

日本列島における地震波異方性速度構造のモデル化に向けて(その1)鉛直異方性を考慮した三次元P波速度構造推定 Toward modeling the anisotropic velocity structure beneath the Japanese subduction zone (1)

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地震波異方性とは弾性的性質の方向依存性であり、異方性鉱物の結晶格子や岩石組織などの選択的配向、および弾性率の異なる物質による互層構造によって生じることが実験的および理論的研究から明らかにされている。一方、地震学的研究においては、様々なスケールの地震波から異方性の影響と考えられる現象(地球自由振動のモードの異常分裂、ラブ波とレイリー波速度の矛盾、P波伝播速度の方向依存性、S波分裂など)が観測されており、地球内部には異方性領域が広く存在しているものと考えられる。また、その程度は等方性速度の不均質性と同程度であり、地球内部構造解析における異方性の重要性は言うまでも無く、地震波異方性は地球内部構造を記述するのに不可欠なパラメータであるといえる。加えて、前述のような異方性構造が地球内部で形成されるには、地球の進化プロセスを支配するダイナミクスやテクトニクスからの強い影響が考えられ、地球内部の異方性構造のモデル化は地球内部構造解析研究における重点課題であると考えられる。

日本列島については、その下に鉛直異方性が広く分布することが表面波などの解析から指摘されている(たとえば Aki, 1968)。これと同時に、水平面内で地震波速度が変化する異方性<方位異方性>が深さを問わず普遍的に存在するという事実も、実体波を用いた地域的な異方性の調査(Kaneshima, 1991; Oda & Shimizu, 1997; Saiga et al., 2003; Nakajima et al., 2004; Ishise & Oda, 2005; Wang & Zhao, 2008 など)から知られている。鉛直異方性と方位異方性の共存は、決して矛盾した状況ではないが、これら観測をうまく説明する異方性構造モデルは未だ確立されていない。

そこで我々は、鉛直方向と水平方向に伝播する地震波速度が異なる異方性<鉛直異方性>に注目し、日本列島における地震波異方性速度構造解析を開始した。解析は、P波走時の逆解析による。弱い異方性媒質を考え、「六方対称軸が鉛直方向にある」という仮定の下、P波等方性速度と異方性の強さの三次元分布を見積もる。本研究で得られる鉛直方向の三次元構造は、過去の研究では提出されていない新たな情報となるため、日本列島下の地震波速度構造を解釈していく上で新たな知見を与えるものと期待される。今回は、当解析法を東北地方(～深さ 160 km)に適用した例を紹介する。また、同じ地震データを用いて方位異方性構造も求めたので、これらを基に、東北地方下のダイナミクスの理解を図る。

今後、同様の調査を日本列島全域について実施し、最終的には既存の異方性観測を包括的に説明する地震波異方性モデルを提案することを目標とする。ただし、本研究で使用を予定している解析手法は、異方性の軸を鉛直または水平に方向に固定するため、構造解釈の際にこの仮定をどう評価するかが当面の課題である。

キーワード: 地震波異方性
Keywords: seismic anisotropy

410-km 不連続面近傍の粘性率モデル：実験鉱物学的アプローチ Viscosity structure model around 410-km discontinuity: mineralogical approach

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The 410-km seismic discontinuity has been attributed to the pressure-induced phase transformation from olivine to wadsleyite in an olivine component of mantle peridotite. The phase transformation may induce abrupt change in viscosity at 410 km depth, and the viscosity discontinuity may play an important role in the dynamics of the upper mantle and the mantle transition zone. Attempts have been made to determine viscosity structure of deep mantle by geophysical observations (e.g., isostasy data of post-glacial rebound and gravity anomaly observations), however, the obtained viscosity-depth profile has been controversial. On the other hand, the viscosity-depth profile of deep mantle can be determined based on experimental data of a deformation experiment at high pressure and temperature. Recently, we made technical developments in the deformation experiment adopting new technique for high-pressure generation, and achieved viscosity measurement at pressure-temperature conditions of the upper part of the mantle transition zone. In order to determine the viscosity at the upper part of the mantle transition zone, we conducted in situ stress-strain measurement of wadsleyite at 13-14 GPa, 1400-1700 K and strain rates of $3.1-15 \times 10^{-5} \text{ s}^{-1}$ using a deformation-DIA apparatus at BL04B1 beamline of SPring-8. We found that water enhanced plastic deformation of wadsleyite and water dependence of wadsleyite creep strength was larger than that of olivine. Based on the experimental result, viscosity decreases at the 410 km boundary at moderate water content while little viscosity contrast exists at dry condition. Moreover, these experimental results suggest that heterogeneity in water at the mantle transition zone leads large viscosity heterogeneity at the upper part of the mantle transition zone.

キーワード: 410-km 不連続面, ウォズリアイト, 粘性率, クリーブ強度, 水, 変形実験

Keywords: 410-km discontinuity, wadsleyite, viscosity, creep strength, water, deformation experiment

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Ca₂AlSiO_{5.5} 欠陥ペロブスカイト低圧相の結晶構造
Crystal structure of low-pressure Ca₂AlSiO_{5.5} defect perovskite

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See English abstract

キーワード: Ca₂AlSiO_{5.5}, 高圧相, 結晶構造, 粉末 X 線回折, 欠陥ペロブスカイト, 核磁気共鳴

Keywords: Ca₂AlSiO_{5.5}, high pressure phase, crystal structure, powder X-ray diffraction, defect perovskite, nuclear magnetic resonance

P-wave tomography of Northeastern China observed with NECESSArray P-wave tomography of Northeastern China observed with NECESSArray

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A passive broadband seismic experiment, NorthEast China Extended SeiSmic Array (NECESSArray) has been deployed since 2009 for two years. Northeastern China is a very interesting region because slabs subducting from the south Kuril and Japan trenches are stagnant in the mantle transition zone and extends to northeastern China, and above the stagnant slabs, Sino-Korea craton and unusual volcanism in the continent exist. The relationships between the deep slabs and shallow structures are important clues to understand the tectonic features.

P-wave travel-time picks of the NECESSArray stations were made interactively, while the teleseismic arrival time residuals were extracted using the adaptive stacking method. We picked more than 13,000 event-station pairs. Relative travel-times of P-wave between different stations were measured as a function of frequency using deep events of which P-waves separate in time from depth phases and very shallow events of which P-waves and depth phases are completely coincide. We found strong dispersive effect that is not predicted by our previous three dimensional (3D) P-wave model. We will combine the picked travel times and the frequency depended relative travel times to image a 3D P-wave heterogeneities of the northeastern China. We will present our first model at the meeting. The result shows fin structures of the stagnant Pacific slab. It is It is particularly worth noting that the northern part of the stagnant Japan slab seems to be buckling.

キーワード: マントル, マントル遷移層
Keywords: Mantle, Mantle transition zone

CaSiO₃ ペロフスカイトの状態方程式 Thermal equation of state of CaSiO₃ perovskite

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CaSiO₃ perovskite (Ca-perovskite) is one of the major constituent minerals in the deep mantle. In the lower mantle conditions, peridotitic mantle and subducted mid-oceanic ridge basalt (MORB) contain ~5 wt% and ~23 wt% Ca-Perovskite, respectively (Hirose et al., 1999, Wood, 2000, Hirose et al., 2005). In addition to MORB, recently, subduction of continental crusts is discussed in relation to the continental growth history. Experimental studies demonstrated that subducted continental crust may also contain Ca-perovskite at the pressure-temperature conditions near the 660-km discontinuity (Wu et al., 2009). Therefore, the density and elastic behavior of Ca-perovskite may be a key to understand the distribution of the subducted materials in the deep Earth. In the present study, we constructed a thermal equation of state of Ca-perovskite based on high-temperature diamond anvil cell (DAC) experiments.

The pressure-volume-temperature (P-V-T) relation of Ca-Perovskite was studied in a DAC with in situ X-ray diffraction method. For high-P-T generation, an externally-heated DAC and laser-heated DAC were used. A membrane gas regulating system was attached to both types of the DAC. Diamond anvils with 150 micron

beveled were used. A starting material was pure CaSiO₃ glass mixed with platinum powder which served as a laser absorber and pressure standard. The sample mixture was sandwiched by NaCl pressure medium and was loaded into 50 micron sample chamber in a rhenium gasket. Angle-dispersive X-ray diffraction spectra were collected on a charge-coupled device (CCD) at the BL10XU beamline, SPring-8. Exposure times were 10 seconds. A monochromatized X-ray with a wavelength of about 0.41 Å was collimated to 20 micron in diameter. Pressure was calculated from the unit-cell volume of Pt, using the thermal equation of state of Pt (Fei et al., 2004).

We conducted three separate compression runs at BL10XU of SPring-8. The sample was compressed to a certain pressure at 300 K and then the temperature was increased by the laser heating to synthesize Ca-perovskite. After the temperature was reached to a desired temperature, we started compression by increasing the gas pressure in the membrane system. During compression, we kept constant temperature so as to make isothermal compression experiments. We collected the XRD pattern at every 3-4 GPa. The maximum pressure we reached was 127 GPa. In one run, we conducted simultaneous heating of laser and external heating systems. First we increased the temperature by the external heating system to 700 K. Then, the laser was turned on to further increase temperature. This technique allowed us to reduce the temperature gradient in the sample and to attain much more stable heating compared to the laser heating alone.

We fitted thus obtained data to a thermal equation of state. We will present new P-V-T data of Ca-perovskite and discuss its density and elastic behavior at the deep lower mantle conditions.

キーワード: CaSiO₃ ペロフスカイト, 状態方程式, X線回折, ダイヤモンドアンビルセル

Keywords: CaSiO₃ perovskite, thermal equation state, X-ray diffraction, diamond anvil cell

地球物理学と物質科学に基づくポスト・スピネル転移に対する制約：トンガスラブの例

Geophysical and mineralogical constraints on the post-spinel transformation: A case study for the Tonga slab

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We investigate the precise depth of the 660 km discontinuity for the Tonga slab, with the aim of determining the Clapeyron slope of the post-spinel transformation. We use data from short period seismic networks at western United States and Japan for about 100 deep ($h > 500$ km) and intermediate-depth ($h > 200$ km) earthquakes within a small (nearly 200 km by 200 km) area near 20S. We analyze later phases in a time window from 3 s to 20 s after direct P waves and search for S-to-P converted waves at the 660 km discontinuity, which should represent the post-spinel transformation. We find that immediately beneath the foci of the deepest earthquakes the discontinuity is depressed down to the depths of 685 ± 5 km on average. We also find that the discontinuity dips toward WNW by 10 ± 3 km within 70 km laterally. We constrain the thermal structure near the S to P conversion points based on a plausible assumption that the deepest earthquakes occur around the coldest core of the Tonga slab. The distribution of the hypocenters relocated in this study and previously published tomographic images of the same region indicate that the Tonga slab bends upward when it approaches the 660 km discontinuity and transiently stagnates around the discontinuity, before it ultimately impinges on the lower mantle. By using these observations as the constraints, we numerically model the thermal structure of the Tonga slab. We find that the S-to-P conversion points are located inside and near the bottom of the Tonga slab. We also estimate the temperature around the conversion points as 1200 ± 100 degrees C, which is 300 ± 100 K colder than the surrounding mantle. As the average depression of the discontinuity (down to 685 ± 5 km) corresponds to an pressure excess over the global average (660 km) by 1.0 ± 0.2 GPa, the assumption of equilibrium post-spinel transformation gives an estimate of the Clapeyron slope (C1) of $-3.3 (+1.3 -2.7)$ MPa/K. On the other hand the observation of the dip of the discontinuity and the computed temperature variation (by about 200 K) leads to another independent estimate of the Clapeyron slope (C2) of $-2.0 (+1.0)$ MPa/K. The discrepancy between C1 and C2 is marginally significant and can be diminished by considering that the slab materials at the conversion points are currently descending across the phase boundary fast enough and thus the depth of the post-spinel transformation is controlled by nucleation kinetics as well as by the temperature. The nucleation overpressure may be on the order of 0.5 GPa for the post-spinel transformation.

キーワード: ポスト・スピネル転移, 660km 不連続面, トンガ・スラブ, クラペイロン勾配, カイネティクス, 地震観測点アレイ

Keywords: post-spinel transformation, 660km discontinuity, Tonga slab, Clapeyron slope, kinetics, seismic array

第一原理計算による格子熱伝導率計算 - MgSiO₃ Pv&PPv への適用 -

Efficient and accurate ab initio calculations on the lattice thermal conductivity: Applications to MgSiO₃ Pv and PPv

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Although thermal transport property of materials under pressure and temperature is of importance for understanding thermal structure and its thermal history of the Earth, both experimental and theoretical determinations of the thermal conductivity still remain technically challenging particularly at the deep mantle and core conditions. However, ab initio computational method has been recently extended to transport phenomena due to some technical advances. The intrinsic bulk thermal conduction of insulator is caused by lattice anharmonicity owing to phonon-phonon interactions. The key parameter to predict the lattice thermal conductivity, k , is thus the anharmonic coupling strength. Earlier theoretical works calculated k of MgO with various approaches such as molecular dynamics simulation and finite difference method. In those approaches, the sufficient simulation cell size should be taken account for accurate description of the long wavelength phonon scattering, and therefore the computational cost to calculate k tends to be expensive particularly for more complex minerals such as MgSiO₃. Actually, to the best of our knowledge, the k of MgSiO₃ perovskite (Mg-Pv) or post-perovskite (Mg-PPv) at high-pressure and high-temperature still not established by ab initio calculation. In contrast to those approaches, we evaluate the anharmonic coupling strength based on the density-functional perturbation theory. In this approach, the higher-order force tensors are calculated through a number of phonon decay channels obtained within the perturbative scheme taking care only of the primitive cell. We have been developing a technique for the calculation of the phonon damping function necessary to obtain the phonon relaxation time. Then k is calculated with additional harmonic-level of calculations.

In this presentation, we show that the k of Mg-Pv and Mg-PPv as a function of pressure and temperature. The k of Mg-Pv calculated at ambient condition is found to be in excellent agreement with the experiment (M. Osako and E. Ito, Geophys. Res. Lett. 18, 239, 1991). The current results are applied to evaluate the effective k and the total heat flow at the core-mantle boundary (CMB) with a composite averaging between MgO and MgSiO₃. This provides better constraints for the thermal evolution of the Earth.

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キーワード: 第一原理計算, 格子熱伝導率, フォノン-フォノン相互作用, マントル深部鉱物

Keywords: ab initio calculations, lattice thermal conductivity, phonon-phonon interaction, deep mantle minerals

Hemispheric variation of the depth dependent attenuation structures of the top half of the inner core

Hemispheric variation of the depth dependent attenuation structures of the top half of the inner core

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Previous studies suggested the existence of the hemispheric heterogeneities in the top 100 km of the inner core (ex. Wen and Niu, 2002). However, the depth dependent profiles of the attenuation have not been well constrained because of the poor resolution due to difficulties in analyzing contaminated core phase data. Iritani et al. [2010, GRL, 2011, SSJ] employed a waveform inversion method based on simulated annealing (SA) that enables to analyze complicated waveforms with phase overlapping and applied it to Hi-net and NECESSArray data. The obtained models show similar features that we have definite high attenuation zone around 200 km depth from ICB.

In this study, we collect high-quality core phase data from large number of broadband arrays to obtain the depth dependent profiles of the top half of the inner core in various regions. The resultant data set consists of about 8,500 waveform traces from PASSCAL arrays deployed in a number of places in the world, permanent European stations and USArray. Sampling regions are beneath northeastern Pacific, American and African continent for the western hemisphere of the inner core, and eastern and central Asia for the eastern hemisphere. We apply the same method as Iritani et al. [2010] to these data. In general, the obtained attenuation models for the western hemisphere show the gradually increase from ICB and have a peak around 200 km depth and those for the eastern hemisphere have a high attenuation zone at the top 150 km layer. However, almost all models show common features below 250 km depth and attenuation gradually decreases with depth. We also obtain the averaged structure models for each hemisphere, and similar features are observed. It appears that hemispheric heterogeneities of the inner core are confined in the top 150 - 250 km of the inner core.

キーワード: inner core, attenuation, hemispheric structure

Keywords: inner core, attenuation, hemispheric structure

地球核条件下にレーザー衝撃圧縮された鉄合金の音速 Sound velocities of laser-shocked iron alloys under Earth's core condition

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When we consider the structure of the Earth's interior, the sound velocity is one of the important physical properties of the interior materials because it can be directly compared with the seismological data which can yield the physical properties of the Earth's interior. Although it needs to measure the sound velocity of the interior material under high pressure and temperature, the sound velocity measurement of the materials on the condition over 200 GPa and 4000 K, such as the Earth's core condition, is technically difficult in static compression technique (e.g. diamond anvil cell: DAC) (1-4). Therefore, in such higher pressure and temperature, dynamic compression technique, such as gas gun, is used. Although some works about the sound velocity of pure iron have been done by gas gun (5-7), it is not enough to discuss about the Earth's core which consists of iron alloy. Although Badro et al. (8) and Fiquet et al. (9) measured compressional sound velocity for some iron alloys (FeO, FeSi, FeS, FeS₂, and Fe₃C) at room temperature by inelastic x-ray scattering (IXS) at the DAC, the sound velocity data of liquid iron alloy is very few (10, 11).

We performed laser-shock experiments of liquid iron alloys at HIPER system of GXII laser in Institute of Laser Engineering, Osaka University (ILE) (12). We measured the sound velocities of iron alloys (Fe-Si, Fe-Ni-Si) under the Earth's core condition. The sound velocities were measured by side-on radiography (7). We will report the results of the sound velocity measurement for the laser-shocked iron alloys.

Part of this work was performed under the Joint Research of Institute of Laser Engineering, Osaka University.

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キーワード: 音速, レーザー, 衝撃波, 鉄合金, 地球核, 実験

Keywords: Sound velocity, Laser, Shock wave, FeSi, Earth's core, Experiment