Mapping the age of the subducting Pacific slab beneath East Asia

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We map the age of the subducting Pacific slab beneath East Asia using a high-resolution model of P-wave tomography and paleo-age data of ancient seafloor. Our results show that the subducting oceanic lithosphere becomes younger from the Japan Trench (~130 Ma) to the slab's western tip (~90 Ma) beneath East Asia. Such a feature indicates that the flat (stagnant) slab now in the mantle transition zone (MTZ) beneath East Asia is the subducted Pacific slab rather than the Izanagi slab which should have already sunk into the lower mantle. The subduction age of the Pacific slab ranges from 0 Ma at the present-day trench to ~30 Ma at the western tip of the flat slab in the MTZ beneath central China. The stagnant duration of the flat Pacific slab in the MTZ is no more than ~10-20 million years, much shorter than the age of the big mantle wedge (BMW) beneath East Asia (>110 million years). It is the present Pacific slab that has contributed to the Cenozoic lithosphere destruction, extensive intraplate volcanism, and back-arc spreading in East Asia, whereas the destruction of the North China Craton during the Early Cretaceous (~140-110 Ma) was caused by the subduction of the Izanagi (or the Paleo-Pacific) plate.

Keywords: Slab age, Pacific plate, East Asia

Mantle convection: clues from lithosphere sinking at subduction zones and numerical modelling.

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Subduction zones show a worldwide asymmetry that can be observed in slab dip, kinematics of the subduction hinge, morphology, structural elevation, gravity anomalies, heat flow, metamorphic evolution, subsidence and uplift rates, depth of the decollement planes, mantle wedge thickness, magmatism, backarc development or not, etc. This asymmetry could be easily explained if related to the geographic polarity of the sinking slabs (Doglioni & Panza, 2015). In fact, geophysical and kinematics constraints show that all the plates move "westward". This preferential flow of plates would suggest a relative "eastward" mantle flow. If we look then to subduction dynamics within this set of conditions, this "eastward" mantle flow should have an important role in influencing subduction dynamics itself. Furthermore, along W-subduction zones slabs sink with a higher velocity with respect to the "easterly or northeasterly" directed ones. The faster "westerly" directed slabs determine that the volume of lithosphere recycled into this kind of subduction is larger than that along the converse ones. This should determine a more vigorous counterflow within the mantle below W-directed subductions with respect to the one below E-directed ones. Starting from these observations we attempted to estimate volumes of lithosphere that are currently subducting below the principal subduction zones: our results show that there are about 288 km^3/yr of lithosphere currently subducting below W-directed subduction zones, while only about 78 km^3/yr of lithosphere are currently subducting below E- to NE-directed subduction zones. Then we tried to demonstrate quantitatively the consequent difference in mantle circulation between the two subduction settings using numerical modelling tools (Gerya, 2010), using data coming from our volumetric calculation as input data for the models. Moreover, we tried to look at these volumes with respect to the latitude of subduction zones, being plates velocities strongly linked to the Earth's rotation. In fact, seismicity is latitude dependent and decreases with increasing latitude (Riguzzi *et al.*, 2010; Varga *et al.*, 2012). Our results show that most of the volume currently subducting below worldwide principal subduction zones is concentrated between 30° and -30° of latitude.

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Keywords: subduction, mantle convection

Quasi-3D seismological imaging of Caroline plate using Monte-Carlo waveform inversion of teleseismic SS phases

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We present a quasi-3D S-wave velocity structure of the upper mantle under Southwest Pacific. Since it is fully covered by the ocean, seismic station coverage in this region is poor, leading a poorer resolution with respect to other regions in previous global tomographic studies. We collect 126 seismic events recorded at 35 AU stations, resulting a dataset of > 4200 pairs of event and station. In order to obtain a high resolving power, we use SS phases that have their bouncing points in the vicinity of the region. We perform regional 1D Monte Carlo waveform inversion using a combination of waveform and traveltime residuals between observed and synthetic data as a cost function. We generate 10.000 1D models for each pair of event and station and each pair chooses its preferred models that minimize the misfit function as a combination of SS-S traveltime double differences and SS waveform residuals. The mantle transition zone beneath the Caroline plate shows 1-3 % higher Vs anomaly with respect to PREM but the anomaly is cutted vertically by a low velocity zone (~1-2 % lower to PREM) underneath the Eauripik Rise which is situated in the center of Caroline plate. This low velocity zone can be interpreted as a thin plume coming from the base of the mantle, which could be locked due to the complex tectonics in the shallower part.

Keywords: Caroline plate, Monte-Carlo inversion, waveform inversion

Effects of rheological parameters on continental drift and water cycling in 3D mantle convection

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The Earth is unique among the solar terrestrial planets, having the continents and the abundant liquid water on its surface. From some previous studies (e.g., Iwamori and Nakamura, 2015, Gondwana Res.; Yanagi et al., 2016, Abstr. of JpGU Meeting), it has been thought that the continental dispersal and coalescence are in a close relationship with water distribution in the mantle. However, there are some problems for reproducing continental dispersal and coalescence. One of the fundamental problems concerns the mechanism of continental dispersal and coalescence. For instance, we do not know when and how the continent would be broken up. In this study, we have varied the values of a yield stress of the lithosphere and an activation energy of the mantle rock, which are thought to be key parameters for mantle convection. The reason we selected these two parameters is that yield stress controls the vulnerability of lithosphere and the activation energy is related to viscosity variation in the mantle, both of which affect the pattern of the continental dispersal and coalescence. The model used in this study is a three-dimensional (3-D) mantle convection model incorporating presence of the continental materials. In this numerical simulation of 3-D spherical mantle convection, the supercontinent is introduced in the initial state of the simulation run in order to study how continental dispersal and coalescence occurs and affect the structure of the Earth's interior. This study will test a hypothesis that there is a close relationship between the mechanisms of continental drift and the lithospheric conditions that depend on the yield stress and the activation energy. In addition, the water solubility of the mantle rock is considered in this model for understanding the effect of continental drift on water transportation in the mantle. Our studies will also examine global structures for water distribution in the mantle as proposed by Iwamori and Nakamura (2015) and Yanagi et al. (2016).

Keywords: three-dimensional mantle convection, continental dispersal and coalescence, water cycling, yield stress, viscosity

Uppermost mantle Pn tomography with Moho depth correction from eastern Europe to western China

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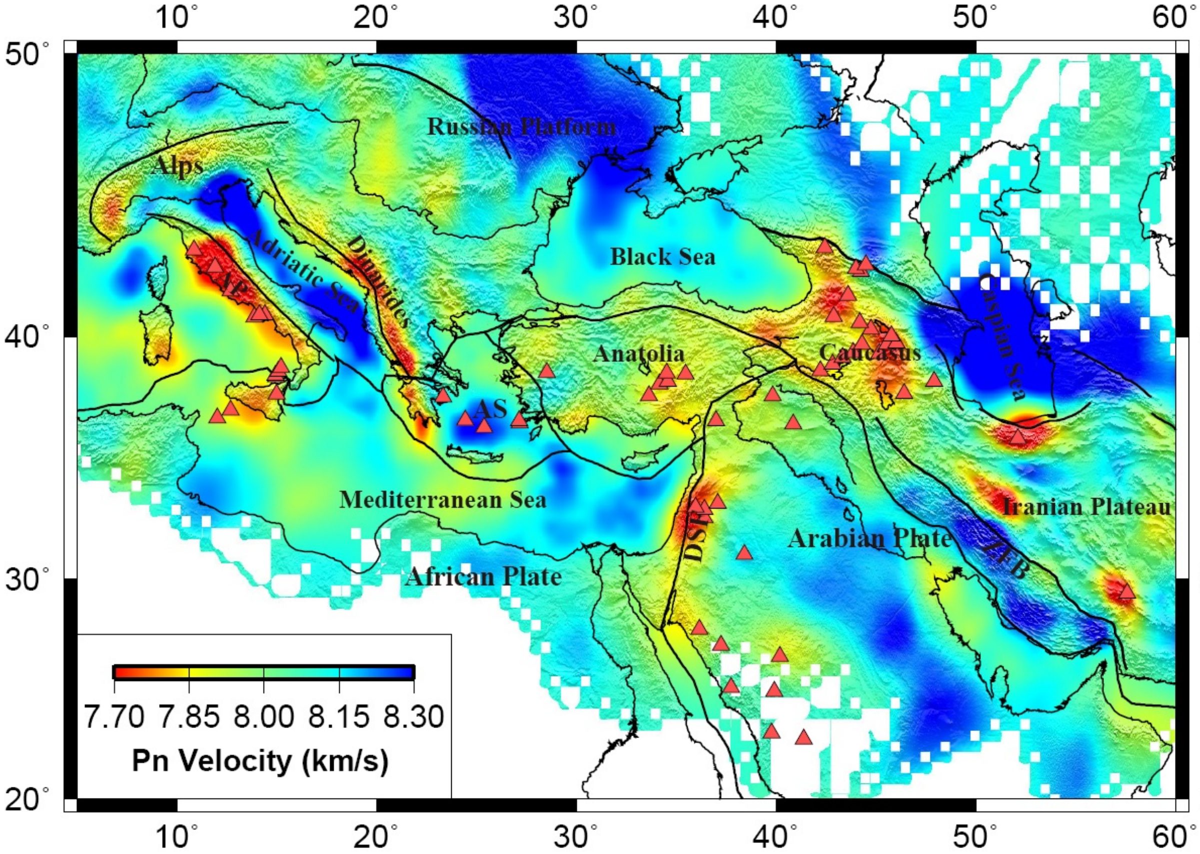
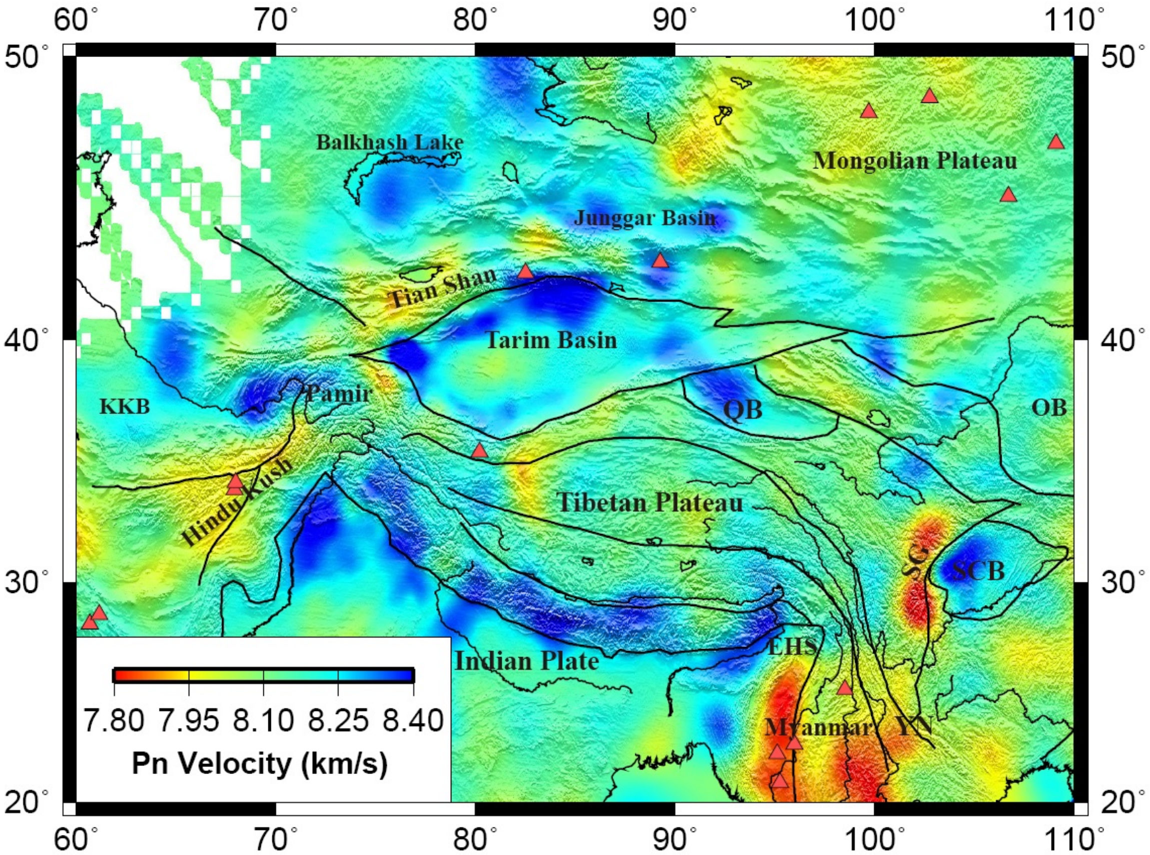
We proposed a modified Pn velocity and anisotropy tomography method by considering the Moho depth variations using the Crust 1.0 model and obtained high-resolution images of the uppermost mantle Pn velocity and anisotropy structure from eastern Europe to western China. The tomography results indicate that the average Pn velocities are approximately 8.0 and 8.1 km/s under the western and eastern parts of the study area, respectively, with maximum velocity perturbations of 3%–4%. We observed high Pn velocities under the Adriatic Sea, Black Sea, Caspian Sea, Arabian Plate, Indian Plate, and in the Tarim and Sichuan basins but low Pn velocities under the Apennine Peninsula, Dead Sea fault zone, Anatolia, Caucasus, Iranian Plateau, Hindu Kush, and in the Yunnan and Myanmar regions. Generally, regions with stable structures and low lithospheric temperatures exhibit high Pn velocities. Low Pn velocities provide evidence for the upwelling of hot material, which is associated with plate subduction and continental collision processes. The Pn anisotropy structure reflects the stress state of the uppermost mantle and indicates the location of the plate collision boundary at the depth of the Moho. Our Pn velocity and anisotropy imaging results indicate that the Adriatic microplate dives to the east and west, the hot material upwelling caused by subduction beneath the Tibetan Plateau is not as significant as that in the Caucasus and Myanmar regions, the lithosphere exhibits coupled rotational movement around the Eastern Himalayan Syntaxes, and the areas to the north and south of 26°N in the Yunnan region are affected by different geodynamic processes. Our newly captured images of the uppermost mantle velocity and anisotropy structure provide further information about continental collision processes and associated dynamic mechanisms.

Keywords: uppermost mantle, Pn, velocity, anisotropy

(a)


Russian Platform
Alps
Adriatic Sea
Dinarides
Black Sea
Anatolia
Caucasus
Caspian Sea
AS
Mediterranean Sea
African Plate
DSF
Arabian Plate
ZFB
Iranian Plateau
7.70 7.85 8.00 8.15 8.30
Pn Velocity (km/s)

(b)


Balkhash Lake
Mongolian Plateau
Junggar Basin
Tian Shan
Tarim Basin
KKB
Pamir
QB
OB
Hindu Kush
Tibetan Plateau
SCB
Indian Plate
EHS
Myanmar
YN
7.80 7.95 8.10 8.25 8.40
Pn Velocity (km/s)

Azimuthal anisotropy of Rayleigh-wave phase velocities in Cameroon, West Africa.

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The Cameroon region contains several tectonic features of interest to earth scientists. One of these is a chain of intra-plate volcanic line (CVL) without age progression. Since the CVL defies common geodynamic explanations, its origin has been subjected to considerable debate without reaching a consensus. Therefore, to advance understanding of the deformation and flow patterns resulting from the CVL and other tectonic processes in Cameroon, we imaged the azimuthal anisotropy of Rayleigh wave phase velocities from 4 to 60 seconds.

The seismic data used for this study was retrieved from both ambient seismic noise records and teleseismic earthquake data recorded by 32 broadband seismic stations deployed during the lifetime of the Cameroon Broadband Seismic Experiment (CBSE). First, we analyzed vertical component seismograms for 310 earthquakes with magnitude 5.0 occurring between the distances of 30^0 to 90^0. The traditional two-station method is adopted for measuring the inter-station phase velocities. Secondly, we processed continuous records of ambient seismic noise data from January to December 2006 following the method detailed in Ojo et al. (2017). For each inter-station path, we measured the phase velocity using the frequency-time analysis method. Following Yao et al. (2008), we averaged the dispersion from both datasets for similar station pairs by effectively weighting up earthquake measurements at long periods and ambient noise measurements at short periods. We eliminated erroneous phase velocity data that lay outside 2σ and those that did not meet the one wavelength criteria. Finally, we used the continuous Tarantola inversion program to obtain 2-D isotropic phase velocity and azimuthal anisotropy (amplitude and fast direction) maps from the path-averaged dispersion at each period.

The results revealed an obvious stratified azimuthal anisotropy beneath the Adamawa Plateau and Garuoa Rift (Northern part of CVL). The fast direction changes from NE–SW in the period band of 4-30s to NW-SE at longer periods which correspond to deeper depths. The distinct pattern of azimuthal anisotropy at short and long periods implies that the deformation varies with depth. Hence, we proposed a layered mechanism of deformation with almost independent processes at shorter and longer periods resulting from both frozen-in and present sources. This may also reflect decoupling of deformation or successive deformation episodes recorded at different depths. A consistent NE-SW fast direction is found at most period band beneath the Congo Craton. However, at around 38-44s a transition zone (probably indicative of the Moho) with N-S fast direction is revealed. This observation suggests a frozen-in anisotropy related to the NE-ward movement of the asthenosphere relative to the African plate. Along the southern part of the CVL, the fast direction trends N-S at short periods and changes to NNE-SSW at longer periods. We interpret this as first-order evidence for dominated northward and upward flow of plume materials associated with magma intrusion. The direction of fast axis beneath the Oubanguides Belt is largely NE-SW. This direction is parallel to the strike direction of known strike-slip faults in the study area, suggesting a lithospheric origin for the observed azimuthal anisotropy.

Our results provide new evidence for the existence of small-scale convection in the asthenosphere related to the formation of the CVL and help constrain the source region of previous shear wave splitting studies in the study area.

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Keywords: Azimuthal Anisotropy, Cameroon, Surface waves

Electrical conductivity as a constraint on lower mantle thermo-chemical structure

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Electrical conductivity of the Earth’ s mantle depends on both temperature and compositional parameters, and radial and lateral variations in conductivity are thus potentially a powerful means to investigate its thermo-chemical structure. Here, we use available electrical conductivity data for the major lower mantle minerals, bridgmanite and ferropericlase, to calculate 3D maps of lower mantle electrical conductivity for two possible models: a purely thermal model, and a thermo-chemical model. Both models derive from probabilistic seismic tomography, and the thermo-chemical model includes, in addition to temperature anomalies, variations in volume fraction of bridgmanite and iron content. The electrical conductivity maps predicted by these two models are clearly different. Compared to the purely thermal model, the thermo-chemical model leads to higher electrical conductivity, by about a factor 2.5, and stronger lateral anomalies. In the lowermost mantle (2000-2891 km) the thermo-chemical model results in a belt of high conductivity around the equator, whose maximum value reaches ~120% of the laterally-averaged value and is located in the low shear-wave velocity provinces imaged in tomographic models. Based on our electrical conductivity maps, we computed electromagnetic response function (C-responses) and found, again, strong differences between the C-responses for purely thermal and thermo-chemical models. At periods of 1 year and longer, C-responses based on thermal and thermo-chemical models are easily distinguishable. Furthermore, C-responses for thermo-chemical model vary geographically. Our results therefore show that long-period (1 year and more) variations of the magnetic field may provide key insights on the nature and structure of the deep mantle.

Keywords: Mantle structure, Electrical conductivity, Electromagnetic C-response

The effect of iron on the elastic properties of wadsleyite at the transition zone condition

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Wadsleyite is believed to be the major component in the upper part of the transition zone. To interpret seismic models in terms of mineralogy and chemical composition, the elastic bulk and shear moduli of wadsleyite and its derivatives as a function of pressure, temperature and Fe concentration are the critical parameters in extrapolating laboratory results to mantle conditions. However, former studies [ex. *Liu et al.*, 2009] on wadsleyite were performed at low pressure (<12 GPa) and temperature (<1100 K) and their extrapolations to the seismic models in transition zone condition are difficult because derivatives of the elastic moduli function to pressure and temperature are non-linear. On the other hand, Fe effect on the seismic velocities has never been systemically studied and poorly constrained.
In this study, we employed ultrasonic method combined with multi-anvil apparatus and in-situ X-ray observations developed by *Higo et al.* [2008] to investigate the elastic properties of wadsleyite at high temperature and pressure. The elastic bulk and shear moduli with diverse Fe concentration (Fe#=0 and 10) have been determined up to 1700K and 20 GPa. Based on our results, derivatives of seismic velocities observed among locations at the transition zone depth could be explained by Fe content variation in wadsleyite except the wedge mantle, which is consistent with the conclusion from electrical conductivities [*Yoshino et al.*, 2009].

Keywords: wadsleyite, elastic properties, the transition zone

The relationship between creep and grain growth rates in forsterite+periclase polycrystals

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Absence of seismic anisotropy in the earth’s lower mantle suggests deformation by diffusion creep mechanism (Karato et al., 1995). The mantle is considered to consist mainly of perovskite and ferropericlase. Thus, it is required to understand a mechanism of diffusion creep of a two-phase material. The diffusion creep is significantly sensitive to grain size such that the flow in the lower mantle is likely to be controlled by grain growth (Solomatov, 1996). Both creep and grain growth require diffusion of atoms with a long-distance, which is almost the size of grains. Thus, it is likely that rate-controlling processes for creep and grain growth are identical. To examine this prediction, we conducted creep and grain growth experiments on an analogue material of the lower mantle, which consists of elements similar to the lower mantle minerals, at high-temperature and atmospheric pressure.
We synthesized highly-dense forsterite + periclase (10vol%) polycrystals from a mixture of fine powders of $Mg(OH)_2$ and SiO_2 (Koizumi et al., 2010). Grain sizes of forsterite and periclase are 0.3 and 0.2 μm, respectively. We performed uni-axial compressional creep experiments on these materials at atmospheric pressure. Prior to the deformation, the sample was annealed at 1420℃ for 12h to avoid grain growth during the experiment. We changed loads ranging from 50 to 200 MPa under constant temperatures of 1180℃~1400℃ during the experiments. At each stress level, we measured a strain rate where we could assume steady-state creep. We also performed grain growth experiments at different temperatures ranging from 1280℃ to 1400℃ for 500h using temperature gradient formed outside the central heat zone in the furnace. We observed microstructures of the aggregates after the experiments using scanning electron microscope (SEM).
Based on creep data, we obtained a relationship of $d\varepsilon/dt \propto \sigma^n$ (n = 1.3~1.6). We observed monotonic increment of grain sizes of both forsterite and periclase grains with increasing temperature. We calculated grain boundary diffusivities from rates of creep and grain growth using theoretical models for grain growth and for diffusion creep (Coble creep), finding both diffusivities are essentially identical. The diffusivities are compared with previously measured grain boundary diffusivity of Si^{4+} (Fei et al., 2016) and MgO (Gardes & Heinrich, 2011) finding our values are comparable to the diffusivity of Si^{4+}. We will discuss the flow mechanism of the lower mantle based on these results.

Keywords: Rheology of the lower mantle, Diffusion creep of a two-phase material, Grain boundary diffusivity

Inversion of waveform data for radial profiles of shear velocity and attenuation of the lowermost mantle beneath the western Pacific

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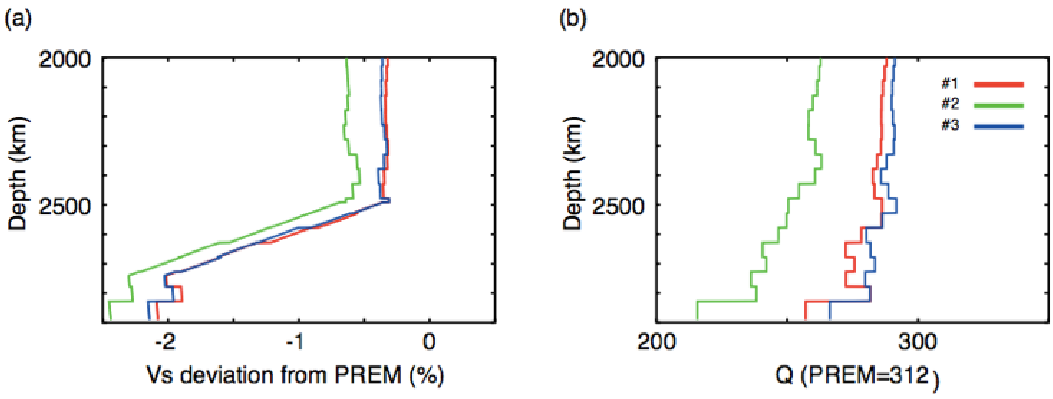
The existence of large low shear velocity provinces (LLSVPs) in the lowermost mantle is widely known by seismological global-scale studies. To understand the nature of these features, we investigate the elastic and anelastic structure of the lowermost mantle at the western edge of the Pacific LLSVP by inverting a collection of S and ScS waveforms. The transverse component data were obtained from F-net for 31 deep earthquakes beneath Tonga and Fiji, filtered between 12.5 and 200 s. We observe a regional variation of S and ScS arrival times and amplitude ratios, according to which we divide our region of interest into three subregions. For each of these subregions, we then perform 1D (depth-dependent) waveform inversions simultaneously for radial profiles of shear wave velocity (VS) and seismic quality factor (Q). In figure, models for all three subregions (#1-3) show low VS (a) and low Q (b) structures from 2000 km depth down to the core–mantle boundary. We further find that VS and Q in the central subregion, sampling the Caroline plume, are substantially lower than in the surrounding regions, whatever the depth. In the central subregion, VS-anomalies with respect to PREM (dVS) and Q are about −2.5 per cent and 216 at a depth of 2850 km, and −0.6 per cent and 263 at a depth of 2000 km. By contrast, in the two other regions, dVS and Q are −2.2 per cent and 261 at a depth of 2850 km, and −0.3 per cent and 291 at a depth of 2000 km. At depths greater than ˜2500 km, these differences may indicate lateral variations in temperature of ˜ 100 K within the Pacific LLSVP. At shallower depths, they may be due to temperature difference between the Caroline plume and its surroundings, and possibly to a small fraction of iron-rich material entrained by the plume.

Keywords: lowermost mantle, waveform inversion, anelastic structure



ab initio calculations reveal why thermal and compositional variations are required to explain observed mantle shear and compressional velocity anomalies

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The sensitivity of seismic velocity and density to composition and temperature determines the ability to detect changes in these properties in the lower mantle. We use recent ab initio calculations to predict the sensitivity of shear, bulk, and compressional velocity and density to changes in composition and temperature under lower mantle conditions. We calculate the predicted seismic signals for a suite of compositions and temperatures. These predictions are then compared to seismic tomography observations. If only shear velocities are used, the magnitude of observed seismic anomalies can be matched by varying temperature alone for any single composition. However, the compressional velocity sensitivity to temperature and composition is complex, in part due to the effects of the iron high spin to low spin transition in ferropericlase. We find it is essentially impossible to account for the observed magnitude of both shear and compressional velocities in a homogeneous mantle. Lateral and/or vertical gradients in composition are required to explain the fundamental properties of almost all joint tomography models.

Keywords: seismic tomography, mantle state and composition

Effect of pressure on temperature measurements using WRe thermocouple and its impact on geophysics

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Our understanding of the Earth's interior highly depends on physical and chemical properties of the Earth materials which were determined based on high-pressure and high-temperature experiments.
Temperature in these experiments is mostly determined using a thermocouple without any pressure correction. This may lead to erroneous results in estimated temperature and thus physical and chemical properties of the Earth materials due to significant pressure effects of the thermocouple electromotive force (EMF). However, knowledge of the absolute pressure effect on the EMF has been limited to relatively low pressures (<3.5 GPa) for more than 40 years (Getting and Kennedy, 1970).
Recently, we have developed a new method to determine the absolute pressure effect on thermocouple EMF at higher pressures based on a single wire method using Kawai-type multi-anvil apparatus (Nishihara et al., 2016). In this method, testing wires are subjected to higher and lower pressures by containing them in semi-sintered MgO and dense Al_2O_3 insulating tubes, respectively. The temperature along the single wires is calibrated by separate experiments employing multiple thermocouples. Pressure conditions along the wires are evaluated based on in situ X-ray diffraction using synchrotron X-ray radiation and their thermal equations of state. The pressure effect of the Seebeck coefficients is determined by the analyses of single wire EMFs and pressure-temperature profiles along the wires.
Based on this method, we have measured pressure effect on the EMF of W3Re-W25Re (type D) thermocouple up to 16 GPa and 900˚C. The difference of the nominal temperature from the real temperature was calculated to be −27˚C at 16 GPa and 900˚C. This absolute temperature correction may be underestimated due to influence of uniaxial stress during measurements. An extrapolation of the raw results suggest the temperature difference of −70˚C at 23 GPa and 1500˚C. *P*-*T* condition of the post-spinel phase boundary in Mg_2SiO_4 determined using type D thermocouple (Irifune et al., 1998; Katsura ae al., 2003) shifts to higher pressure by 0.5–0.7 GPa when temperature values are corrected. This corresponds to 12–16 km change of depth of the 660 km discontinuity. The temperature correction also has significant influence on the activation volumes for thermally activated processes such as element diffusion and rheology. The real values of activation volume determined at 0–10 GPa and 1500˚C is calculated to be ~1.3 cm^3/mol higher than nominal values when they are determined by experiments using type D thermocouple and the activation energy is 500 kJ/mol. This means that element diffusion and rheology are getting more sluggish with increase of depth in the Earth's mantle than previously estimated.

Keywords: temperature measurement, high-pressure and high-temperature, thermocouple, 660 km discontinuity

Dynamics of the fault motion and the origin of the contrasting tectonic style on Earth and Venus

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Earth is a unique terrestrial planet on which plate tectonics operates. On a similar terrestrial planet like Venus (~95 % size of Earth), there is no evidence for plate tectonics at least in the recent ~500 Myrs. Various models have been proposed to explain this enigmatic observation including the difference in the water content and/or in the surface temperature. However, none of the previous models provide satisfactory explanation because they invoke processes that have not been quantitatively explored in any detail. For instance, models invoking different water content are difficult to explain weakening of the deep portions of the Earth's oceanic lithosphere. Similarly, proposed mechanism of grain-size reduction cannot explain weak shallow lithosphere without requiring unreasonably small grain-size. Here we propose an alternative model to explain the Earth-Venus contrast based on the well-established experimental observations on the dynamics of fault motion. Unstable, accelerated fault motion, which occurs only below ~400°C in the crust and ~600°C in the mantle that leads to the reduction of friction coefficient by melting. Based on the laboratory data on high-velocity friction, we show that thermal weakening makes Earth's lithosphere weak enough to make plate tectonics possible. In contrast, this weakening process is prohibited by the high surface temperature (~470°C) on Venus keeping the Venusian lithosphere strong. In this model, the difference in the surface temperature leads to the different tectonic style between Earth and Venus through the difference in the degree of dynamic weakening of fault motion.

Keywords: faults, thermal weakening, plate tectonics, Earth-Venus contrast

Proton conduction in hydrous forsterite aggregate at different buffered (MgO or SiO_2) conditions

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Hydrogen in magnesium site is expected to be the most active type in dominating hydrogen lattice diffusion and thus proton conduction in nominally anhydrous minerals (NAMS) (e.g. olivine) in past decades. However, an unexpected small amount of hydrogen in magnesium site pointed out by a growing number of researchers put it into question (e.g. Ingrin et al., 2013; Xue et al., in press). Even if it is not that case, water effect on electrical conductivity quantified by total water content has been inaccurate given the hypothesis that hydrogen diffusion rate was site-specific in forsterite (Padron-Navarta et al., 2014). Therefore, a further evaluation on proton conduction in olivine is required. To clarify the contribution of hydrogen in different sites, we measured the electrical conductivity of hydrous forsterite as a function of water content at different buffered conditions (MgO-buffered and SiO_2-buffered).
Forsterite aggregate with various water contents were synthesized at MgO- and SiO_2-buffered conditions from 4 GPa to 8 GPa, 1373 K in a multi-anvil apparatus. Water content was determined by FTIR using Paterson calibration and occasionally SIMS. Absorption peaks of FTIR were assigned to different sites and water contents in each specific site were calculated. Electrical conductivity measurements were performed at the same pressure from 500 to 800 K.
The maximum water content in MgO-buffered sample (1500 wt. ppm) at 4 GPa was found to be near 10 times that of SiO_2-buffered sample, indicating its superior water storage capacity. Compared with water content calibrated by Paterson method, SIMS measurement usually gives more than 3 times and more than 1.5 times amount of water for MgO-buffered sample and SiO_2-buffered sample respectively at 4 GPa. FTIR spectra in the former shows extremely high intensity of peaks at wavenumbers higher than 3500 cm^{-1}, while broad and noisy peaks at lower wavenumbers dominate in the latter. Peak assignment shows a dominance of hydrogen associated with silicon site in MgO-buffered sample and magnesium site in SiO_2-buffered sample. With increasing pressure, difference in FTIR spectra in these two buffered conditions minimized. Both samples were dominated by peaks at wavenumbers higher than 3500 cm^{-1}, indicating an increasing preference of hydrogen for silicon site at 8 GPa even in SiO_2-buffered forsterite. Water content measured by SIMS in one SiO_2-buffered sample is more than 3 times that of FTIR calibration, similar to the situation of MgO-buffered at lower pressure.
For electrical conductivity measurement, high resistance of forsterite close to the background insulation at low temperature and dehydration at relatively higher temperature prohibited us to obtain good spectra. Preliminary results show that for MgO-buffered sample at 4 GPa, electrical conductivity increases with increasing water content (from 760 wt. ppm to 1470 wt. ppm) while their activation enthalpies decrease from 0.79 eV to 0.61 eV. For SiO_2-buffered sample, activation enthalpy is 1.23 eV for the only one sample. And its extrapolated conductivity to lower temperature crosses with that of MgO-buffered sample containing about 800 wt. ppm water at around 675 K. Combined with the FTIR peak assignment, such coincidence is probably caused by a different contributing factor of hydrogen in different sites. To verify our speculation, more experiments are needed, both at 4 GPa and 8 GPa. To prevent early dehydration during conductivity measurement, new setups aimed at controlling water fugacity will be tried.

Keywords: Proton conduction, Hydrous forsterite, Hydrogen position, Incorporation preference, Peak assignment and deconvolution

Occurrence of plate-like behavior and deep mantle water absorption in hydrous mantle convection system – 'Burst' of mantle water content

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We investigate the occurrence of plate-like behavior in hydrous mantle dynamics as a function of friction coefficient and its influence on evolution of the mantle water content. The hydrous mantle model can generate the long-term plate-like behavior with the higher friction coefficient, taken from Byerlee's law of brittle deformation, than the dry mantle, which is consistent with petrological estimate. The strength of oceanic lithosphere corresponding to friction coefficient plays a significant role with creating the global-scale mantle heterogeneity in hydrous mantle convection as well as strength of viscosity dependence due to water content. In vigorous plate motion, the mantle water content indicated rapid increase by up to 4–5 ocean masses called as the 'burst' effect. A 'burst' is related to the mantle temperature and water solubility of mantle transition zone. When the mantle cools below ~2380 K, mantle transition zone could store water transported by subducted slabs that can pass through the 'choke-point' of water solubility. The onset of 'burst' effect is strongly dependent on the friction coefficient, which gets delayed as the friction coefficient gets higher. The 'burst' effect of mantle water content could have seriously influenced the evolution of surface water ocean if the burst started early in which the Earth's surface cannot preserve the surface water ocean over the age of the Earth. This suggests that the boundary condition should be represented as a finite volume of surface ocean rather than constant water content of oceanic crust as a function of time (infinite water reservoir).

Keywords: water, mantle, plate motion

Reactions of chromite with olivine at high pressures with implications for ultrahigh pressure chromitites

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Podiform chromitites which contain high-pressure minerals such as diamond and coesite as mineral inclusions are called ultra-high pressure (UHP) chromitites. The UHP chromitites were found in the Luobusa ophiolites of Tibet and Ray-Iz massif of the Polar Urals. Recently, mantle recycling models of the UHP chromitites have been proposed, in which the podiform chromitites were formed at shallow levels of the upper mantle, subducted into the transition zone, and returned to the earth's surface (Arai, 2013, Griffin et al., 2016). However, high-pressure experimental studies on chromitite would be insufficient to evaluate the mantle recycling models. Therefore, as a simple system for natural chromitites, we examined phase transitions in the system $MgCr_2O_4$-Mg_2SiO_4 at the conditions of the transition zone and the upper part of the lower mantle.

High-pressure high-temperature experiments were performed at 9.5-27 GPa at 1600 °C in $MgCr_2O_4Mg_2SiO_4$ composition with Kawai-type multianvil apparatus. The synthesized samples were examined by micro-focus and powder X-ray diffraction methods and by composition analysis using a scanning electron microscope with an energy-dispersive X-ray spectrometer.

The results indicate that complex, sequential phase changes occur in the system, as follows. Mg_2SiO_4 olivine (Ol) coexists with $MgCr_2O_4$-rich chromite (Ch) up to 13 GPa. However, above the pressure, they react to form garnet (Gt), $Mg_{14}Si_5O_{24}$-rich anhydrous phase B (Anh-B) and modified ludwigite (mLd) type $Mg_2Cr_2O_5$ phase. At 20 GPa, Anh-B was replaced with wadsleyite (Wd). At 21-23 GPa, $MgCr_2O_4$-rich calcium-titanate (CT) type phase coexists with ringwoodite (Rw). Above 23 GPa, $MgSiO_3$-rich perovskite (Pv, bridgmanite), periclase (Per) and CT are stable. In the transition sequences, the stability pressure of Anh-B is consistent with that in $Mg_{14}Si_5O_{24}$ in our recent study.

Based on the analyzed compositions of the coexisting phases, we calculated mineral proportions and densities of the above phase assemblages by mass balance calculation. Accompanying with the changes of phase assemblages, density increases from 3.84 g/cm^3 of Ol + Ch to 4.10 g/cm^3 of Gt + Anh-B + mLd, and finally to 4.43 g/cm^3 of Pv + Per + CT.

Our experimental results on the phase changes in the system are different from those postulated in the mantle recycling models of the UHP chromitites. In the models, it is assumed that no reactions occur between Ol and Ch and also transitions of Ol to Wd and of Ch to CT separately occur. Because evidences on the reaction products, Gt + Anh-B (or Wd) + mLd, have not yet been reported in the UHP chromitites, our experimental results suggest that the UHP chromitites did not experience P, T conditions of the transition zone and therefore recycled within the upper mantle. If the reaction products are found in the chromitites in future, they would be good indicators showing how deep the chromitites were subducted.

Keywords: ultrahigh pressure chromitite, chromite, mantle recycling, transition zone, high-pressure experiment

Thermodynamic calculations of high-pressure phase relations in the systems Mg_2SiO_4 and $MgSiO_3$

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Since Mg_2SiO_4 and $MgSiO_3$ are the most abundant endmembers of the Earth's mantle constituent minerals, their high-pressure phase relations have been investigated in detail by high-pressure high-temperature experiments. On the other hand, the stability of phases in the systems has been also studied by thermodynamic approach in conjunction with the high-pressure experiments. In the thermodynamic calculation of phase equilibrium boundary, thermodynamic parameters such as enthalpy, entropy, heat capacity, thermal expansivity and bulk modulus reported by different researchers are used. Some thermodynamic parameters which have not been experimentally obtained are optimized using experimentally determined phase boundaries. From these reasons, the thermodynamic parameters for one material are sometimes not internally consistent. This causes large uncertainties in the calculated phase equilibrium boundaries.

Recently, more accurate enthalpy, heat capacity and entropy data and equations of state for high-pressure polymorphs in Mg_2SiO_4 and $MgSiO_3$ and their constituent oxides have been experimentally determined. In this study, the internally consistency among the thermodynamic parameters for each material was examined. For example, high-temperature isobaric heat capacity of a high-pressure phase which collapsed by heating at 1 atm was estimated by the following method. Isochoric heat capacity was calculated using a vibrational density of state model which reproduced experimentally determined low-temperature heat capacity. The contribution of anharmonic effect was, then, added to the isochoric heat capacity using the same thermal expansivity and bulk modulus as those applied to the equation of state of the high-pressure phase. In addition, formation enthalpies for all the phases in the systems Mg_2SiO_4 and $MgSiO_3$ considered in the present calculations were determined from the difference in drop-solution enthalpy between constituent oxides and them. This gives unified relative enthalpy relations among the materials. Finally, using the obtained thermodynamic data set, we calculated high-pressure phase relations in the Mg_2SiO_4 and $MgSiO_3$ systems up to 26 GPa and 2300 K in dry condition.
In both the systems, calculated phase boundaries are consistent with those determined by high-pressure in situ experiments. It is noteworthy that, in the Mg_2SiO_4 system, the calculation result predicts the existence of the stability field of $MgSiO_3$ akimotoite + MgO between Mg_2SiO_4 ringwoodite and $MgSiO_3$ bridgmanite + MgO below about 1500 K. In subducted slabs whose temperature would be lower than that of surrounding mantle rocks, ringwoodite might first decompose to akimotoite + ferropericalse with increasing pressure and then transform to bridgmanite + ferropericlase.

Keywords: mantle minerals, Mg2SiO4, MgSiO3, thermodynamic stability, high-pressure phase relation

Fate of $MgSiO_3$ post-perovskite in super-Earths

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$MgSiO_3$ post-perovskite (ppv) is the final form of $MgSiO_3$ in the Earth. However, what happens in super-Earths in which pressure and temperature are much higher than those of the Earth's lower mantle? Understanding of fate of $MgSiO_3$ ppv under ultrahigh pressures is crucial for nature of interiors of super-Earths. Computational studies so far have predicted several pressure-induced dissociations of $MgSiO_3$ in super-Earths. Recent studies agree that $MgSiO_3$ ppv undergoes three-stage dissociations involving MgO, SiO_2, Mg_2SiO_4, and $MgSi_2O_5$ [1,2]. Based on these studies, we reinvestigate the high PT phase diagram of MgO-SiO2 system and we propose a new phase transition in MgO-SiO_2 system in super-Earths. Clapeyron slope of the new transition and thermodynamic quantities calculated for these phases should provide fundamental information for numerical simulation of mantle dynamics in super-Earths.

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Keywords: MgSiO3 post-perovskite, pressure-induced phase transition, first-principles calculation, terrestrial exoplanets

High body wave attenuation in the upper mantle and the role of melt

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Seismic attenuation offers a powerful constraint on the physical state of the Earth’s interior. Anelastic processes can generate strong variation in amplitudes and wave speeds of P and S waves, seen in both regional and teleseismic observations. The effect of temperature on attenuation in mantle rocks is reasonably well calibrated in the laboratory. However, these laboratory predictions deviate systematically from seismic observations. We demonstrate this with analysis of a new ocean-bottom seismometer dataset spanning the Juan de Fuca plate and ridge system, measuring seismic attenuation and velocity across an entire oceanic plate. Spectral ratios of teleseismic P and S waves show the highest attenuation anomalies and largest delays at in a narrow zone <50 km from the Juan de Fuca and Gorda ridge axes, with implied seismic quality factor for shear waves (Qs) 25 (extrapolated to 1 Hz) over the upper 150 km of the mantle beneath the ridge, among the lowest observed worldwide. We compare these results with measurements of Qs in subduction zones, observed from regional intraslab earthquakes. In those data, attenuation is strongest (Qs ~ 20-70) for paths traversing the mantle beneath arcs and backarcs. Although these two sets of observations (teleseismic Qs beneath a ridge and regional Qs beneath arcs) are made at different frequencies, when corrected for laboratory-calibrated frequency dependence they show comparable values. However, these Qs values are 2-5 times lower than predicted for any reasonable extrapolation of laboratory measurements in dry rocks. We infer a large effect of melt on Qs both beneath ridges and beneath arcs, with forward calculations suggesting up to 2% in situ melt.

Keywords: mid-ocean ridge, subduction zone, seismic attenuation

Viscosity of silicate melts at high pressure measured by *in-situ* falling sphere method

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The Earth experienced an early episode of magma ocean, in particular after the giant Moon-forming impact. Some partial melting still occurs today in the upper mantle. The viscosity of magma is a key to understand the various magmatic processes that can occur within the Earth. However, the accurate measurement of the silicate melt viscosity at high pressure has been limited to 13 GPa due to the high melting temperature and extremely low viscosity of silicate melt. We succeeded to extend the viscosity measurement to higher pressure by devising the *in-situ* falling sphere viscometry with boron doped diamond heater and ultra-fast cameral (1000 f/s) in Multi-anvil apparatus. Boron doped diamond is an ideal heater material for *in-situ* falling method because of its X-ray transparency and refractoriness exceeding 3000 C.

Viscosities of forsterite and diopside compositions were measured at 10 GPa, just above the liquidus temperature.The viscosity of enstatite composition was measured twice at 10 and 15 GPa, to confirm the good reproducibility.The viscosity of forsterite, enstatite, and diopside composition at 10 GPa are measured to be 0.023, 0.023 and 0.038 Pa.s, respectively. Forsterite and enstatite melts have similar viscosities, while diopside melt has much higher viscosity.The viscosity of forsterite composition at 15 GPa is 0.013 Pa.s, which is much lower than that at 10 GPa.

The experimental pressure range can be extended to higher than 23 GPa with the present cell assembly. The viscosity data at the higher pressure can be used to constrain the partitioning of gravity energy between the metal and silicate melts during the core formation. It can be used as well to estimate the largest grainsize of crystals entrained during the magma ocean solidification, which enables us to distinguish fractional or batch solidification of the magma ocean.

Keywords: viscosity, silicate melts, boron doped diamond, high pressure

Geo-neutrino measurement with KamLAND

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The **Kam**ioka **L**iquid-scintillator **A**nti-**N**eutrino **D**etector (KamLAND) is located in a rock cavern in the Kamioka mine, 1,000 m below the summit of Mt. Ikenoyama in Japan. KamLAND is marked by the ability to detect low-energy anti-neutrino signals at 1,000 tons of ultra pure liquid scintillator (LS) through the inverse β reaction. We demonstrated the oscillation nature of neutrino flavor transformation by observing electron anti-neutrino from nuclear reactors and neutrino properties have been explored precisely. Since neutrinos interact with other particles only via weal interaction, they have extremely low reaction probabilities. Such elusive property of neutrinos provides us with the ability to investigate optically invisible deep interior of the astronomical objects, such as the Earth. Neutrino measurement evolved understanding of neutrino properties to utilization of neutrino as a “probe”.
The detection of geo-neutrinos, anti-neutrinos produced in β-decays from primordial radioactivite elements (uranium, thorium and potassium) within the Earth’s interior, brings unique and direct information about the Earth’s interior and thermal dynamics. KamLAND detects geo-neutrino signals above 1.8 MeV due to the reaction threshold energy of the inverse β-decay, resulting to have sensitivity to anti-neutrinos from the decay chains of ^{238}U and ^{232}Th. The KamLAND collaboration reported the result of the first study of geo in 2005. Later the geo signals at KamLAND were used to estimate our planet’s radiogenic heat production and constrain composition models of the bulk silicate Earth (BSE). Following the Fukushima nuclear accident in March 2011, the entire Japanese nuclear reactor industry, which generates >97% of the reactor neutrino flux at KamLAND, has been subjected to a protracted shutdown. This unexpected situation allows us to improve the sensitivity for geo-neutrinos. In 2016, we presented that KamLAND started to have a sensitivity of Th/U mass ratio of entire Earth.
Currently, geo-neutrino observed rate is in agreement with the prediction from existing BSE composition models within 2σ C.L., but some extreme models start to be disfavored. This ability to discriminate is limited by the experimental uncertainty and crust modeling. Continuing the data taking under the present low-reactor situation yields better signal-noise ratio and provides promising power of uncertainty.
Enhanced geo-neutrino flux calculation model using latest crustal structure model and geochemical understanding around Japan Island Arc will be a key issue for the further constraint on the Earth models and observation of mantle contribution.

Keywords: Geo-neutrino, radiogenic hear, Th/U mass ratio

Defining the deep Earth with the OBK detector

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The global surface heat flow reflects the combine contributions of primordial and radiogenic heat, with the former comprised of accretion and core formation sources. The continental crust contributes 7 TW of radiogenic power and a sub-MOHO flux of 10 to 30 mW/m^2 for a total surface flux of 65 mW/m^2. The continents contribute about 1/3 of the total power lost from the Earth. At its present spreading rate, the oceans contribute 2/3 of this flux, but we do not know how much of this flux is primordial versus radiogenic contributions. Earth models collectively allow up to a factor of 30 in the spread of estimates of the present-day mantle’ s radiogenic power. Moreover, the surface heat flux is likely to be a relative constant over the continents, whereas in the oceans it is unlikely to remain a constant over the last few billion years given variations in spreading rates. Our understanding of the Earth’ s thermal evolution history is intimately linked to knowing the total radiogenic power of the mantle.

OBK (Ocean Bottom KamLAND) is the next generation underwater geoneutrino detector designed to measure the Earth’ s abundance and distribution of Th and U inside the mantle. We have shown that such a detector is capable of identifying and mapping out large deep Earth structures (e.g., LLSVP), where they have enrichments in these elements relative to the ambient mantle.

Following on from the successes of the existing detectors in Japan and Italy, we propose an international effort, with Japanese geoscientists and particle physicists leading, to construct and deploy an ocean-going detector (OBK) to (1) map out structures in the mantle, (2) constraint the cooling history of the planet, (3) distinguish continental and mantle Th/U ratios, which documents the Earth’ s biological imprint on the mantle, and (4) define the power driving plate tectonics. Beyond these goals in Earth Sciences, this instrument will have spinoffs for particle physics and astroparticle physics. This field of science has been richly acknowledged by Nobel prizes; the science proposed here has the potential to continue this great tradition.

Keywords: geoneutrino, mantle, heat flow, radiogenic power, thermal evolution

Asteroid impact-induced magmatism and tectonics on the Hadean-Archean Earth

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In the previous talk by Graham et al., we suggested that: (1) The numerous fragments of Ti-Fe-rich meteorites, discovered in the ~3.45 Ga Apex Basalt near Marble Bar, Western Australia, most likely represent parts of a large (~10-20 km diameter?) asteroid body that created a large (~150 km diameter?) impact-crater on a deep (2,000 m) ocean floor; and (2) The Apex Basalt (~3-4 km thick) represents the crater-fill basalt magmas that were generated by the impact-induced, rapid decompression-melting of the deep-mantle peridotite. The close similarities in the abundance ratios of the high-field-strength elements (e.g., REEs, Nb, Y, Zr) between the Apex Basalt and the 120-90 Ma Ontong Java Oceanic Plateau Basalt, which has been suggested by some researchers to be the product of an ~20-30 km-diameter bolide impact, support the above model for the magmatism in the East Pilbara district ~3.5 Ga ago.

We have extended the examinations of the geological, petrological, and geochemical characteristics of the pre-3.0 Ga geologic formations in the Pilbara- and Kaapvaal Cratons, and suggest the following models for the magmatism, tectonics, and evolution of the oceanic and continental crusts of the early Earth: (1) The Last Heavy Bombardment of asteroids lasted until at least ~3.2 Ga ago, possibly until ~2.5 Ga ago. (2) Prior to ~3.2 Ga (or ~2.5 Ga), magmatism and tectonics on the Earth were mostly dictated by the impacts of asteroids (mostly in the oceans), rather than by the plate (horizontal) tectonics or the plume (vertical) tectonics that are caused by the large-scale convections in the mantle. Punctuations of the thick oceanic (and continental) crusts, as well as the large-scale melt-generation in the upper mantle by large bolide-impacts provided the effective mechanism to release the interior heat of the early hot Earth. (3) Rapidly declining meteorite impact events after ~3.2 Ga (or ~2.5 Ga) was the probable cause for the initiation of the plate- and plume tectonics, because the Earth had to find alternative ways to release its interior heat. (4) All major igneous-rock formations in the Archean greenstone belts, including komatiite, basalt, and granitoiods, were formed from the magmas generated by impact-induced, rapid decompression-melting of mantle peridotite, and by the interactions between these magmas and the oceanic crust. (5) Until ~3.2 Ga (or ~2.5 Ga) ago, no significant difference in composition and thickness existed between the continental and oceanic crusts, i.e., the true continental crust did not exist. The oceanic (and continental) crusts were comprised of large circular/oval-shaped "blocks" (~10^6–10^7 km^2 in area) which were created by different asteroid impacts. Each "block" was chemically heterogeneous, and vertically zoned (generally by composition) from ultramafic in the lower zones to felsic in the upper zones. (6) The plate tectonics, which began ~3.2 Ga (or ~2.5 Ga) ago, caused preferential melting of the felsic to intermediate rocks (compared to the mafic and ultramafic rocks) of the Archean oceanic crust during its subduction, because of their lower temperatures of melting. The andesitic/felsic melts generated from the subduction zones ascended to create the continental crust. Because silicic continental crust is buoyant compared to the mafic oceanic crust, the continental crust has remained at a higher level than the oceanic crust since ~3.2 Ga (or ~2.5 Ga) ago. (7) Slower melting of the upper mantle peridotite by the hotter materials from the lower mantle in the post-Archean eras, compared to the rapid melting of the mantle peridotite due to sudden decompression caused by meteorite impacts during the Archean era, have created chemically homogeneous basalt magmas that have erupted at mid ocean ridges to create chemically homogeneous oceanic crust since ~3.0 Ga ago.

Keywords: Asteroid, magmatism, tectonics, early Earth

˜3.45 Ga meteorite fragments suggest the Earth is poorer in Fe and Ni and richer in Ti and V than the current model

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Previous researchers have estimated elemental abundances of the solar system and of the Earth mostly from the compositions of carbonaceous chondrites and other meteorites that have fallen recently on the Earth. The modern metal-rich meteorites are comprised of Fe-Ni alloys (Ni contents 5-20 wt%) with minor Co.

In the ABDP #1 drill core from Marble Bar, Western Australia, we have discovered numerous fragments (up to ˜2 mm in size and often >5 volume % of the rock) of metal-rich meteorites throughout a ˜40 m section of the ˜3.45 Ga Apex Basalt that overlies the thick (up to ˜200 m) Marble Bar Cher/Jasper (MBC) beds. The meteorite fragments occur together with impact spherules made of the melted volcanic rocks, angular fragments of the MBC, and the tsunami-disturbed MBC beds. The underlying MBC beds exhibit shocked- and brecciated textures and host numerous quartz veinlets that intruded along the impact-induced fractures. These features, and the areal extents of the Apex Basalt (˜3-4 km thick), suggest that the meteorite fragments are part of a large (˜10-20 km diameter?) bolide that created a large (˜150 km diameter?) impact crater on a deep (>2,000m) ocean floor, and that the Apex Basalt was the crater-fill basalt magma that was generated by the impact-induced, rapid decompression-melting of the mantle peridotite.

To our surprise, the meteorite fragments in the Apex Basalt have entirely different chemistries than the modern iron meteorites. They are mostly made of oxidized forms of Ti-Fe (Ti Fe) alloys with various amounts of Si, Al, V, Cr, and Cu as solid solutions; but Ni is very low (<0.1 wt%). Oxidation of the metal alloys probably occurred through reactions with the atmospheric O_2 in the “impact clouds”. Thermodynamic data suggest that the original metal-alloys in our meteorites were formed in the core of a planet with more reducing conditions than the cores of the planets that formed the modern iron meteorites. Our findings suggest that: (1) The asteroids that formed the early Earth may have had very different compositions than the meteorites that have fallen recently on the Earth--consequently, the early-Earth materials may have come from different parts of the asteroid belt than the modern meteorites; (2) The age of the Earth may be older (or younger) than 4.54 Ga, an age which was determined using the modern meteorites; (3) Elemental abundances of the solar system and of the Earth are possibly much higher in Ti and V, and lower in Fe and Ni, than those estimated by previous researchers. This would explain why the previously-estimated solar abundances for Ti and V are much lower (whereas those for Fe and Ni are much higher) than those estimated using the Oddo Harkin’s Rule of nucleosynthesis; and (4) The Earth’s core is possibly made of Ti-Fe-Si-Al alloys, rather than of Fe-Ni alloys. This would explain why the density of the core is much lighter than the densities of Fe-Ni alloys. It would also explain why the Moon, which formed at ˜4.40 Ga, is characterized by Ti-rich basalts.

Keywords: Ti-rich meteorites, solar abundances, Earth's core

