様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）高圧実験と地震波観測による統合的アプローチを用いた沈み込み帯下の構造と進化の解明

研究課題名（英文）Elucidation of the Structure and Evolution of the Subduction Zone Using an Integrated Approach of High-Pressure Experiments and Seismic Wave Observations

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　13,700,000円

研究成果の概要（和文）：本研究プロジェクトでは、地球規模のモデルとは独立して、停滞するスラブを持つ地域の地震活動を調査しました。調査は、実験室での音速測定、スラブの地質記録、そして局所的な地震観測に基づいています。当研究チームは、先鋭的な超音波干渉計やシンクロトロンX線技術を用いて、上部マントル、マントル遷移層、そして下部マントル最上部における実験を行いました。パイロライト、中央海嶺玄武岩、ハルツバーグ岩だけでなく、他の関連する鉱物や岩石についてもこの手法を適用し、国際的な共同研究の結果、地球惑星科学の分野に広範な示唆を与える成果を得ました。

研究成果の学術的意義や社会的意義
The velocity models derived from our datasets enable us to constrain the local structure and composition of the mantle and subducted slabs, extending up to the uppermost lower mantle. This has implications for our understanding of Earth's internal dynamics and evolution throughout geological time.

研究成果の概要（英文）：In this research project, we conducted an investigation into the seismicity of regions with stagnating slabs, independently of global models. Our investigation was based on laboratory sound velocity measurements, geological records of the slab, and local seismological observations. Through the application of advanced ultrasonic interferometry and synchrotron X-ray techniques, we were able to perform experiments at the pressures and temperatures of the upper mantle (up to 2300 K at pressures of ~3-10 GPa), mantle transition zone (up to 2100 K at pressures of ~12-22 GPa), and uppermost lower mantle (up to 2100 K at pressures of ~24-27 GPa). These techniques were applied to investigate the sound velocities of pyrolite, Mid-Ocean Ridge Basalt (MORB), and harzburgite rock aggregates, as well as other relevant minerals and rock compositions. The results of our investigation have broad implications for the fields of Earth and planetary sciences.

研究分野：Solid Earth

キーワード：mantle composition　high pressure　ultrasonic measurement　seismological model　triplication

１．研究開始当初の背景

P- and S-wave elastic velocities are unique tools we have to explore the chemical composition and structures of the inaccessible deep Earth, by comparing high pressure mineral physics data with seismological observations. Laboratory measurements generally proposes that pyrolite, a hypothetical rock derived as an equilibrated mixture of mid-ocean ridge basalts (MORB) and harzburgite, agree well with seismological observations at depths of 560 km. In the deeper parts of the mantle transition zone (MTZ; at depths of 410-660 km)however, there is no clear answer. Although theoretical studies and numerical simulations proposed an unequilibrated mixture of pyrolite, MORB and harzburgite could provide an explanation for the seismic observations in the MTZ, in absence of experimental data, there is currently no model that can explain a number of structures evidenced by anomalous seismic reflections widespread at multiple depths across the globe.

２．研究の目的

The aim of this study is to resolve the discrepancies between mineral physics data and seismological observations in the bottom part of the Earth’s MTZ on the basis of in situ elastic wave velocity and synchrotron X-ray measurements on mantle and slab rock aggregates under high-pressure and high-temperature. In order to achieve this goal, we further developed the ultrasonic techniques at the beamline BL04B1 in SPring-8, and achieved such experiments at P up to 30 GPa and T up to 2000 K, which are relevant to the P and T conditions of the lowermost MTZ. Using these newly established techniques we investigated the effect of chemical variation on P- and S- elastic wave velocities (Vp and Vs) of mantle rocks by measuring Vp and Vs of pyrolite, MORB and harzburgite mineral assemblages, which are believed to represent the composition of mantle and subducted slab rocks, respectively. The experimental data are directly compared with P- and S-wave velocity structures, derived from "triplication method", thus combining experimental and seismological models to resolve the composition and temperature and well as the thickness of the MTZ.

３．研究の方法

We carried out VP and VS measurements on Pyrolite, MORB and harzburgite rock aggregates synthesized below subsolidus P and T conditions, using a combination of in situ ultrasonic interferometry, X-ray radiography and X-ray diffraction techniques at high pressure and high temperature. Starting materials were synthesized from a mixture of oxides, which were packed in a metal capsule and hot pressed at P up to 27 GPa and T= 1400-1800 °C, thus covering a large range of mineralogical assemblages for pyrolite, MORB and harzburgite in the MTZ (Fig. 1a). Recovered samples were quasi-cylindrical in shape, with a diameter of 1.5-2.0 mm and length > 1.0 mm (see some examples on Fig. 1b, 1c, 1d, 1e). Chemical composition and texture of the recovered samples were analyzed by an electron microscope equipped with an energy dispersive spectrometer. Samples with low-porosity and so-called phase equilibrium texture (Fig. 1f) were polished on both faces to 0.5 μm mirror-surface and used for ultrasonic measurements at SPring-8.

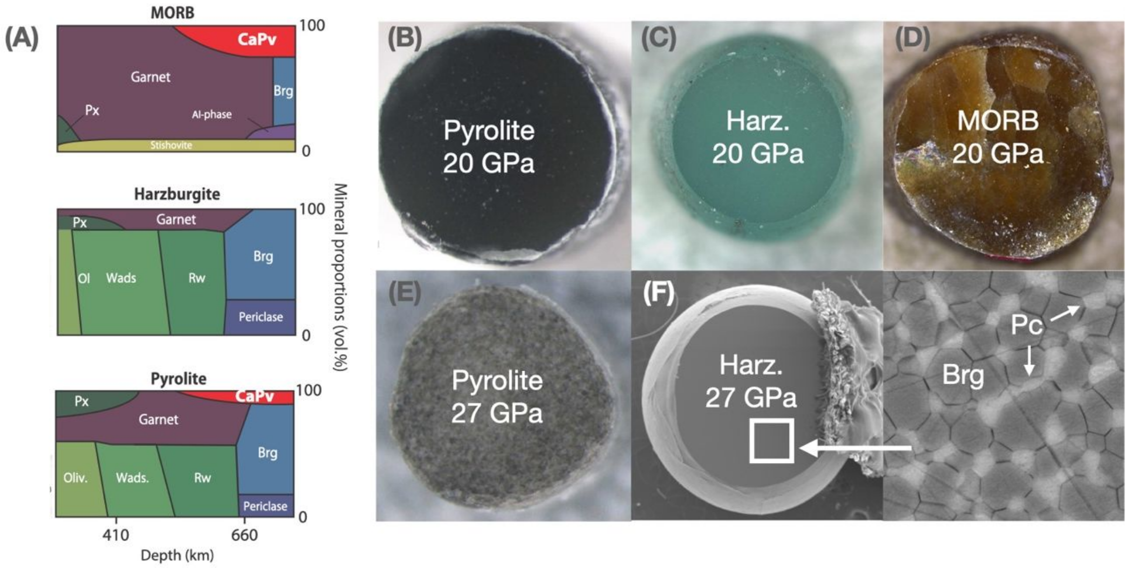

Figure 1. (a) Mineral proportions as function of depth. Images of (b) Pyrolite, (c) harzburgite and (d) MORB samples synthesized at 20 GPa and (e) pyrolite synthesized at 27 GPa. Electron image showing the texture of harzburgite synthesized at 27 GPa

The ultrasonic experiments on the rock aggregates were carried out in the multi-anvil press apparatus SPEED1500 located at the beamline BL04B1 (Fig. 2a).Samples were surrounded by a MgO sleeve and placed in a (Mg,Co)O pressure medium equipped with a cylindrical Re heater (Fig. 2a). A pellet of NaCl + Au + BN is placed at the back of the sample to enhance hydrostatic conditions at high-pressure and monitor pressure by using energy dispersive X-ray diffraction measurements of the gold unit-cell volume and its equations of state. Temperature is measured with a W97Re3-W75Re25 thermocouple, whose hot-junction is placed at the bottom of the pressure marker. Travel times of P- and S-wave are measured by the pulse echo overlap method at the resonant frequencies of 60 MHz and 40 MHz (Fig. 2b), respectively, while sample length is determined by X-ray radiography imaging (Fig. 2a) using a high-resolution CCD camera (HAMAMATSU C11440) with a resolution of ~1 μm/pixel. Generally, samples were compressed to a target pressure, identical to the synthesis pressure. Samples were then annealed for about 1 hour to release non-hydrostatic stress that may develop during cold compression, then ultrasonic data were collected during cooling to room T. Vp and Vs of the investigated samples are calculated using P- and S-wave travel times, combined with the samples length (Fig. 2c).After experiment, samples were recovered to atmospheric pressure and analyzed by an electron microprobe, to assess that no chemical reaction occurred during the ultrasonic measurements.

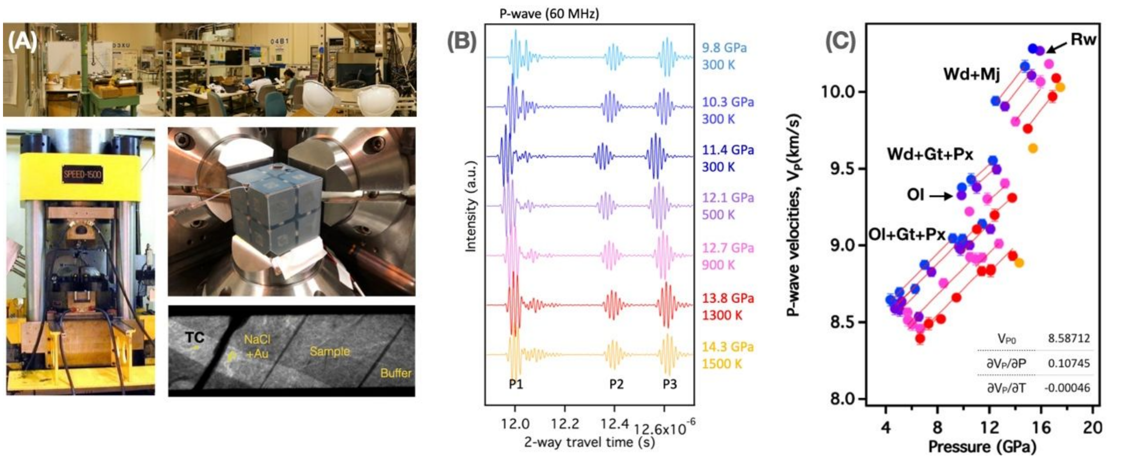

Figure 2. (a) Pictures of the beamline BL04B1, SPEED1500 press apparatus, cell assembly and radiography image of the sample at high P. (b) Ultrasonic waveforms at simultaneous high P-T. (c) P-wave velocities of pyrolite samples derived from the ultrasonic waveform and radiography images.

4．研究成果

Our results showed that pyrolite can mostly explain the seismic velocities of the MTZ, except for the bottom part, above the 660. The velocity jump at the Ol+Px+Gt → Wd+Gt is larger than the seismic observations, which cannot be explained by the presence of basalts, because MORB also has relatively high Vs/Vp in this region (Fig. 3a). The presence of accumulated MORB below ~500 km depth would result in low Vs/Vp. We found however that the post-spinel transformation in pyrolite can explain most of the velocity jump at 660 km depth, which may limit the presence of basalts at those depth to low Vs/Vp provinces within the subducted slab. MORB are also unlikely to explain the difference of pyrolite and PREM beneath 660, which suggest that basalts may sink even further in the uppermost lower mantle (Fig. 3b). These conclusions are compatible with an estimates of the rock components in the MTZ on the basis of a comparison between our data and 1D global seismic models.
Velocity data at high-temperature, up to 1700 K, for all compositions and recent runs at P > 25 GPa for MORB and harzburgite are still under preparation and will be used to further interpret seismic observations of the mantle and subducted slabs, taking into consideration the temperature variation from the cold inner part of the slab to the hot outer part, at the contact of the mantle. To carry out this task, we are still developing the local seismic models that will serve as a comparison to infer the composition and structure of the subducted slabs.

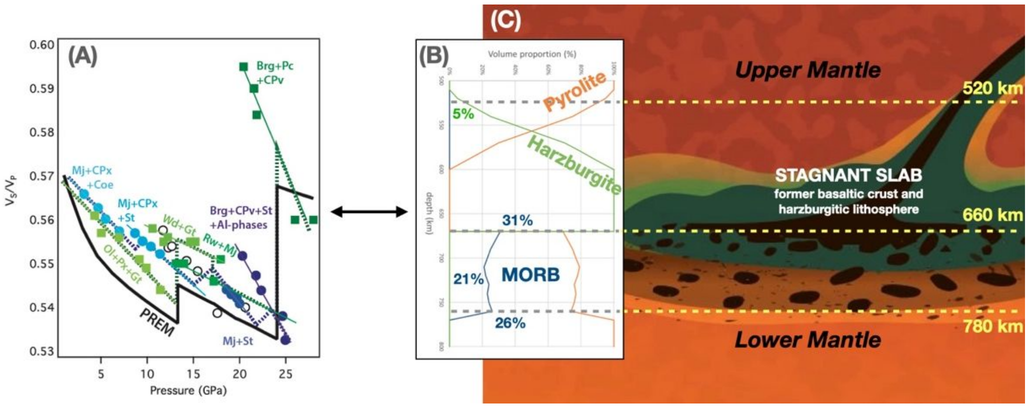

Figure 3. (a) Ratio of Vs/Vp as a function of pressure for the pyrolite and MORB compositions. (b) Proportions of pyrolite, MORB and harzburgite as function of depth. (c) Illustration representing the distribution of the slab components across the 660 km depth discontinuity.

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　9件／うち国際共著　9件／うちオープンアクセス　2件）

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２．論文標題 Al partitioning between phase D and bridgmanite at the uppermost lower mantle pressure	５．発行年 2021年
３．雑誌名 Physics and Chemistry of Minerals	６．最初と最後の頁 p. 0
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/ s00269-021-01163-5	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Xu F., Siersch N.C., Greaux S., Rivoldini A., Kuwahara H., Kondo N., Menguy N., Kono Y., Higo Y., Plesa A.-C., Badro J. and Antonangeli D.	４．巻 48(19)
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/08957959.2021.1941000	査読の有無 有
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１．発表者名
Greaux S.

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3．学会等名 27th IUGG General Assembly (Montreal, Canada)（招待講演）（国際学会）
4．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関