Transient creep in olivine controls the post-seismic deformation

The flow of the crust (thickness of ~50 km) and uppermost mantle (depth: 50–150 km) is a fundamental process that controls post-seismic deformation (Fig. 1). Geodetic observations have revealed that the deformation of the crust and uppermost mantle after a great earthquake sometimes continues for decades. Viscosities of the uppermost mantle estimated from early post-seismic deformation are often significantly low (10^{17}–10^{18} Pa·s) and continuously increase to a typical value of ~10^{20} Pa·s. Such time-dependent and short-term (on the geological timescale) phenomena needs to be considered from the viewpoint of the transient creep of olivine, which is the most abundant mineral in the lower crust and upper mantle [1].

The deformation of rocks can be divided into three regimes: i) elastic, ii) transient, and iii) steady-state regimes. The elasticity and steady-state creep strength are independent of time. However, the strength changes with time during the transient creep. The time-dependent behavior of the transient creep can be described by the Burgers model, which can be expressed as the follows:

$$\dot{\varepsilon} = \dot{\varepsilon}_{ss}\left[1 - \exp\left(-\frac{t}{\tau}\right) + \frac{\eta_{ss}}{\eta_t}\exp\left(-\frac{t}{\tau}\right)\right] \qquad (1)$$

where $\dot{\varepsilon}$ is strain rate, $\dot{\varepsilon}_{ss}$ is the steady-state strain rate, t is time, τ is the transient relaxation time, and η_{ss}/η_t is the ratio of the steady-state to the transient viscosity [2]. The Burgers model has been adopted in numerical studies to evaluate the three-dimensional response of the lower crust and uppermost mantle following a large earthquake [3]. However, such studies assumed hypothetical values for the constants (τ and η_{ss}/η_t) in Eq. (1). This is because the values of the constants in Eq. (1) have not been determined for olivine at upper mantle pressures and temperatures because of the challenges in obtaining laboratory measurements. The transient creep of olivine was observable within a few minutes of a deformation experiment. Observations of such "short-term" characteristics of the transient creep inevitably require high time-resolution stress/strain measurements for experiments. For the first time, my colleagues and I performed stress-relaxation (i.e., deformation just after stress release) experiments on olivine using advanced high-flux synchrotron X-ray technology under upper mantle pressures and temperatures. We successfully constrained the time dependence of transient creep of olivine [4].

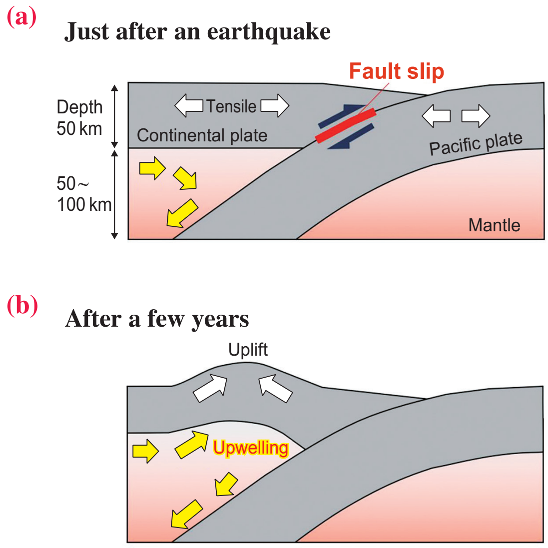

Fig. 1. Post-seismic deformation. **(a)** Cross-sectional view of a subduction zone just after an earthquake on the plate boundary. Tensile stress is coseismically induced in the plates. **(b)** Few years after the earthquake. Post-seismic displacements of land are significant due to the upwelling flow of the uppermost mantle induced by the earthquake [5].

We conducted stress-relaxation experiments on mantle olivine samples combined with synchrotron *in situ* X-ray observations at pressures of 1.7–3.6 GPa and temperatures up to 1020 K using a "mobile" multianvil apparatus at SPring-8 **BL05XU**. This "mobile" multianvil apparatus (~5 ton in total weight), specifically designed for high-pressure experiments at this beamline, was transported into the experimental hutch just before each beamtime (Fig. 2) and was returned to a repository area (SPring-8 BL04B1) after the end of the beamtime. The temperature and pressure ranges were set equivalent to those of the shallow upper mantle. The olivine sample was first semihydrostatically pressurized to the desired pressure at room temperature. Shortening of the sample started when the temperature rapidly increased (up to 1020 K) at high pressures. The combination of a high-flux pink beam (energy 100 keV) from an undulator source and a cadmium telluride (CdTe) imaging detector (WidePix 5×5) with 0.4 s of exposure time enabled us to acquire two-dimensional radial diffraction patterns (for the determination of pressure and stress) and radiographic images (for strain measurements). The exposure time for the two-dimensional radial diffraction pattern (0.4 s) was two orders of magnitude shorter than that for BL04B1.

A series of stress-relaxation runs showed that the transient creep of olivine followed Eq. (1) with the transient relaxation time (τ) ranging from 50 to 1880 s. To confirm the occurrence of the transient creep of olivine, the temperature was rapidly increased from 570 to 840 K to observe the responses of pressure, stress, and strain to the increase in temperature (~100 $K \cdot s^{-1}$: Fig. 3). An instantaneous pressure increase ($\Delta P \sim 0.5$ GPa) caused by the thermo-elastic expansion of olivine crystals was synchronized with the temperature increase. Figure 3 shows a 25-second delay of softening –indicated by a decrease in stress and an increase in strain– following the temperature increase. This observation supports the conclusion that a value of $\tau \sim 50$ s is the most accurate for describing the transient creep of olivine, rather than the significantly higher τ observed in other runs. Based on the obtained values of the parameters in Eq. (1), the time-dependent increase in viscosity of the shallow upper mantle reported in late post-seismic deformation (10^{18}–10^{20} Pa·s) is explained by the Burgers rheology for olivine. Time-dependent crustal deformation, which continues for decades after a great earthquake (Fig. 1), is explained by the transient creep of olivine.

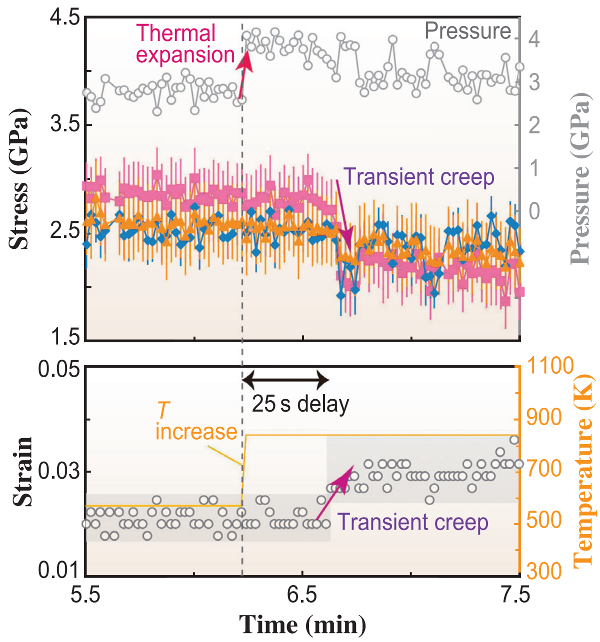

Fig. 3. Differential stress (color symbols), pressure and strain (gray circles), and temperature (orange line) plotted against time in a stress-relaxation run for an olivine sample. A sudden increase in temperature (from 570 to 870 K) was followed by a synchronized pressure jump (due to thermal expansion of olivine). The decrease in stress and the increase in strain (due to transient creep of olivine) delayed for 25 s. Note that stress values were obtained from the diffraction peaks of olivine (blue: 021; pink: 101; orange: 130).

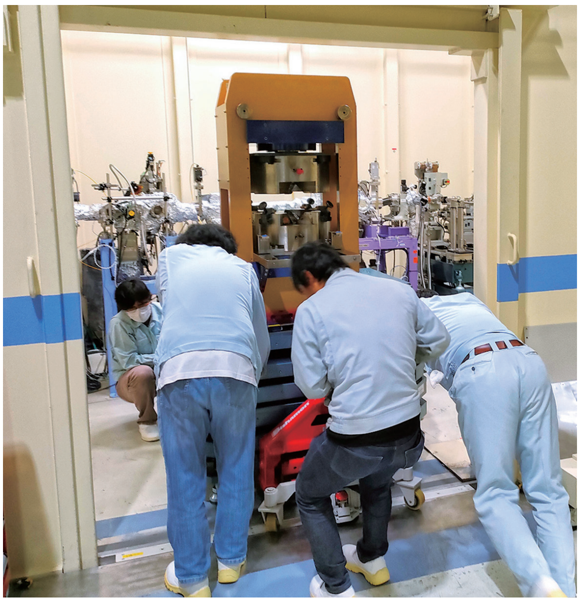

Fig. 2. Installation of the "mobile" multianvil apparatus to the experimental hutch of beamline BL05XU just before a high-pressure experiment.

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