Toward proper characterization of seismic radial anisotropy of the lithosphere-asthenosphere system

Toward proper characterization of seismic radial anisotropy of the lithosphere-asthenosphere system

*川勝 均[1]
*Hitoshi Kawakatsu[1]

1.東京大学地震研究所
1.Earthquake Research Institute, the University of Tokyo

Kawakatsu et al. (2015) recently proposed a new fifth parameter, η_k that properly characterizes the incidence angle dependence (relative to the symmetry axis) of seismic bodywaves in a transverse isotropy (TI) system. When existing models of upper mantle radial anisotropy (TI with a vertical symmetry axis) are compared in terms of this new parameter, PREM shows a distinct property. Within the anisotropic layer of PREM (a depth range of 24.4-220km), $\eta_k < 1$ in the top half and $\eta_k > 1$ in the lower half. If $\eta_k > 1$, anisotropy cannot be attributed to the layering of homogeneous layers, and thus requires the presence of intrinsic anisotropy (Kawakatsu, 2016, GJI).

Partial derivatives of surface wave phase velocity and normal mode eigen-frequency for the new set of five parameters indicate that the sensitivity of η_k is about twice as large as that of the conventional η, indicating that η_k is more resolved than is usually considered. While sensitivities for (anisotropic) S-velocities are not so changed, those for (anisotropic) P-velocities are greatly reduced. In contrary to Dziewonski and Anderson (1981)'s suggestion, there is not much control on the anisotropic P-velocities; on the other hand the significance of η_k for the long-period seismology is clear.

Considering now that a variety of seismic body waves with different incidence angles (receiver functions, multiple S, SS-precursors, SKS, etc.), as well as surface waves and normal-modes, are available to constrain the property of the lithosphere-asthenosphere system, and that the presence of strong radial anisotropy in the suboceanic asthenosphere is well established, we should properly characterize seismic radial anisotropy of the lithosphere-asthenosphere system using the new fifth parameter.

Reference:
Kawakatsu, H., J.-P. Montagner, and T.-R. A. Song (2015), On DLA's η, in The Interdisciplinary Earth: A volume in honor of Don L. Anderson, edited by Foulger et al., PP. 33-38, GSA and AGU.
Kawakatsu, H. (2016), A new fifth parameter for transverse isotropy, Geophys. J. Int., 204, 682-685.

キーワード：地震波異方性、PREM、表面波、実体波
Keywords: seismic anisotropy, PREM, surface wave, body wave

広帯域アレイを用いた日本海下の2点間表面波位相速度計測

Interstation phase speed measurements of surface waves in the Sea of Japan using broadband seismic arrays

*成田 涼[1]、浜田 広太[1]、吉澤 和範[2]、川勝 均[3]
*Ryo Narita[1], Kouta Hamada[1], Kazunori Yoshizawa[2], Hitoshi Kawakatsu[3]

1.北海道大学大学院理学院、2.北海道大学大学院理学研究所、3.東京大学地震研究所
1.Graduate School of Science, Hokkaido University, 2.Faculty of Science, Hokkaido University, 3.Earthquake Research Institute, University of Tokyo

Seismic structure in the crust and upper mantle beneath the Sea of Japan reflects its complex tectonic history including back-arc spreading and the subsequent formation of the Japanese islands. The seafloor topography and the crustal thickness of this marginal sea are quite variable, characterized by several basins and rises. Although the upper mantle structure beneath the Sea of Japan has been investigated with surface wave tomography using permanent broadband seismic networks in Japan and in East Asia by Yoshizawa et al, (2010, PEPI), the horizontal resolution of this earlier model was limited due to the small numbers of ray paths across the marginal sea.
A temporary broadband seismic array, which has recently deployed across Northeast China (NECESSArray) from 2009 to 2011, can be of great help in enhancing the ray coverage across the Sea of Japan, by employing interstation dispersion measurements of surface waves. In combination with the Japanese permanent broadband network (F-net), a large number of interstation phase speeds information across the Sea of Japan can be extracted. In this study, we employ a fully non-linear waveform fitting technique to measure interstation phase speeds using a method developed by Hamada & Yoshizawa (2015, GJI). Through the waveform analysis of the combined data sets in the period range between 20 and 150 seconds, we collected about 5000 new measurements of phase speeds using seismic events with moment magnitude greater than 6.0 during the temporary deployment of NECESSArray (2009-2011). With the additional data set, we are now able to resolve the smaller scale heterogeneity of about 1.5 degrees or less in the Sea of Japan. The updated preliminary phase speed maps of Rayleigh waves show significant fast phase speed anomaly beneath the Japan Basin in the period shorter than 45 s, while, in the longer periods, slow anomalies are found in most areas beneath the Sea of Japan, suggesting relatively thinner lithosphere (about 60 km) compared with the typical oceanic plate like the Pacific. One of the striking features of the new model is that the phase speed maps at shorter period than 45 s shows conspicuous regional variations in the Sea of Japan; i.e., phase speeds beneath southwestern areas, including the Tsushima Basin, tend to be slower, while the northeastern half of the sea, including the Japan Basin, is characterized by faster phase speeds, which may reflect the lateral variations of the lithospheric thickness. Furthermore, a localized fast phase speed anomaly is found beneath the Yamato Rise in the period shorter than 60 s, which may suggest relatively thicker lithosphere of about 80-90 km beneath it.

キーワード：日本海、表面波、トモグラフィー、位相速度
Keywords: Sea of Japan, Surface waves, Tomography, Phase speed

Po/So波から推定した北西太平洋海洋リソスフェアの異方性
Anisotropy in the Northwest Pacific oceanic lithosphere inferred from Po/So waves

*志藤 あずさ[1]、末次 大輔[2]、古村 孝志[3]、塩原 肇[3]、一瀬 建日[3]、杉岡 裕子[4]、伊藤 亜妃[2]、竹尾 明子[3]、歌田 久司[3]
*Azusa Shito[1], Daisuke Suetsugu[2], Takashi Furumura[3], Hajime Shiobara[3], Takehi Isse[3], Hiroko Sugioka[4], Aki Ito[2], Akiko Takeo[3], Hisashi Utada[3]

1.九州大学 大学院理学研究院附属 地震火山観測研究センター、2.海洋研究開発機構　地球深部ダイナミクス研究分野、3.東京大学　地震研究所、4.神戸大学　理学研究科　惑星学専攻
1.Institute of Seismology and Volcanology, Kyushu University, 2.Department of Deep Earth Structure and Dynamics Research, Japan Agency for Marine-Earth Science and Technology, 3.Earthquake Research Institute, University of Tokyo, 4.Department of Planetology, Graduate School of Science, Kobe University

Po/So waves, which have a high frequency, large amplitude, and long duration, propagate for large distances across oceanic lithosphere. These waves are generated by multiple forward scattering of P- and S-waves due to small-scale heterogeneities in oceanic lithosphere and P-waves trapped in seawater. To study the origin of such small-scale heterogeneities, we analyzed the azimuthal anisotropy of Po/So waves propagating in the Northwest Pacific.

Seismological observations using Broad Band Ocean Bottom Seismometers (BBOBSs) were conducted in the Northwest Pacific from 2010 to 2014 as a part of the Normal Oceanic Mantle Project. During the experiments, high-quality Po/So waves were recorded from earthquakes in the subducting Pacific plate. We determined travel times of the Po/So waves using an auto-picking algorithm based on an AR model, and estimated the average velocities of the Po/So waves between sources and stations. The average velocities of the Po/So waves traveling in the Northwest Pacific show clear variations as a function of azimuth, as follows:
$V_{Po} = 8.25 + 0.20 \cos 2(x - 153)$,
$V_{So} = 4.71 + 0.04 \cos 2(x - 159)$.
The magnitudes of the anisotropy for Po and So waves velocities are 2.4% and 0.8%, respectively, which are smaller than the results of previous studies for Pn and Sn waves [Shimamura, 1984; Shinohara et al., 2008]. The fast direction is parallel to the past spreading direction of oceanic crust as estimated from magnetic anomalies [Nakanishi et al., 1992], which is roughly consistent with the previous studies [Shimamura, 1984; Shinohara et al., 2008].

We investigate the mechanism of the azimuthal anisotropy of Po/So wave propagation, which should be relating to the generation and evolution of the oceanic lithosphere using a Finite Difference Method (FDM) simulation of seismic wave propagation. We compare observed and calculated Po/So waves, and discuss the mechanism of their azimuthal anisotropy.

キーワード：Po/So波、異方性、海洋リソスフェア
Keywords: Po/So waves, anisotropy, oceanic lithosphere

北西太平洋リソスフェア・アセノスフェアの電気伝導度構造に異方性はあるか？
Possibility of anisotropic structure in electrical conductivity for the upper mantle beneath northwestern Pacific Ocean

*馬場 聖至[1]、歌田 久司[1]
*Kiyoshi Baba[1], Hisashi Utada[1]

1.東京大学地震研究所
1.Earthquake Research Institute, The University of Tokyo

We have estimated isotropic one-dimensional (1-D) structure in electrical conductivity beneath the northwestern Pacific through Normal Oceanic Mantle Project. However, the model did not explain observed magnetotelluric (MT) responses perfectly. The misfits should be attributed to the lateral heterogeneity and/or anisotropic structure. In this study, we examined if some possible anisotropic structures can explain the observed MT responses better or not. We consider anisotropic structures that the conductivity in the asthenospheric mantle is higher in the direction parallel to the current plate motion (~N63°W) and that the conductivity in the lithospheric mantle is higher in the direction parallel to the past plate spreading direction (~N22°W). We also consider the effect on surface heterogeneity due to ocean-land distribution and bathymetric change. We simulated MT responses in the survey area A (northwest of the Shatsky Rise) to the 3-D surface heterogeneity over 1-D anisotropic structures and compared with the MT responses observed and simulated to the isotropic model. The result showed that any models considered in this study did not improve the misfit to the data, suggesting that rather laterally heterogeneous structure is more likely.

キーワード：海底MT、電気伝導度、異方性、リソスフェア、アセノスフェア、北西太平洋
Keywords: marine magnetotellurics, electrical conductivity, anisotropy, lithosphere, asthenosphere, Northwestern Pacific Ocean

Constraints on mantle anisotropy from the NoMELT magnetotelluric data set

Constraints on mantle anisotropy from the NoMELT magnetotelluric data set

*松野 哲男[1]、ロブ エバンス[2]、馬場 聖至[1]
*Tetsuo Matsuno[1], Rob L. Evans[2], Kiyoshi Baba[1]

1.東京大学地震研究所、2.ウッズホール海洋研究所
1.Earthquake Research Institute, The University of Tokyo, 2.Woods Hole Oceanographic Institution

The formation of lithosphere at a mid-ocean ridge and the subsequent movement of that lithosphere across the underlying convecting asthenosphere result in deformation through shearing. This deformation can result in anisotropy in measureable physical properties such as the lattice preferred orientation of olivine, with the a-axis aligned in the direction of mantle flow. Patterns of anisotropy and the depths over which anisotropy occurs can, in turn, constrain models of lithospheric formation and evolution. Seismic results from the NoMELT data at 70 Ma Pacific seafloor reveal strong anisotropy through the lithosphere, with fabric aligned parallel to the fossil spreading direction. There is a decrease in anisotropy through the lithosphere-asthenosphere boundary and almost no anisotropy in the asthenosphere (Lin et al., submitted). Despite the strong patterns of anisotropy seen in the seismic data set from the NoMELT experiment, a previous analysis of coincident magnetotelluric (MT) data showed no evidence for anisotropy in the electrical conductivity structure of either lithosphere or asthenosphere (Sarafian et al., 2015). This apparent discrepancy raises two questions: 1) Could the MT data detect the seismic anisotropy layer in the lithosphere if it existed? 2) Is such a layer compatible with observations from the NoMELT region and, if so, what are the constraints on the properties of such a layer? To answer these questions, we revisit the MT data and use 1-D anisotropic models to demonstrate the limits of acceptable anisotropy within the data. We construct 1-D anisotropic models by varying the thickness of the anisotropic layer and the degree of anisotropy in the lithosphere, based on the results of Sarafian et al. (2015), and carry out a series of forward modeling to generate a suite of MT responses. We compare the values of the calculated splits in the off-diagonal elements of the MT responses with those seen in the NoMELT data, which allows us to place some constraints on the permissible anisotropic models. We discuss several topics including consistency with the seismic anisotropy, consistency with the electrical anisotropy model by shearing (Pommier et al., 2015), and whether our result is helpful to discriminate between water and melt models of upper asthenosphere.

What controls the rate of seafloor subsidence?

Tomoko Korenaga[1], *Jun Korenaga[1]

1.Department of Geology and Geophysics, Yale University

The seafloor subsides as it moves away from mid-ocean ridges, and the rate of subsidence can largely be explained by thermal isostasy. There exists, however, an important difference between theoretical predictions and the observed rate for normal seafloor, even if we restrict ourselves to relatively young seafloor with ages less than 70 Ma. Two hypotheses have been put forward to explain this discrepancy, one with the incomplete thermal contraction due to the strongly temperature-dependent viscosity of oceanic lithosphere, and the other with dynamic topography originating in radioactive heating in the convecting mantle. These two mechanisms are not mutually exclusive. As the degree of incomplete thermal contraction can be bounded by theoretical consideration, we may be able to use the observed discrepancy to infer the amount of radioactive heating in the convecting mantle. We will present a unified theoretical model that can treat these two effects simultaneously and quantify how the rate of seafloor subsidence is controlled by different processes.

強磁場コロイダルプロセスを用いた一軸および三軸配向オリビン多結晶体の創製

Fabrication of uni- and tri-axially oriented olivine aggregates using colloidal processing under high magnetic field

*小泉 早苗[1]、鈴木 達[2]、目 義雄[2]、平賀 岳彦[1]
*Sanae Koizumi[1], Thoru S Suzuki[2], Yoshio Sakka[2], Takehiko Hiraga[1]

1.東京大学地震研究所、2.物質・材料研究機構
1.Earthquake Research Institute,The University of Tokyo, 2.National Institute for Material Science

Olivine is the most abundant mineral in the Earth's upper mantle and it is considered to orient crystallographically in response to the mantle flow. Physical properties of olivine such as elasticity, plasticity, thermal conductivity, thermal expansion and electron conductivity are known to be very anisotropic so that geophysical observations that show directional dependence in the mantle are often attributed to the result of crystallographic preferred orientation (CPO) of this material. To understand the CPO effects on bulk rock properties, it is ideal d to prepare a material that reproduces the rock texture and measure its properties directly.
Magnetic field (up to 12 T) was applied to fine-grained (~120 nm) equigranular Fe-free and Fe-bearing olivine particles, which were dispersed in ethanol (solvent) with expectation of alignment of certain crystallographic axis of the particles with respect to the magnetic direction due to the olivine magnetic anisotropy. To align the magnetic easy and hard axes of olivine, we used a vertical static magnetic field and horizontal magnetic field with rotating suspensions of the olivine particles, respectively. For tri-axial alignment, we used a horizontal magnetic field with changing rotation rate of the suspensions. The dispersed and aligned particles in a strong magnetic field were gradually deposited on a solid-liquid separation filter during ethanol drainage. The dried particles were then densified isostatically and sintered under vacuum condition out of magnet. With this technique, we could obtain c-, b-axes uniaxially and triaxially aligned Fe-bearing (Fe : Mg = 1 : 9) olivine aggregates with achievements of high density (≥ 99%) and fine grain size.

キーワード：オリビン、格子選択配向
Keywords: olivine, crystallographic preferred orientation

オリビン多結晶体の高温クリープへの添加物効果
Doping effect on high-temperature creep of olivine aggregates

*谷部 功将[1]、平賀 岳彦[1]
*Kosuke Yabe[1], Takehiko Hiraga[1]

1.東京大学地震研究所
1.Earthquake Research Institute, The University of Tokyo

マントル対流やアセノスフェアの成因を理解する上で、上部マントルの流動特性を決定することは非常に重要である。これまで、天然で産出したオリビンから作製されたオリビン多結晶体を用いた高温変形実験により、オリビン多結晶体の流動特性に対する温度、粒径、応力依存性や水やメルトによる効果が調べられ、上部マントルの理解が進んできた（Karato et al. 1986, Hirth and Kohlstedt 1995, Mei and Kohlstedt 2000)。しかしながら、Faul and Jackson（2007）によって、試薬からゾル・ゲル法で人工的に合成したオリビン多結晶体の粘性率は、拡散クリープ領域でこれまでの天然由来のオリビンよりも約 2桁固大きいことが報告された。後にHansen et al.（2011）によって、Hith and Kohlstedt（1995）の試料の粒径が過大評価されていたことが示されたが、それを考慮しても人工合成オリビンは天然由来オリビンよりも粘性率にして1桁程度大きいことがわかっている。この違いの要因は未だに解明されておらず、オリビン多結晶体の流動特性は確立されていないのが現状である。

先行研究の固さの違いはおそらく試料のわずかな化学組成の違いによるものと考えられる。天然由来試料には微量な不純物が存在するが、人工合成試料には不純物は存在しない。材料科学の分野では、粒界に偏析する微量（<0.1 wt%）の不純物が酸化物多結晶体の流動特性を大きく変化させることが知られており（Yoshida et al. 1997)、また天然のオリビンの粒界にもCaO, Al_2O_3及びTiO_2の偏析が確認されている（Hiraga et al. 2003)。そこで、本研究では微量な添加物を含む試料と含まない試料を合成し、それらについて変形実験することで添加物が流動特性に与える影響を調べた。

試料作製には、高純度かつ細粒（<100 nm）の試薬を用いて細粒な鉱物粉末を合成し、それを真空で焼結するという手法を用いた(Koizumi et al 2010)。添加物を含まない試料と、微量（<1%）のAl_2O_3、CaO、TiO_2をそれぞれ含む試料を作製し、それらについて変形実験を行った。その結果、不純物を含まない試料は拡散クリープ領域で粒径指数3、活性化エネルギー462 kJ/mol が得られ、粒界拡散クリープで変形したことが示唆された。また不純物による大きな固さの変化は見られなかった。先行研究と比較すると、本研究の試料の固さはFaul and Jackson（2007）の人工合成オリビンと一致した。

キーワード：オリビン多結晶体、レオロジー、添加物効果
Keywords: olivine aggregates, rheology, doping effect

合成レールゾライトの粘性率と電気伝導度における化学成分効果とメルティング効果

Effects of chemical composition and melting on viscosity and electrical conductivity of synthesized lherzolite.

*末善 健太[1]、平賀 岳彦[1]
*Kenta Sueyoshi[1], Takehiko Hiraga[1]

1.東京大学地震研究所
1.Earthquake Research Institute, The University of Tokyo

マントルの粘性率と電気伝導度はマントル上昇中にソリダス温度で急激に変化すると考えられている。上昇マントル（例：中央海嶺）の物性へのメルトの影響を評価するため、またメルトを含まない試料との間の相違をはっきりさせるため、合成レールゾライト試料の粘性率と電気伝導度を大気圧下でソリダス以下から温度を上げつつ測定した。
50nm以下の$Mg(OH)_2$, SiO_2, $CaCO_3$ とスピネル粉末を原料とし、フォルステライト，エンスタタイト，ダイオプサイド，アノーサイトの4相で構成されるレールゾライトを合成した。試料はソリダス温度(～1230°C)以下で焼結され、添加するAl量（スピネルとして添加）を調節することによりソリダス温度以上で生じる初期メルト量を調節し、メルト分率φ = 0.005 ~ 0.06 の範囲で測定した。
ソリダス以上でのメルトの効果を評価する基準となるソリダス温度以下での測定結果にも、新しい発見がいくつかあった。Alによる粘性率の減少と、Caによる電気伝導度の増加である。フォルステライト + エンスタタイト + ダイオプサイドにスピネルを加えた試料は加えない試料と比べて1桁近く柔らかい。fo + en + diはfo + en (Tasaka et al., 2013)と一致し、フォルステライト + エンスタタイトにスピネルを加えた試料においても同様の粘性率低下が見られたことから、これはAlの効果であると推定できる。一方でダイオプサイドを含む全ての試料の電気伝導度は、フォルステライト + エンスタタイト で報告されているMg^{2+}の粒界拡散（活性化エネルギー～320kJ/mol)による値（ten Grotenhuis et al., 2004）よりも高い値と低い活性化エネルギー(～180kJ/mol)を示し、粒径依存性は見られなかった。このことから、添加されたCaによってフォルステライトの粒内拡散速度が上がったと解釈できる。
ソリダス以上では、生じたメルト量に応じた変化が粘性率と電気伝導度の両方で見られた。初出メルト量の最も少ない（φ= 0.005）試料ではサブソリダスから連続的な変化が見られたが、φ= 0.04の試料ではソリダス前後で粘性率・電気伝導度にそれぞれ階段状の減少・増加が見られた。粘性率へのメルトの効果は、経験的な表式$\eta \propto \exp(\alpha\varphi)$で表すと$\alpha$ = 69となり、この値は天然鉱物を原料とするレールゾライトの拡散クリープにおいて報告されている値α= 21 (Zimmerman and Kohlstedt, 2004)と比べてかなり大きい。

キーワード：粘性率、電気伝導度、メルト
Keywords: viscosity, electrical conductivity, melt

鉄なしかんらん石+輝石の2相系変形メカニズムの応力と温度に対する依存性

Dependency of creep mechanism on stress and temperature for two phase system of forsterite + enstatite

*仲小路 理史[1]、平賀 岳彦[1]
*Tadashi Nakakoji[1], Takehiko Hiraga[1]

1.東京大学地震研究所
1.Earthquake Research Institute, The Univeristy of Tokyo

Flow mechanism of the earth's upper mantle is estimated based on observation of microstructure of natural rocks, geophysical observation and experimental results obtained in laboratory. The experimental results are extrapolated to the mantle condition by using flow law. Therefore, obtaining precise flow-law parameters are key to understand the mechanism. However it is difficult to determine their values with small error range because of their strong dependency on stress, grain size and temperature. Tasaka et al. (2013) developed a viscosity model which includes a fraction of second phase for forsterite + enstatite system. They showed that a combination of flow laws for each mineral phase is applicable to polymineralic system with incorporating the fraction of mineral phases. However, their proposed activation energy of creep have a large error of ±50 kJ/mol, and obtained stress exponent, n, varies from 1.0 to 1.5 so that application of their results to nature is not precise yet.
We conducted two different types of creep experiments with synthetic sample of forsterite + 10vol% enstatite under high temperature ranging from 1150°C to 1370°C with application of various constant loads of 3 to 320 MPa. One was aimed for evaluating activation energy of creep and the other was for obtaining a precise stress exponent. We obtained stress-dependent activation energy and temperature-dependent stress exponent. At lower stress condition, apparent activation energy is ~ 600 kJ/mol. In contrast, at stress range of 60~120 MPa, the lower energy of ~ 370 kJ/mol was obtained. At 1370°C, the apparent stress exponent of ~ 1.2 was obtained whereas a larger value of ~ 1.5 was obtained at 1150°C. These results indicate that two types of deformation mechanisms were operated during our experiments.
In two-phase system, Burton (1973) proposed that the second phase particle on grain boundaries of the primary phase inhibits diffusion creep, because the second phase limits grain boundary to act as a perfect sink or source of vacancy. When density or mobility of defects at grain boundary is small, deformation will be rate-controlled by defect formation at interfaces. In this case, strain rate is proportional to ~ s^2/d (Ashby and Verrall 1973) where s is applied stress and d is grain size. Since such interface reaction-control creep and diffusion creep both are rate-limiting processes for bulk deformation, reciprocal bulk strain rate can be expressed by a sum of reciprocal strain rate of interface-controlled diffusion and normal diffusion creep. Based on our obtained flow-law parameters, interface-reaction controlled diffusion creep dominated at lower temperature and lower stress conditions, and Coble-type diffusion creep dominated at higher temperature and higher stress conditions.

キーワード：変形機構、苦土かんらん石、界面反応、2相系、律速過程、活性化エネルギー
Keywords: creep mechanism, forsterite, interface reaction, two-phase system, rate-controlling process, activation energy

