In situ X-ray and acoustic observations of deep seismic faulting upon phase transitions in mantle olivine

The surface of the Earth consists of plates, which move and subduct along with the flow of the mantle beneath the plates. Earthquakes occur upon the collision and subduction of plates, even at depths of several hundred kilometers in the mantle, which are called "deep-focus earthquakes." Such earthquakes occasionally result in serious disasters as shown, for instance, by the 1994 Bolivian earthquake that occurred at a depth of 638 km with a magnitude of 8.3. The cause of deep-focus earthquakes, however, has been a mystery, because the occurrence of earthquakes requires the rapid sliding of the fault, which is difficult under great pressures in the deep mantle. It is well recognized that the frequency of earthquakes monotonically decreases with depth. However, an increase in the frequency of earthquakes at depths from ~400 km to ~600 km seems to be linked to the phase transitions of olivine to high-pressure phases (i.e., wadsleyite at ~400 km; ringwoodite at ~500 km) [1]. Attempts have been made to understand the mechanism behind the occurrence of deep-focus earthquakes through laboratory deformation experiments, but such experiments under deep mantle conditions have not been performed owing to technical difficulty. In most of the previous studies, a germanate analog (Mg_2GeO_4), which transforms directly to the spinel phase at 1 to 2 GPa without passing through the modified spinel phase (i.e., wadsleyite), has been used. Moreover, the net temperature increment due to the release of latent heat across the phase transition of the germanate analog is much lower than that of mantle olivine [2], implying that this might not be a perfect analog of mantle olivine [3]. Here, we, for the first time, performed deformation experiments on natural olivine, which is the major mineral of the mantle and subducting oceanic lithosphere (slab), using a state-of-the-art large-volume deformation apparatus combined with synchrotron X-ray observations [4].

We have conducted uniaxial deformation experiments on mantle olivine samples combined with synchrotron *in situ* X-ray observations at pressures of 11–17 GPa, temperatures of 860–1350 K, and strain rates of $10^{-5}-10^{-4}$ s^{-1} using a deformation-DIA apparatus at SPring-8 **BL04B1**. These temperature and pressure ranges are equivalent to the conditions in deep subducted slabs. Acoustic emissions (AEs) were monitored using six piezoceramic lead-zirconate titanate transducers that were attached to the side of each second-stage anvil. Our AE monitoring technique allowed us to evaluate the three-dimensional location and magnitude of microcracks (i.e., hypocentres of AEs) in a deforming sample. The mechanical and statistical similarities between AEs and earthquakes have been verified in terms of the Gutenberg-Richter relationship and other models.

Within a narrow temperature window (~800°C), the semi-brittle flow of olivine resulted in formation of throughgoing faults (Fig. 1). At the timing of faulting, one or two large AEs occurred inside the sample, followed by relatively large AEs outside the sample, radiated around the fault plane crossing the sample. This suggests that the occurrence of a throughgoing fault slip caused by rupture was followed by rupture propagation outside the sample. After careful analyses of the recovered sample, we found that faulting was induced by the growth of 'new' olivine/wadsleyite with diameters of tens of nanometers upon the phase transition of 'old' olivine. The gouge layer, which consists of the nanograins of olivine/wadsleyite, acts as a lubricant for the rapid sliding of the fault.

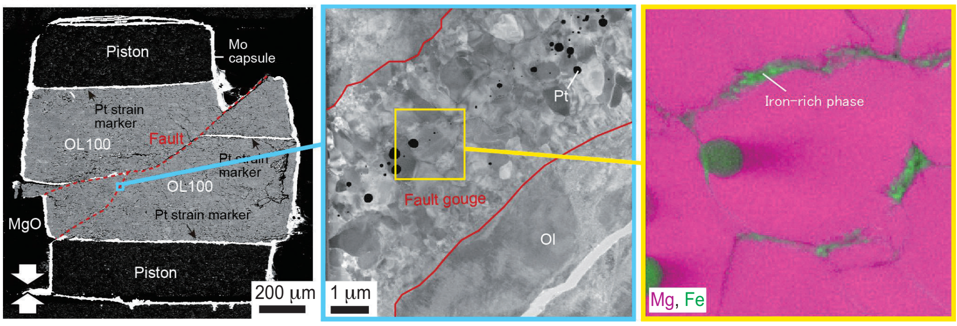

Fig. 1. Faults developed in the olivine aggregate deformed at 15.5 GPa and 850°C. **(a)** The recovered sample. Red dashed lines represent faults. **(b)** The fault filled with nanocrystalline olivine and wadsleyite. **(c)** A close-up view of the fault gouge. The iron-rich phase (a product of partial melting of olivine: green) is distributed along the grain boundaries of nanocrystalline olivine.

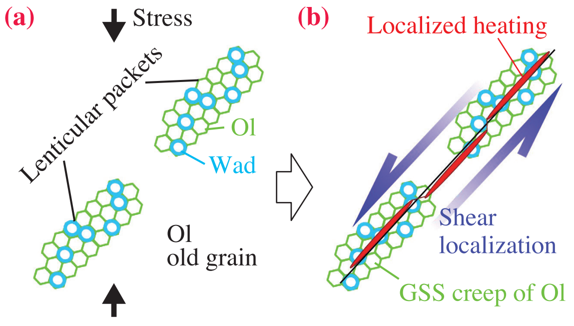

Fig. 2. Faulting triggered by the phase transition of olivine. **(a)** Formation of lenticular packets filled with nanocrystalline olivine (Ol)/wadsleyite (Wad). **(b)** Shear localization on the weak layer formed by the coalescence of the lenticular packets. This results in shear heating followed by faulting (i.e., deep-focus earthquakes).

Platinum-iron alloy blobs with a diameter of 10–200 nm and an interconnected iron-rich silicate phase (FeO = 20–37 wt%) are also observed in the gouge core (Fig. 1), showing the melting of the platinum strain marker and olivine during throughgoing faulting. The melting curves for the platinum-iron alloy and olivine polymorphs constrains the peak temperature during throughgoing faulting to the range of ~1900–2200°C or higher.

In a few runs deformed at 600–800°C without throughgoing faulting, the formation of lenticular packets filled with nanocrystalline olivine and wadsleyite (20–300 nm in diameter: Fig. 2) was observed, showing the grain size reduction of olivine and the nucleation of wadsleyite induced by the olivine-wadsleyite transition. The lenticular packets are aligned with high angles (~30°) to the compression direction and have a width of 2–3 μm. The linking-up of the lenticular packets should be the cause of weak fault gouge layers observed in the faulted samples (Figs. 1 and 2).

Our model based on the results of laboratory experiments well explains the distribution of the deep-focus earthquakes, which increase with depth from ~400 km to ~600 km, where the metastable 'old' olivine is expected to form ultrafine-grained 'new' olivine/wadsleyite. The seismic imaging of the deep mantle demonstrates the presence of the metastable olivine wedge (MOW), accompanied by deep-focus earthquakes, in a low-velocity zone with a thickness of tens of kilometers inside the subducted slabs (Fig. 3). The results of the present study suggest that a deep-focus earthquake nucleates when the temperature of the MOW becomes close to 800°C at pressures of the mantle transition region. The nanocrystallization of olivine occurs upon the phase transition (i.e., formation and linking-up of the lenticular packets filled with nanocrystalline olivine/wadsleyite) followed by throughgoing faulting due to shear instability (Fig. 2), although this critical temperature may be lower on the geological time scale. In fact, the observed deep-focus earthquakes are reported to be located along an isotherm of ~700°C in subducted slabs [5]. The shear zones filled with nanocrystalline olivine required for throughgoing faulting would not be preserved in subducted slabs at depths beyond this kinetic boundary of ~630 km, which is consistent with the abrupt decrease in seismicity at depths below ~600 km [1].

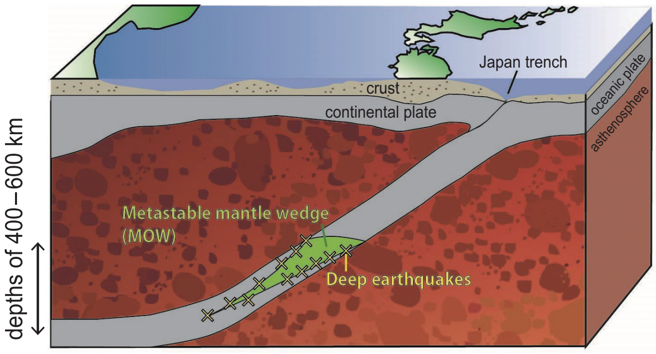

Fig. 3. Deep-focus earthquakes occurring in the subducted slab underneath Honshu Island. Our results suggest that hypocenters of deep-focus earthquakes are preferentially distributed around the surface of the metastable olivine wedge (MOW), which forms the central part of the subducted slab.

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References

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