionary complex in the Shimanto Belt, Japan

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ABSTRACT

Reactions involving clay minerals during low-grade metamorphism at the depth of an ancient accretionary complex in the Shimanto Belt, Kyushu, Japan, were studied by integrated transmission electron microscopy–energy dispersive X-ray spectroscopy and X-ray diffraction analyses of the bulk rock and clay fraction. The analyzed metasediment (the Kitagawa unit) contain an incipient sub-horizontal slaty cleavage. Illite crystallinity data and mica *b* dimensions indicate that the conditions of metamorphic deformation were anchizone–epizone grade and intermediate pressure. Cleavage formation was linked to two reactions involving clay minerals: (1) the recrystallization of 1*M*-dominant matrix mica, inherited from the original sedimentary fabric, into thick, defect-free $2M_1$ packets along cleavage planes; and (2) the formation of chlorite from 7 Å berthierine. Balanced equations among the clay phases, based on compositional data and their relative abundance, suggest that the decomposition of matrix mica resulted in the formation of paragenetic mica and chlorite along the cleavage planes, without significant elemental outflux. Although a modal increase in phyllosilicates is not indicated by the data, the growth of chlorite and mica along cleavage planes may have a large influence on the rheological properties of a décollement and may be related to the occurrence of the seismic–aseismic transition at ~350 °C.

1. Introduction

The mechanical properties of sediments entering a subduction zone are progressively modified by dewatering, lithification, and deformation (Byrne, 1984; Cowan, 1982; Hashimoto et al., 2006; Kimura et al., 2007; Moore and Saffer, 2001; Moore et al., 2001; Taira et al., 1992). Such modification along a plate boundary fault (i.e., a décollement) has a major influence on several aspects of accretionary prism dynamics, such as wedge geometry, internal structure, and seismicity (Hyndman, 2007; Kimura et al., 2007; Wang and Hu, 2006). In general, a décollement can be divided into three segments in terms of its mechanical regime: shallow and deep aseismic portions, and an intermediate seismic region (Hyndman, 2007; Hyndman et al., 1997). The upper of the two seismic–aseismic transitions occurs at temperatures of ~150 °C and is believed to be related to dewatering of subducted sediments due to tectonic loading and diagenetic dehydration reactions (e.g., smectite–illite transition and opal–quartz transition), which allow increase in effective normal stress of the décollement (Moore and Saffer, 2001; Spinelli and Saffer, 2004). Moreover, active carbonate, clay and quartz cementations around this temperature condition may cause sliding instability of the sediments (Moore and Saffer, 2001). On the other hand, onset of the aseismic behavior above ~350 °C is inferred to be related to the mechanical properties of subducted sediments subjected to low-grade metamorphism (Hyndman, 2007; Hyndman et al., 1997).

Although the nature of deep crustal structure in subduction zones remains debated, several seismic reflection surveys (particularly those undertaken at the Cascadia margin) suggest that the décollement widens with increasing depth to be several kilometers thick, forming reflection banding in a seismic profile (e.g., Calvert et al., 2006; Nedimovic et al., 2003). A candidate material for such reflectors is plastically deformed metasediments affected by low-grade metamorphism, with a structure similar to that of mylonite zones. Therefore, phase transitions in subducted sediments, particularly those for phyllosilicates, are likely to influence aseismic faulting along deep décollements (Hyndman, 2007; Hyndman et al., 1997). Nevertheless, the brittle–ductile transition is rarely exposed at the surface, as most accretionary prism rocks do not reach the transition or are overprinted by late-stage higher-grade metamorphism. Consequently, little is known of the prograde evolution of mineral assemblages and their reaction pathways around the down-dip part of the seismogenic zone, which may control the mechanical transition from seismic to aseismic behavior.

The Kitagawa unit, exposed on the easternmost side of the Kyushu Shimanto Belt, Japan, provides an opportunity to trace the progress of

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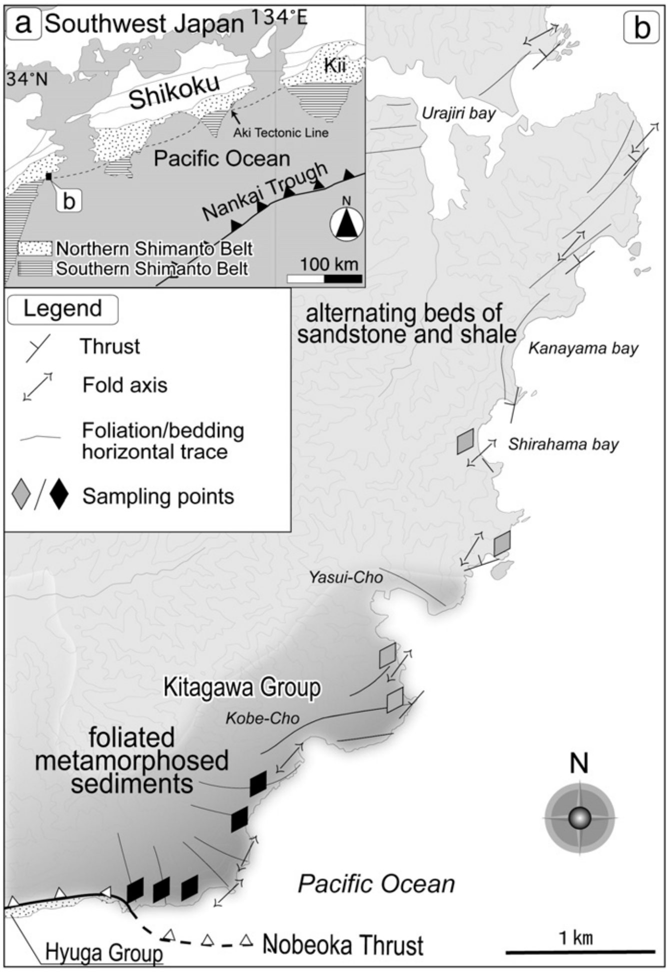

Fig. 1. Geological map of the Kitagawa unit in the northern Shimanto Belt, Kyushu, Japan. The gray level (from light to dark) assigned to the Kitagawa unit corresponds to the intensity of deformation (disruption of bedding and the development of a metamorphic foliation).

low-grade metamorphism within a subduction zone, because this unit records the highest metamorphic grade of the rocks within the Shimanto Belt (320–330 °C; Kondo et al., 2005) and comprises a complete succession ranging from shale/sandstone to intensely cleaved metasediment (Raimbourg et al., 2009). A structural analysis of the unit indicates that vertical loading, probably in a setting around the plate interface, produced the ubiquitous subhorizontal cleavage defined by networks of recrystallized chlorite and mica (Raimbourg et al., 2009).

Illite crystallinity (IC) measurements on micas of the Kitagawa unit (Mukoyoshi et al., 2007, 2009) yield lower values at a site located close to the Nobeoka Thrust (0.24 Δ°) compared with a site located more than 5 km from the thrust (0.31 Δ°). Because the intensity of deformation in this unit shows an increase toward the Nobeoka Thrust (Raimbourg et al., 2009), the observed trend in IC values is inferred to reflect the extent of mica growth, although additional analyses are needed to characterize the complete sequence of metamorphic processes that occurs during the formation of a mature metapelite.

The aim of the present study is to clarify several aspects of low-grade metamorphism of the Kitagawa unit, including its metamorphic setting, evolution of the mineral assemblage and bulk chemistry, and the reaction pathways of clay minerals. To this end, we subjected bulk samples and the clay fraction (<2 μm) to quantitative analyses by X-ray diffraction (XRD) and high-resolution transmission electron microscopy (HR-TEM), for samples that record varying degrees of deformation. Based on these data, we discuss the influence of low-grade metamorphism on the aseismic behavior of deep décollements.

2. Geological setting

The Shimanto Belt is an ancient accretionary complex that extends for 800 km along the Pacific side of southwest Japan (Fig. 1a). The belt is divided into northern and southern sub-belts, separated by the Aki Tectonic Line in the Shikoku and Kii regions, and by the Nobeoka Thrust in Kyushu. In eastern Kyushu, the Kitagawa Group was exhumed north of the Nobeoka Thrust, emplaced over the southern Hyuga Group (Fig. 1b). Metamorphic mineral assemblages suggest that the northern belt was metamorphosed in the greenschist facies (Toriumi and Teruya, 1988), whereas the southern belt was metamorphosed in the prehnite–pumpellyite to zeolite facies.

The Kitagawa unit, a turbiditic sequence of alternating sandstone- and mudstone-rich layers that contain Eocene radiolarian fossils (Ogawauchi et al., 1984), records two stages of deformation: an early stage of horizontal contraction, characterized by folding and thrusting, was overprinted by the development of a pervasive slaty cleavage during vertical shortening (Raimbourg et al., 2009). The slaty cleavage is more pronounced in the deeper levels of the Kitagawa unit; i.e., closer to the Nobeoka Thrust.

Vitrinite reflectance values (%Rm) obtained for the Kitagawa unit range from 5.33 to 5.63 (Kondo et al., 2005), corresponding to maximum paleotemperatures of 320–330 °C based on the method proposed by Sweeney and Burnham (1990). These temperatures are similar to the estimated formation temperature of metamorphic chlorite (Raimbourg et al., 2009).

The Hyuga Group, located south of the Nobeoka Thrust, possesses a shale-dominant mélange texture. Vitrinite reflectance data indicate temperatures of 250–270 °C (%Rm = 2.58–2.75; Kondo et al., 2005), which are 50–80 °C lower than those obtained for the Kitagawa unit. This difference in temperature suggests that the Nobeoka Thrust was active as an out-of sequence thrust (Ohmori et al., 1997), responsible for exhuming the unit from deep within the accretionary complex (Raimbourg et al., 2009). Faulting is thought to have occurred during ~40–48 Ma, as inferred from illite K–Ar and zircon fission track ages (Hara and Kimura, 2008).

3. Experimental procedure

Samples with various densities of cleavage planes were collected from the Kitagawa unit and were classified into the three groups proposed by Raimbourg et al. (2009): non-cleaved samples (NM) do not contain slaty cleavage; slightly cleaved samples (SlM) possess both cleavage and bedding; and strongly cleaved samples (StM) contain an intensively developed cleavage with little sign of the original bedding fabric. A total of 13 samples (6 NM samples, 3 SlM samples, and 4 StM samples) were analyzed (Table 1).

Representative portions of each sample were ground using a vibrational mill for 2 min under dry conditions for bulk XRD analyses. Each powder, mixed with high-purity corundum (AX-5H, Hinomoto Kenmazai Co., Japan) as an internal standard, was mounted on an XRD glass holder in a side-load manner to minimize any preferred alignment of phyllosilicates. The patterns were recorded using a Rigaku Rint-2000 with monochromatized Cu$K\alpha$ radiation at 40 kV and 30 mA, with 1° divergence and anti-scattering slits, and a 0.3 mm receiving slit. The 2θ range of 2°–65° was scanned in step scan mode for 4 s, at steps of 0.04° 2θ. The RockJock program, developed by Eberl (2003), was used for quantitative analyses of rock composition. The XRD patterns were fitted using reference patterns for quartz, albite, calcite, pyrite, 1*M* and 2M_1 micas, and trioctahedral chlorite, as stored in the program.

To obtain the clay size fraction (<2 μm), rock chips were gently crushed by hand and dispersed ultrasonically in distilled water. The