Laboratory measurements of sound velocities of $CaSiO_3$ perovskite reveal the fate of subducted oceanic crust into the Earth's deep interior

Laboratory measurements of sound velocities of minerals at high pressures and high temperatures play an important role in enabling scientists to interpret seismic data in terms of chemical and mineralogical compositions of the Earth's mantle by direct comparison with global seismic models. Previous studies have demonstrated that velocities of pyrolite, a hypothetical rock derived as a mixture of mid-ocean ridge basalts (MORB) and peridotite, agree well with those of geophysical observations at depths down to ~560 km [1]. There is, however, still no unique interpretation of seismic data at depths below 560 km where pyrolite sound velocities fail to explain the high seismic gradients observed at the bottom of the mantle transition region (MTR; 410–660 km in depth), as well as the low-velocity zones beneath the 660-km discontinuity. Recent seismic tomography studies revealed that the oceanic lithosphere descend into the deep mantle at subduction zones [2], forming at these depths, gravitationally stable layers of chemically distinct materials such as MORB or harzburgite, which constitute the main bodies of the subducted slab. However, what exactly happens to those slab components as they remain deep into the mantle remains relatively unknown.

Calcium silicate perovskite (CaPv) constitutes 7–10 vol% pyrolite and up to 30 vol% MORB below a depth of ~560 km and therefore is an important constituent mineral in both the peridotitic mantle and basaltic crust in the MTR and lower mantle. Despite this importance, measurements of its sound velocity under the corresponding *P*, *T* conditions have never been performed because this phase is unquenchable to atmospheric pressure and adequate samples for such measurements are unavailable. This lack of constraints leads to unresolved debates as to whether pyrolite and MORB can reproduce seismic velocity profiles throughout the mantle.

We measured simultaneously the sound velocity and density of CaPv using ultrasonic interferometry combined with synchrotron X-ray techniques and the multianvil apparatus at SPring-8 **BL04B1** [3] (Fig. 1). Starting from a $CaSiO_3$ glass rod, a polycrystalline sintered body of CaPv was first synthesized *in situ* at 21 GPa and 1300 K. Once the transformation is confirmed from the diffraction peaks of CaPv (Fig. 1(d)), the travel times of P- and S-waves (Fig. 1(b)), sample length (Fig. 1(c)), and density (Fig. 1(d)) are measured following the procedures described in [3]. Five independent experiments were carried out at pressures up to 23 GPa and temperatures of 700–1700 K in the stability field of the cubic CaPv. The thermoelastic properties (e.g., K_S: adiabatic bulk modulus, G: shear modulus) were determined using our experimental P- and S-wave velocities and densities (Fig. 2). We found that cubic CaPv has a

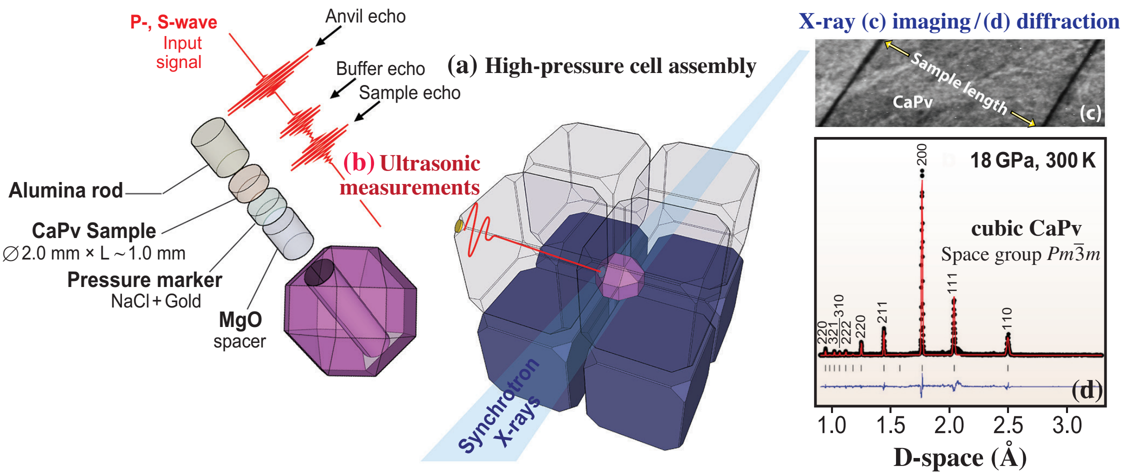

Fig. 1. Schematic diagram of the ultrasonic measurements at BL04B1. **(a)** Eight WC anvils are used to compress the cell assembly to the target pressure. **(b)** Travel times of P- and S-waves were measured by recording arrival times of the acoustic echoes at the buffer rod and sample interfaces. **(c)** Sample length was determined by X-ray imaging techniques. **(d)** CaPv density and pressure were determined *in situ* from the X-ray diffraction pattern of the sample and the gold pressure marker, respectively.

shear modulus G_0 = 126(1) GPa, which is about ~26% lower than theoretical predictions (~171 GPa) [4], leading to substantially lower shear velocities in CaPv-bearing compositions than those predicted under the *P*, *T* conditions of 660–770 km depths.

Our CaPv elasticity data, combined with those from previous experimental studies show that shear velocity increments due to the formation of CaPv in pyrolite and MORB are insufficient to explain the high shear-wave velocities below a depth of ~560 km [3] and suggest the presence of a nearly pure harzburgite region (Fig. 3) at the bottom of the MTR. The basaltic crust in the remaining part of the stagnated slab would descend to the lower mantle where it should remain trapped owing to the density contrast between MORB and the pyrolitic mantle changing at a depth of ~780 km. Our results show that the discrepancy between the velocities of pyrolite and those of seismological models at depths of 660–780 km can be reconciled if ~20–30 vol.% MORB is globally present in this region (Fig. 3), which is consistent with the recent discovery of CaPv in natural diamond [5]. Our results also provide further evidence for the presence of oceanic crust materials in the uppermost lower mantle. Basalt enrichment below 660 km would stabilize regimes of slab stagnation above this depth of 660 km, in the MTR, and down to a depth of ~1000 km in the lower mantle, as predicted by global-scale geodynamics calculations [6]. CaPv, which has velocities substantially lower than those of bridgmanite, should greatly contribute in tracing the existence and recycling of the former oceanic crust in the Earth's lower mantle.

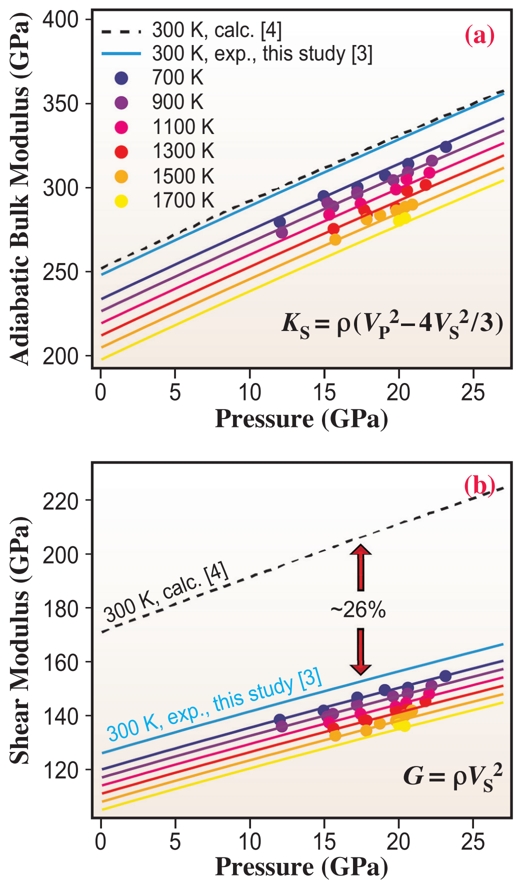

Fig. 2. **(a)** Adiabatic bulk and **(b)** shear moduli of CaPv as functions of pressure and temperature determined in our experimental study, compared with those determined in a previous theoretical study [4]. Cubic CaPv has a shear modulus that is about ~26% lower than theoretical predictions [3,4].

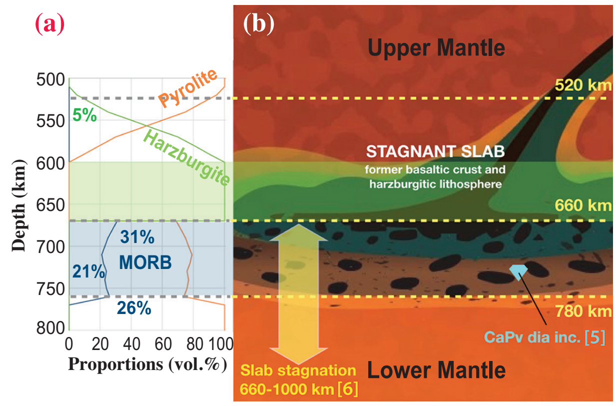

Fig. 3. **(a)** Estimates of mineralogical proportions of harzburgite and MORB relative to that of pyrolite, on the basis of shear wave velocity model. **(b)** Schematic of mantle regions beneath subduction zones. The high seismic velocities above a depth of 660 km is explained by the gradual increase of harzburgite components from ~500 to 600 km, below which a nearly pure harzburgite region should be formed. The basaltic crust, which is denser than pyrolite and harzburgite in the MTR but less dense than those two in the lower mantle, is likely to remain trapped at depth between 660 and 780 km.

Steeve Gréaux[a,b,*] and Tetsuo Irifune[a,b]

[a] Geodynamics Research Center, Ehime University
[b] Earth-Life Science Institute, Tokyo Institute of Technology

*Email: greaux@sci.ehime-u.ac.jp

References

[1] T. Irifune *et al.*: Nature **451** (2008) 814.
[2] Y. Fukao & M. Obayashi: J. Geophys. Res. **118** (2013) 5920.
[3] *S. Gréaux, T. Irifune, Y. Higo, Y. Tange, T. Arimoto, Z. Liu and A. Yamada: Nature* ***565*** *(2019) 218.*
[4] L. Stixrude *et al.*: Phys. Rev. B **75** (2007) 024108.
[5] F. Nestola *et al.*: Nature **555** (2018) 237.
[6] M.D. Ballmer *et al.*: Sci. Adv. **1** (2015) e1500815.