博士論文

Rheology of the Subducting Slab Illuminated by Rock Deformation Experiments and Numerical Simulations

（岩石変形実験及び数値シミュレーションによる沈み込むスラブレオロジーの解明）

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Only the Earth has the subduction zones as of now. The subduction zone is one of the drivers of plate tectonics and our planet's largest recycling system (Stern 2002). Water is delivered into the Earth's interior through the subducting slabs and can generate melts, earthquakes, and mantle convection. Although most of the rocks in the subducting slabs are deformed plastically due to the elevated pressure and temperature, earthquakes in the subducting slabs occur at a depth from a few km to 660 km. Such characteristics of the subduction zones are different from each other. However, what parameters control the diversity and characteristics of the subduction zones remain unclear because the complicated interaction occurs among many parameters such as the age of slabs, the thermal structures and stress fields in the slab, and the heterogeneous distribution of water and mineral phases. In particular, the questions of how much water the subducting slab can deliver into the Earth's interior and why earthquakes occur even at great depths have attracted the interest of many researchers. To answer these questions, the clarification of slab rheology is indispensable. Therefore, it is important to conduct deformation experiments under high pressure and temperature using rock samples with well-controlled chemical compositions and microstructures, mimicking the subducting slabs. Furthermore, temporal and spatial scales in the experiments, such as strain and reaction rates, are largely different from natural scales in the subduction zones, so numerical simulations capable of calculating elementary physicochemical processes are also useful. To reveal the complicated rheology of the subducting slab, I studied the following four topics (Part 2-5).

In part 2, I attempted to reveal the experimental conditions for sintering a homogeneous starting material for deformation experiments. Strain localization bands are often observed in natural and experimentally deformed porous rocks in the stress state of the transitional regime from brittle faulting to cataclastic flow (Baud et al. 2004). The rock samples used in most previous studies were natural porous coarse sandstones. Meanwhile, fine-grained aggregates from powders were used as an initial sample for high-pressure deformation experiments. Generally, compaction for sintering these aggregates was performed before the experiments. No coaxial experiments have been performed on

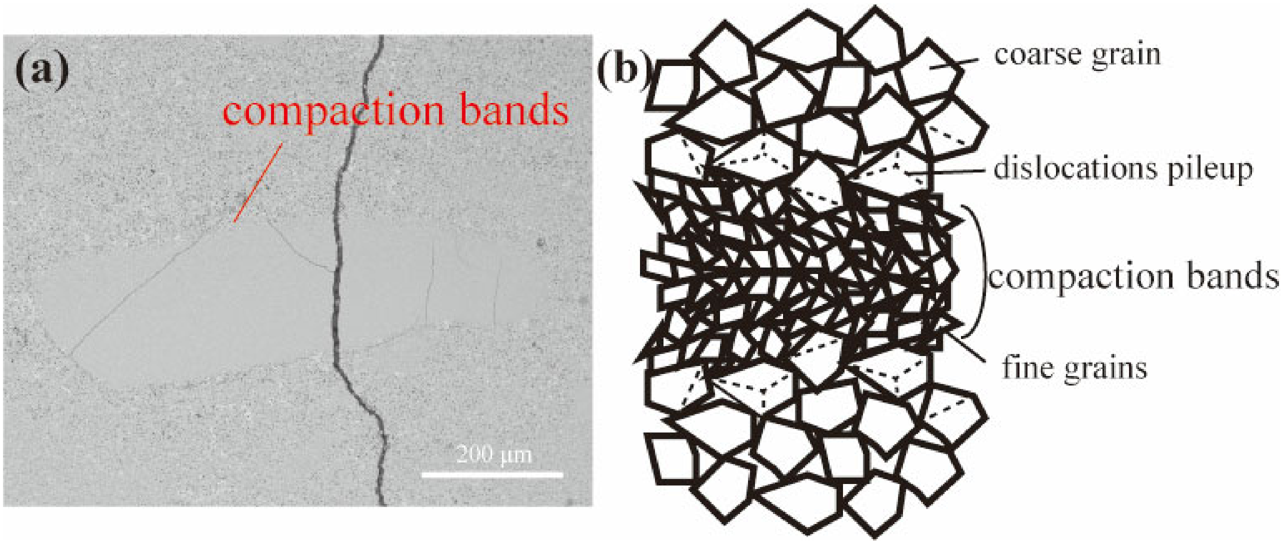

Figure 1. (a) compaction band modified after Sawa et al. (2021b). (b) Formation mechanism for compaction

the compaction of the powder under high pressure and low temperature during experiments (cold pressing). This stress state during sintering is close to the transitional regime from brittle faulting to cataclastic flow; hence, there is a possibility that compaction bands, a type of strain localization bands, may form at the cold pressing stage of deformation in laboratory experiments. I conducted cold pressing experiments on the powder of fine-grained germanate olivine and pyroxene with approximately 30 % porosity using a Griggs-type apparatus. The experiments reveal that compaction bands form in the compacted and sintered sample (Fig. 1a). Microstructural analysis revealed that grains with a high dislocation density rotate and crush with shear strain concentration during compaction. At the end of the compaction, the grain size becomes small, and bands are made of fine-grained material (Fig. 1b). This indicates that high pressure and low temperature conditions should be avoided for sintering.

In part 3, I attempted to reveal how much amount of hydrous minerals can exist in the lower double seismic plane of the subducting slab, even if only a small amount of fluid can infiltrate the plane. Antigorite, a high-pressure polymorph of serpentine, is considered the most abundant hydrous mineral in the subduction zone (Hacker et al. 2003). Although the antigorite is presumed as one of the origins of intermediate-depth earthquakes in the subduction zone (Raleigh and Paterson 1965; Ferrand et al. 2017), the amount of antigorite is uncertain because the amount of water infiltrated into the oceanic lithosphere is still debated. To investigate whether antigorite can be formed even under the limited availability of water, I conducted the axial deformation experiments of magnesium germanate, an analog material of magnesium silicate, at 1.2 GPa and $T =$ 500-800 °C using a Griggs-type deformation apparatus. Although the absorbed water in the starting material was eliminated preliminary, the samples initially had high porosity. Hence, a small amount of water (about 200 ppm wt% H_2O) was retained in the samples. In the samples deformed at 600 °C, the stable slip occurred,

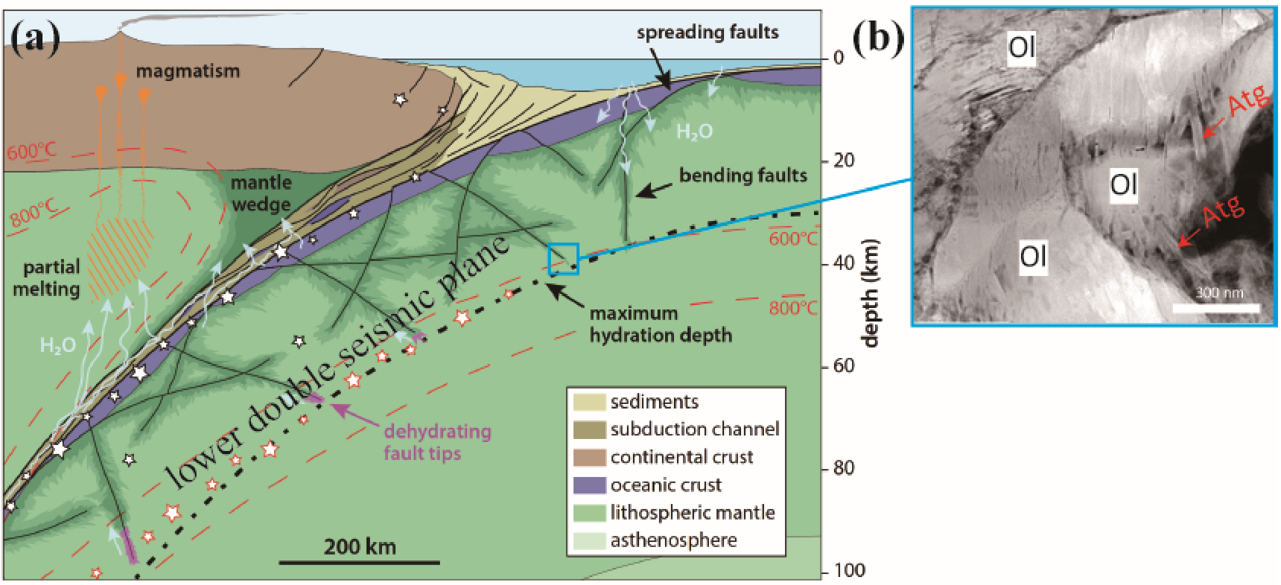

Figure 2. (a) Cross section of the slabs modified after Ferrand (2019). (b) Antigorite near olivine grain (ol: olivine Atg: antigorite) modified after Sawa et al. (2021a)

and TEM analysis revealed that fine-grained platelets of germanate antigorite existed along the faults (Fig. 2b). Sharp absorption band assigned to the OH stretching vibration of antigorite in Fourier transform infrared spectroscopic (FT-IR) analysis also implies that antigorite was widely formed in the samples deformed at a temperature lower than 600 °C. Considering that it takes tens of hours to form germanate antigorite under hydrothermal conditions (Roy and Roy 1954) and tens of minutes to form it in these experiments, our results indicate that strain-induced hydration of germanate olivine results in antigorite formation even under a small amount of water. Thus, partly hydrated peridotite in the oceanic lithosphere can be formed under slight water infiltration due to the high strain accumulated by the subduction (Fig. 2).

In part 4, I attempted to reveal what parameters control the form of grains of spinel (γ) phase nucleated by the phase transformation from the olivine phase under a differential stress. Burnley and Green (1989) reported that deep-focus earthquakes occurred by the strain localization on anticracks, which were lens-shaped with a strong preferred orientation normal to the maximum compression direction. Furthermore, the grain growth rate of spinel phase would affect the width of the metastable olivine wedge in the subduction zones (Chien-Min and Burns 1976). Therefore, it is crucial to reveal the kinetics of olivine-spinel phase transformation under differential stress. To investigate the effect of microstructural properties on phase transformations such as grain boundary energy and plastic strain, I conducted a phase-field simulation using germanate olivine as an analog of silicate olivine. I conducted the simulations under various confining pressures of 1-5 GPa, temperatures of 1000 and 1200 K, with/without plastic strain, and various grain boundary energy. At this experimental conditions, germanate spinel is stable; thus, germanate olivine is metastable.

In part 5, I attempted to reveal what parameters control the seismological properties (e.g., *b* values in Gutenberg-Richter law) in the phase transformational faulting, which is one of the proposed mechanisms for deep-focus earthquakes. The phase transformational faulting occurs due to the localization on dense spinel phases (wadsleyite and ringwoodite) that olivine undergoes the phase transformation to. The geophysical observation reported that the *b* value in the Gutenberg–Richter law was close to 1 in the cold slabs, whereas the *b* value was close to 0.5 in the warm slabs for intermediate magnitudes (Mw 5.3-6.5), which was derived from the rupture geometry of the phase transformational faulting (Zhan 2017). Previous deformation experiments indicated that the grain size of olivine would control the occurrence of transformational faulting. Therefore, I conducted deformation experiments of germanate olivine aggregates with various grain sizes from a few microns to more than hundreds of microns using a transducer that can detect acoustic emissions (AE) to reveal the effect of grain size on the difference in *b* values for the phase transformational faulting.

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