Synchrotron Radiation Study of the Reaction-Deformation Coupling Processes in Earth's Mantle Minerals at High Pressures

The reaction-deformation coupling in silicate minerals is a critical issue to understand the dynamics of subducting oceanic plates in deep Earth. We conducted high-pressure eutectoid transformation experiments with constant strain-rate deformation. High-energy monochromatic X-rays were used to measure reaction kinetics and creep behavior simultaneously at high pressures. These quantitative measurements combined with microstructural observations of recovered samples suggest sequential variation of creep mechanisms from dislocation creep of the eutectoid colonies to grain-size sensitive creep in the deformation-induced degenerated colonies. These reaction-deformation coupling processes are very important to understand the large deformation and the cessation of deep earthquakes in the lower mantle.

Oceanic plates are subducting into deep Earth as cold currents of mantle convection. When the subducted plates (slabs) pass through the mantle transition zone (between the two major seismic discontinuities at 410 and 660 km depths), most of the constituent minerals undergo high-pressure transformations, resulting in significant changes of rock density, microstructures, and viscosity. This has been thought to be responsible for deep slab deformation and deep earthquakes. Seismological and mineral physics studies have revealed that non-equilibrium phase transformations control density and viscosity structures of subducting oceanic slabs [1]. Especially, the processes of reaction-enhanced ductility and reaction-induced faulting are crucial for understanding deep slab deformation and deep earthquakes. In order to reveal such reaction-deformation coupling processes, we have started to conduct simultaneous and quantitative measurements of creep behavior and reaction kinetics at high pressures by combining high-pressure deformation apparatus with synchrotron monochromatic X-ray measurements. Here we report experimental results on creep behavior during eutectoid transformation [2].

When a slab enters the lower mantle across the 660 km discontinuity, post-spinel eutectoid transformation occurs, which is thought to be very important for understanding the slab deformation and the cessation of deep earthquakes [3]. There have been two controversial ideas on the effects of this transformation on the strength of the lower-mantle slab. One is that the slab material in the lower mantle becomes weak due to the grain-size reduction of the eutectoid transformation [3, 4]. Another is that it is not weak because the eutectoid colony is a single crystalline composite material [5]. To solve the problem, we conducted *in-situ* X-ray observations on the creep behavior during the eutectoid transformation using a deformation-DIA (D-DIA) apparatus [6] at the beamline of AR-NE7A of the Photon Factory. The decomposition reaction of $NaAlSi_3O_8$ albite into $NaAlSi_2O_6$ jadeite and SiO_2 quartz was used as an analogue reaction of the post-spinel transformation. Sintered starting material of albite was deformed at 400-800°C and 1.5-4.0 GPa with constant strain rates of 0.3-6.1 x10^{-5} s^{-1}, and the decomposition reaction started during the deformation (Fig. 1). The overpressures needed for the initiation of the transformation increased with decreasing temperature. The transformation-time data was estimated from time-resolved two-dimensional X-ray diffraction measurements (2θ<10°) by imaging plate every 3-5 min. The distortion of the Debye ring was used to estimate differential stress of the sample based on the lattice strain equation [7]. The sample strain was measured by using X-ray radiography imaging. In this way, we could quantitatively obtain both transformation-time and stress-strain curves during the deformation with reaction as shown in Fig. 2.

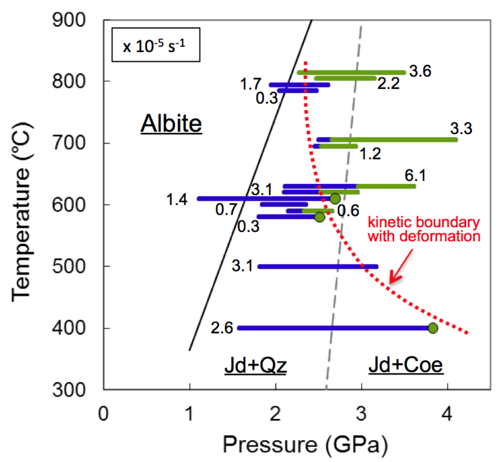

Figure 1: P-T conditions of the transformation-deformation experiment with constant strain-rate mode. The numbers indicate the strain rate (x 10^{-5} s^{-1}). Green and blue bars indicate the deformation with and without transformation, respectively.

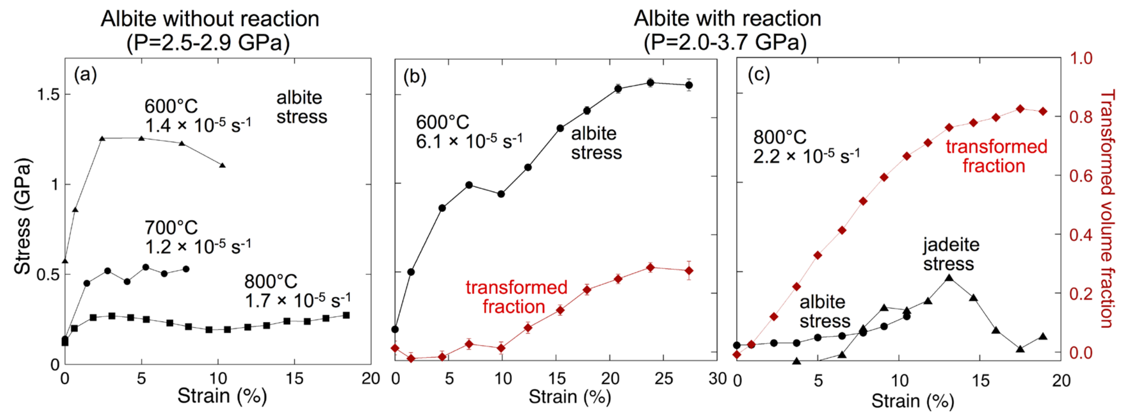

Figure 2: Stress-strain (black) and transformation-time (red) curves obtained during constant strain-rate deformation at high pressure.

In the case of the deformation without reaction, the flow stress of albite was almost constant, showing a steady state at the strain of more than 3% [Fig. 2(a)]. The stress exponent in the flow law was estimated to be 2.4, suggesting dislocation creep of parental albite. On the other hand, hardening occurred when the reaction proceeded [Fig. 2(b, c)]. Scanning electron microscopy (SEM) of recovered samples indicates that eutectoid colonies of fine-textured jadeite and silica nucleated on the albite grain boundaries. Electron back-scattered diffraction (EBSD) analysis suggests that jadeite in a colony is not fine grained but an interconnected single crystal. We also found the deformation-induced lattice preferred orientation of the eutectoid colonies, suggesting that they deform by dislocation creep.

Further transformation after the hardening causes weakening of the sample as shown by the stress drop in jadeite [Fig. 2(c)]. SEM and EBSD analysis of the weakened samples suggests that degeneration of the eutectoid colony occurs by the deformation. This possibly changes the deformation mechanism from dislocation creep to grain-size sensitive creep, resulting in the weakening. Thus, the degeneration process of the interconnected eutectoid colonies is likely to be a key issue for large deformation of the lower-mantle slab.

In a future study, we intend to develop the experimental method demonstrated here to detect shear instability by multiple acoustic emission measurements, which would be a powerful tool for the study of deep earthquakes occurring in subducting slabs.

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