Metastable olivine wedge in the Pacific slab and deep earthquakes beneath the NE Asia margin

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Seismic tomography and numerical simulations show that the western Pacific slab bends horizontally when it reaches the boundary between the upper mantle and lower mantle beneath northeast Asia. It is considered that a metastable olivine wedge (MOW) exists in the cold core of the slab because of a delayed phase transition from olivine to its high-pressure polymorphs. However, it is still debated whether the MOW actually exists or not, and even if it exists, its physical properties, such as seismic velocity and density, are still unclear. In this work we have used high-quality arrival-time data of 17 deep earthquakes occurring within the Pacific slab under the Japan Sea and NE Asia margin to study the detailed structure of the slab. The deep earthquakes are relocated precisely by applying a modified double-difference location method to arrival-time data recorded at both Chinese and Japanese stations. The hypocentral locations are accurate to 2 km. Travel-time double-residuals are used to estimate seismic velocity within the slab. Our results show that MOW does exist within the Pacific slab under NE Asia and the Japan Sea, and the MOW has a P-wave velocity 7~9% lower than the iasp91 Earth model. We relocated all the 17 deep events using the final slab model containing the MOW, and the results show that all the deep events are located within the MOW, rather than along the MOW boundary as suggested by the previous studies. The MOW in the slab can reduce the speed of slab subduction, and it plays an important role in the generation of deep earthquakes.

Keywords: deep earthquakes, subducting slab, metastable olivine wedge

The waveguide/anti-waveguide effect of the subducting Pacific slab for deep-focus earthquakes

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It has long been considered that the large ground motion from deep-focus earthquakes traveling long distances along the plate is explained by efficient guiding of seismic wave inside the high-V and high-Q plate in the subduction zone. However, the seismic wave is easily escaping into the surrounding low-V mantle from the high-V slab with a strong velocity gradient from the center to the outer part of the slab constrained by its thermal regime. The observed ground motions traveling long distances along the slab show low-frequency (f < 0.25 Hz) onset for P and S waves, followed by large, high-frequency (f > 2 Hz) coda with long tail, but such feature of the slab guided wave cannot be explained by the traditional simple high-Q and high-V model.
Now, the character of the high-frequency and lengthy seismic waves is explained by multiple forward scattering of seismic waves in the heterogeneous slab (Furumura and Kennett, 2005). The heterogeneity is well modeled by stochastic representation of velocity fluctuations using the von-Karman distribution function with horizontally elongated correlation length of about 10 km and much shorter (0.5 km) correlation length in vertical, with a standard deviation of about 2%, or more reality it grows from 0.5 to 2.5 % from the top to bottom of the slab (Kennett and Furumura, 2015). Such a quasi-lamina feature of the heterogeneities in the slab is very efficient to develop forward scattering of high-frequency wave with much shorter wavelength than heterogeneity scale, and low-frequency onset as a result of multiple diffractions. The net result of high-Q and high degree of heterogeneity in the slab is a strong frequency-dependent, which capture only high-frequency (f > 2 Hz) and escapes intermediate-frequency (f=0.1-1 Hz) signals. Very low-frequency signals (f < 0.15 Hz) with much longer wavelength than the slab thickness are not affected by the slab.
As for very deep-focus (h > 400 km) earthquakes, the waveguide effect for the intermediate frequency (f=0.2-1 Hz) signal will be changed and is captured inside the slab due to an additional low-V anomaly inside the slab. As is recognized that the phase transformation from olivine to spinel in the subducting cold slab develops wedge-shape anomaly (metastable olivine wedge; MOW) at the center of the slab at depth between 400 and 560 km. The sudden change in the waveform for very deep (> 400 km) events with much elongated P and S wave precursors than those for shallower events (< 400 km) was noticed in the F-net broadband records of the Pacific slab events beneath Sea of Japan (Furumura and Padhy, 2014). This observation should be a strong evidence for the existence of low-V anomaly at the depth to capture and guide intermediate frequency signal. The detectability of the MOW inside the slab in the waveform anomaly had been discussed based on numerical simulation (e.g., Vidale, 1991; Koper and Wiens, 2000; Yoshioka and Murakami, 2012) and analysis of observed long-period records at teleseismic distances (e.g., Kaneshima et al., 2007). This additional waveguide property of a thinner low-V MOW resembles to the previously reported oceanic-crust guided wave occurred for shallower events in the brittle oceanic crust (e.g., Fukao et al., 1983; Hori et al., 1985). The finite difference method (FDM) simulation demonstrated the preferred MOW model in the Pacific slab is about 100 km wide at 400 km depth and wave-speed anomaly is 6% lower than the surrounding slab to explain observation. This is consistent with the previously investigated MOW model based on travel time anomaly analysis (e.g., Iidaka amd Suetsugu, 1992; Jiang et al., 2008; PanKow et al., 2012) and receiver-function studies (e.g., Kawakatsu and Yoshioka, 2011) etc.

Keywords: deep-focus earthquake , slab guided wave

Rupture initiation of deep-focus earthquakes

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As part of the deep-focus earthquake mechanism puzzle, the initiation mechanism, which needs to be spontaneous, is particularly important and enigmatic. Once rupture is initiated, various feedback mechanisms, such as shear heating/melting, can potentially be triggered and promote further slip. However, accurate characterization of the initiation phase is difficult due to the limited data resolution and complex high-frequency Green’s functions. Here we develop a new method to jointly invert teleseismic and regional P waveforms for a Haskell-style model, assuming unilateral rupture with constant rupture speed. Small aftershocks’ waveforms are used as Empirical Green’s functions when available. We apply this method to large deep-focus earthquakes to zoom in on their first 2~3 seconds of rupture. We found that their initiation phases often show relatively high, sometimes supershear rupture speeds, depending the fracture modes. For example, the 2015 M7.9 Bonin Islands earthquake shows a supershear initiation, and the 1994 M8.2 Bolivia earthquake’s initial rupture speed is also higher than its later stages. The observed high-speed initial ruptures may suggest a more efficient initiation mechanism than the later rupture propagation mechanism(s).

Keywords: deep-focus earthquakes, rupture initiation

Static and dynamic parameters of deep earthquakes from global seismic data

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We study the radiated energy and rupture duration for more than 500 deep and intermediate depth earthquakes (depth>50km and M>5.5). The average source time function is obtained by stacking broadband P-wave pulses recorded globally and used to measure the rupture durations, by comparing alternative versions of the same waveform. The radiated energy is obtained by integration of velocity spectrum observed at each station and corrected for radiation pattern and propagation effects.
The global analysis of the rupture duration show how beyond the scattering of the scaled duration seen on the data, the depth reduction of the duration can principally be explained by incremental shear velocity with depth. Furthermore, the duration to moment comparison shows how 1/3 scaling is not valid for deep seismicity, suggesting a difference in dynamic for small and large events. The existence of a different scaling law is further corroborated by the analysis of scaled energy, which is not constant as function of moment.
The radiated energy and rupture duration are combined to derive stress drop, apparent stress, efficiency and other parameters of the rupture. The global analysis of these parameters suggests how deep and intermediate depth events are systematically different from shallow earthquakes. We further derive rupture velocity for some of the studied events, to get further information on the dynamic properties of the rupture process.
Coherent variation of the derived rupture parameters are seen when along strike events are analyzed by clusters, suggesting how deep earthquakes cannot be reduced in a single group, while a diversity of deep and intermediate depth earthquakes should exists. Comparison of our measures with independent geophysical properties of slabs as plate age, thermal parameter and convergence rate is done, in order to unravel any possible relation between the subudction zone style and its associated seismicity.

Keywords: Deep and intermediate depth earthquakes, Seismology, P waves

Full moment tensor inversion for the large deep earthquakes

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We have performed full six component moment tensor inversions for the three large deep earthquakes: the June 6, 1994 Bolivia deep earthquake (M_w 8.2), the May 24, 2013 Sea of Okhotsk deep earthquake (M_w 8.3), and the 30 May 2015 off Bonin Islands deep earthquake (M_w 7.9) (Hara and Kawakatsu, 2014, JpGU; 2014, SSJ; 2015, SSJ). The VHZ channel waveform data were retrieved from the IRIS DMC. The data in the period range between 550 s and 1000 s, which are suitable to determine the isotropic component independently from other components (Hara et al., 1995, GRL, 1996, GJI; Kawakastu, 1996, GJI), were used. The Direct Solution Method (e.g., Hara et al., 1991, 1993, GJI) was used to calculate Green's functions for moment tensor inversion. The spatial and temporal grids for possible centroid locations and times are set and linear moment tensor inversions were performed for their pairs. The uncertainties of the analyses were estimated by the bootstrap method (e.g., Efron, 1982, SIAM).

For the 1994 Bolivia and the 2015 off Bonin Islands deep earthquakes, the isotropic components of the optimal solutions were in the ranges of the uncertainties obtained from the bootstrap analyses. For the 2013 Sea of Okhotsk deep earthquake, the isotopic component of the optimal solution was about 3 per sent (implosive) of the seismic moment. The uncertainty estimated from the bootstrap analysis was on the order of 1 per cent. This result is consistent with Okal (2013, AGU), although further uncertainty evaluations are necessary.

Hara and Kawakatsu (2015, SSJ) calculated the non-double couple component of the deviatoric moment tensor (epsilon, Giardini, 1983, 1984) of the sets of solutions obtained by the bootstrap analyses. The relatively large non-double couple components (around -0.08) were obtained for the 2013 Sea of Okhotsk deep earthquake, which implies the possibility that the moment tensor for this event is affected by velocity structures such as anisotropy in the source region.

Keywords: Deep earthquake, Moment tensor, Isotropic component, Non-double couple component

Deep Earthquakes Isolated from Present-Day Active Wadati-Benioff Seismic Zones: Seismogenesis in Detached and Fragmented Slabs associated with the M7.9 Bonin Deep Event of 30 May 2015 and Similar Examples

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The Mw 7.9 earthquake of 30 May 2015 at 680 km in the vicinity of the Bonin subduction zone was more than 150 km distant from the nearest deep earthquake in the active Bonin Wadati-Benioff (WB) earthquake zone that is well west of the big event of 30 May. Moreover, well-located deep events in the Bonin system dating as far back as 1925 show that the WBZ system in this latitude deep events are limited to depths of 500-600 km and extend as much as 200 km to the west of the deepest events of the inclined section of the Bonin W-B zone and occur in high-wave-speed, high-Q, stagnant slab material previously described by others (Fukao et al., 1992; van der Hilst et al. 1993; Okal, 2001).

Events in this class of deep earthquakes that are isolated from active W-B zone earthquakes are reported in other localities worldwide, including *Tonga*, *Vityaz* (North Fiji Basin), and possibly *southern Spain*. Such deep events have been considered as seismogeneis in detached or fragmented slab material that has foundered to near the bottom of Earth’s transition zone (Kirby et al., 1996; Okal and Kirby, PEPI, 1998; Okal, PEPI, 2001) where stresses may be generated by heterogeneous volume changes associated with the metastable olivine->spinel metamorphic reaction. How and why slab fragments become detached has been suggested to be a possible consequence of collisions of oceanic plateaus or island arcs with oceanic forearcs leading to arc reversal and/or fragmentation of normal oceanic lithosphere from plateau lithosphere. The *Igasawara Plateau* is currently colliding with the Bonin forearc just to the south of the 30 May 2015 deep event. The *Bonin Ridge* may represent a thick section of thick remnant crust that detached its slab that later foundered in mantle fall free to the bottom of the mantle transition zone in the source region of the 2015 shock. This ridge is an unusual feature of the Bonin forearc with its steep scarp-like western margin and rift between it and the Bonin arc massif to the west. The most straightforward interpretation of the above facts is that the Bonin Ridge is a collisional arc remnant accreted to the Bonin forearc and that the western part of the Pacific Plate detached via normal faulting and foundered to mantle transition zone depths.

Keywords: Deep earthquake, Slab detachment, Isolated intraslab earthquakes

Constraints on the Mechanism of Intermediate and Deep Earthquakes from Local Array Studies of the Tonga Subduction Zone

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The Tonga slab shows the highest rates of intermediate and deep seismicity of any subduction zone worldwide. It also has the highest convergence rate and the lowest estimated slab temperatures, and the convergence rate varies along strike from about 240 mm/yr in the north to 100 mm/yr in the south, making it ideal for studying the effect of slab temperature on the mechanism of intermediate and deep earthquakes. However, the remote oceanic location has limited resolution of earthquake processes. Here we use 17 land and 50 ocean bottom seismographs deployed from 2009-2010, as well as previous local seismograph deployments, to carry out more detailed studies.

Relocation of intermediate depth seismicity reveals that the double seismic zone (DSZ) in northern and central Tonga, first discovered by Kawakatsu (1985), extends from 70 to 300 km depth (Wei, 2016). This is deeper than has been observed previously in NE Japan and other subduction zones worldwide, where DSZs are limited to about 180 km depth. Examination of numerical thermal models for the different subduction zones suggest that the existence of a DSZ is controlled by a range of slab temperatures, which occur deeper in Tonga due to its rapid convergence rate. Additionally, we observe a band of high seismicity extending from the upper zone into the center of the DSZ at a depth of 300 km in the north, decreasing continuously to 200 km depth in the south. Numerical models reveal that these events occur at various pressures but at nearly constant temperatures because of the changing convergence rate. We suggest that the band of seismicity delineates the depth at which the subducted uppermost mantle reaches temperatures high enough to dehydrate serpentine (500-600 degrees C) and possibly other higher pressure hydrous phases, as the phase diagrams are poorly known at these pressures. The liberation of large amounts of water by dehydration reactions greatly increases the pore pressure within this part of the slab, producing the band of seismicity.

The Tonga subduction zone is also associated with a wide region of “outboard” 500 to 680 km deep earthquakes to the west of the main slab, which are poorly understood. The 9 November 2009 earthquake (Mw 7.3, depth 591 km) in a previously aseismic region beneath the Fiji Islands represents the largest earthquake located in this area. Waveform inversion shows a compact bilateral rupture in a NE-SW direction and an overall fault length of 30 km, yet the aftershocks are widely distributed along a sharp EW line at distances of up to 140 km from the mainshock (Cai and Wiens, manuscript in preparation). This line extends towards the Vitiaz deep earthquake cluster to the west, and is consistent with tectonic reconstructions of the fossil Vitiaz trench which subducted Pacific lithosphere from the north prior to 10 Ma. We suggest that this line of earthquakes represents the remnants of the Vitiaz slab in the transition zone. Many of the aftershocks were dynamically triggered along this line, suggesting that this fossil slab is composed of material with faults near the critical stress, but where earthquake nucleation is difficult without triggering by a nearby large earthquake.

Kawakatsu, H. (1985), Double seismic zone in Tonga, *Nature*, *316*(6023), 53-55.

Wei, S. (2016), Seismic studies of the Tonga Subduction Zone and the Lau Back-arc Basin, PhD Thesis, Washington University, Saint Louis, USA.

Keywords: Double Seismic Zone, Dehydration, Earthquake Triggering

Dehydration of lawsonite in blueschist could directly trigger intermediate-depth earthquakes in subducting oceanic crust

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Intermediate-depth earthquakes in cold subduction zones (e.g., northeast Japan) are observed within the subducting oceanic crust, as well as the mantle. In contrast, intermediate-depth earthquakes in hot subduction zones (e.g., Cascadia and southwest Japan) predominantly occur just below the Moho. These observations have stimulated interest in relationships between seismicity and blueschist-facies metamorphism occurring typically at cold subduction zones, particularly through dehydration reactions involving lawsonite.
We conducted deformation experiments on lawsonite, while monitoring acoustic emissions (AE), in a Griggs-type deformation apparatus. Results were compared to experiments on antigorite serpentine, for which stable frictional behavior has been observed during dehydration at similar deformation conditions. Deformation was initiated at a confining pressure of 1.0 GPa, temperatures of 300 °C (for lawsonite) and 400 °C (for antigorite), and constant displacement rates of 0.16 to 0.016 μm/s (corresponding to equivalent strain rates of 8 $\times 10^{-5}$ to 8 $\times 10^{-6}$ s^{-1}). Samples were first loaded at conditions within the lawsonite/antigorite stability field. Next the temperature was increased to 600 °C for lawsonite and 700 °C for antigorite at temperature ramping rates of 0.5 to 0.05 °C/s to induce dehydration reactions while the samples continued to deform.
In contrast to similar tests on antigorite, rapid stress drops occurred during dehydration reactions in the lawsonite. Microstructural observations indicate that strain is highly localized along the fault (R_1 and B shears), and that the fault surface develops mirror-like slickensides. Cumulative AEs for the lawsonite sample continuously increase at temperatures >450°C, indicating unstable microcrack growth during fault slip. In contrast, the AE signal for the antigorite sample is essentially the same as that observed from the control experiment using an aluminium sample. Rapid stress drops with unloading slopes similar to the apparatus stiffness at all experimental conditions (regardless of the strain rate and temperature ramping rate) indicate that unstable fault slip (i.e., stick-slip) occurred during the lawsonite experiments. The unloading slope for antigorite is primarily controlled by the effects of the dehydration reaction rate and the strain rate on the evolution of pore fluid pressure. A time-independent thermal-mechanical scaling factor for the experiments covers the range estimated for natural subduction zones, indicating the potential for unstable frictional sliding within natural lawsonite layers appropriate for intermediate-depth earthquakes.

Keywords: lawsonite, dehydration embrittlement, intermediate-depth earthquake

Laboratory earthquakes triggered by metamorphic reactions during the eclogitization of blueschist

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The phenomenon of intermediate depth seismicity has been highly debated for several decades. The term dehydration embrittlement refers to one of the developed theories that specifically relates the formation of deeper earthquakes to the breakdown of hydrous phases in the subducting oceanic plate and in the hydrated mantle. Especially the dehydration of lawsonite in blueschists and eclogites is a potential candidate to explain the formation of those intermediate depth earthquakes in the down-going slab that represent the upper Wadati-Benioff plane of seismicity. It was recently shown that the breakdown of lawsonite triggers unstable slip accompanied by acoustic emissions (AE) while deforming the samples in the Griggs apparatus. Our experimental results reveal either one or two clusters of AEs depending on the confining pressure of the experiment while deforming natural lawsonite bearing blueschists under eclogite facies conditions. These clusters can be linked to two different metamorphic reactions: the growth of omphacite and garnet and/ or actinolite which liberates only minor amounts of water in expense of glaucophane and lawsonite under lower temperatures (300 –450 °C) and the reaction between lawsonite and glaucophane to clinozoisite, paragonite, and actinolite (+/- garnet) and water at higher temperatures (600 –850 °C). The experimental results indicate that more than one metamorphic reaction may trigger intermediate depth earthquakes at different stages during cold subduction of the oceanic crust.

Keywords: subduction zone, dehydration reactions, eclogitization

Seismic evidence for fluid-related embrittlement at intermediate depths

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Genesis of intermediate-depth earthquakes is an enigma, because high lithostatic pressures render ordinary dry frictional failure unlikely. Earthquakes in a subducting crust can be linked to the dehydration of lawsonite (Okazaki and Hirth, 2016), but earthquakes in a mantle have been discussed in terms of dehydration of hydrous minerals (e.g., Yamasaki and Seno, 1996; Peacock, 2001) or thermal instability (e.g., Kelemen and Hirth, 2007; Prieto et al., 2014). Here I show waveform analyses of two small seismic clusters in the subducting crust and mantle, providing lines of evidence for fluid and phase-transformation related embrittlement in both the crust and mantle. For the cluster in the crust, I reveal that tensional earthquakes are located 1 km above compressional earthquakes, suggesting that the shear strength of faults is too weak to response to different stress regime over a short distance. In addition, earthquakes with highly similar waveforms lie on well-defined planes with complementary rupture areas, suggestive of progressive ruptures along pre-existing fossil faults. The tensional stress is interpreted as a dimensional mismatch between crust transformed to eclogite and underlying untransformed crust. I observe a marked migration of a seismic sequence in the mantle that started with an M 4.1 event at the deepest part of the cluster. The seismic sequence continued for 6 month with upward seismicity migration by 6 km. An upward migration of overpressurized fluids reduces effective normal stress and weakens the strength of the faults sufficiently to bring the system into the brittle regime under the deviatoric stress. The permeability of the mantle is estimated to be 10^{-15}–10^{-19} m^2.

Keywords: Intraslab earthquakes

Dehydration-driven stress transfer as a mechanism for lower Wadati-Benioff earthquakes

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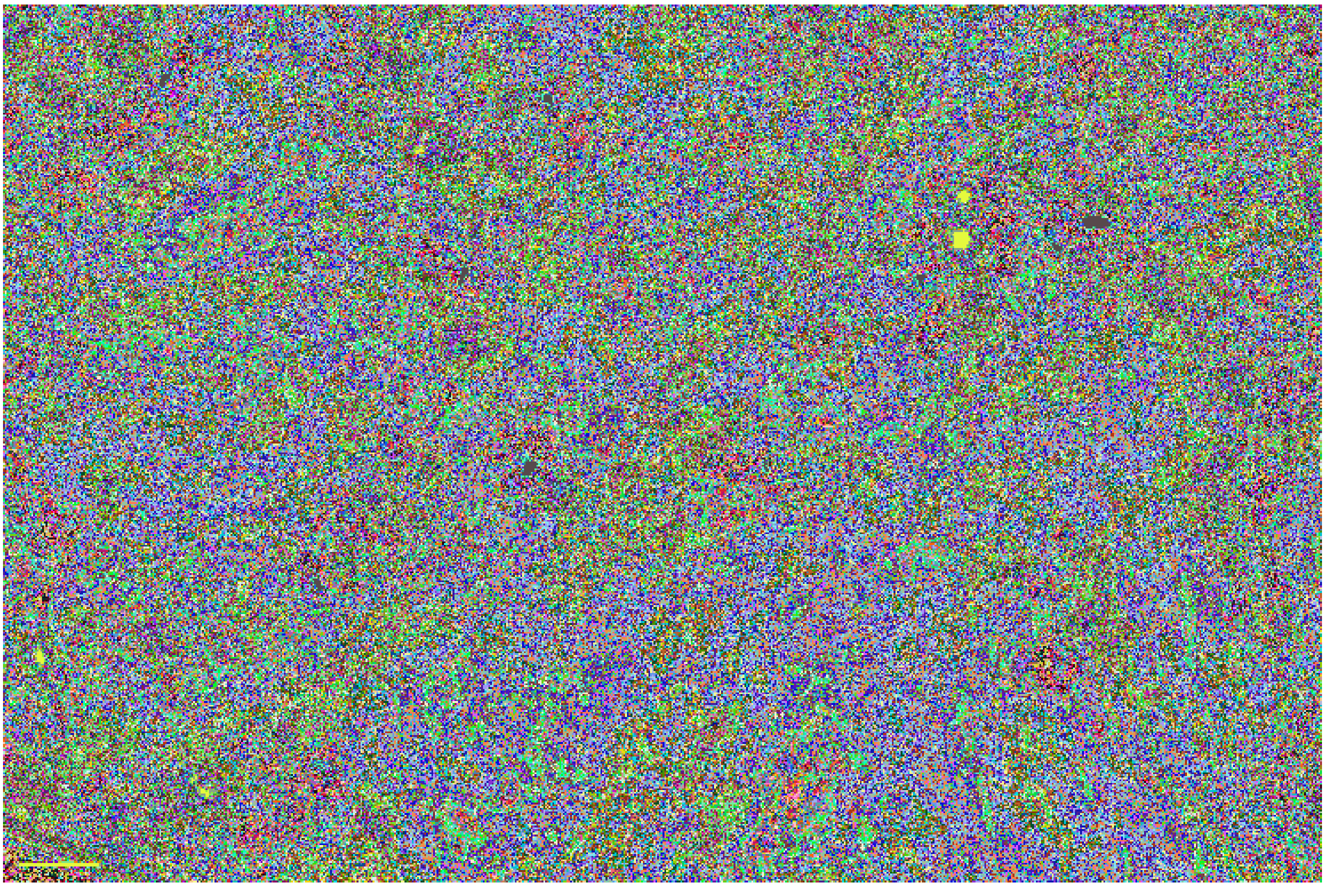
Although extensively documented, intermediate-depth earthquakes (40-400 km) within subducting oceanic slabs remain enigmatic. Here we reconcile more than a decade of apparently contradictory experimental studies on the possible link between these earthquakes and serpentine dehydration. We show that for realistic compositions, antigorite dehydration triggers dynamic embrittlement of sintered olivine-antigorite aggregates deformed at confining pressure and temperature conditions representative of intermediate-depth seismicity (1 to 3.5 GPa, 500 to 800°C). At 1.1 GPa pressure, dehydration of antigorite in volume proportion as low as 5% triggers dynamic shear failure of the olivine load-bearing network. For higher contents, deformation remains silent and distributed. At 3.5 GPa pressure, acoustic emissions are observed for mixtures with up to 50% antigorite. In both cases, dehydration of antigorite proportion as low as 5% is sufficient to trigger analogs of lower Wadati-Benioff earthquakes in the laboratory. Intermediate-depth seismicity could therefore ultimately be seen as an indicator for the degree of hydration in subducting lithospheric mantle.

Keywords: Antigorite, Olivine, Earthquakes, Mantle, Lower Wadati-Benioff Plane, Pseudotachylyte



Semibrittle flow of olivine aggregates under the conditions of subducting slab

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The subduction zone produces a major fraction of the Earth’s seismic activity. The mechanisms of intermediate-depth (> 40 km depth) and deep-focus (> 300 km) earthquakes are fundamentally different from those of shallow (≤ 40 km) earthquakes. This is because the frictional strength of silicate rocks is proportional to the confining pressure and it exceeds the upper limit of the stress level in the upper mantle (< 600 MPa: Obata and Karato, 1995) at pressures higher than 1 GPa (~30 km depth). Furthermore, brittle fracture associating dilatancy is difficult at high pressures. The fracture strength of silicate rocks is much higher than 600 MPa at upper mantle pressures due to the positive pressure dependence of the strength (Masuda et al., 1987). Therefore, the cause of intraslab seismicity at intermediate depths have been attributed to dehydration of serpentinite (i.e., the dehydration embrittlement model: e.g., Peakock, 2001) because the water released during dehydration reaction of serpentinite reduces the effective confining pressure. The dehydration embrittlement model is now widely accepted, because the location of the double seismic zone in the subducting Pacific slab corresponds to the main dehydration field in the pressure-temperature diagram of the hydrous peridotite (Omori et al., 2002). However, a recent experimental study using the techniques of acoustic emission (AE) monitoring and in-situ x-ray diffraction showed that antigorite-rich serpentinite samples produced no detectable AEs in the samples in the course of their dehydration. Another explanation for the origin of intermediate-depth earthquakes is the hypothesis of a periodic shear-heating mechanism (Kelemen & Hirth, 2007). The occurrence of ultramafic pseudotachylite in natural peridotite shear zones supports the validity of the shear-heating mechanism. The hypothesis of a periodic shear-heating mechanism explains the origin of seismicity in the dry upper mantle.
To investigate the origin of intraslab earthquakes at intermediate depths, we conducted uniaxial deformation experiments on anhydrous dunite at pressures 1-3 GPa and temperatures 600-1100 degC with a constant displacement rate using a deformation-DIA apparatus. Pressure, stress, and strain were measured in situ by using x-ray diffraction patterns and radiographies. AEs were also recorded continuously on six sensors, and three-dimensional AE source location were determined.
At temperatures lower than 950 degC, dunite samples tend to develop throughgoing faults. In the regions away from faults, formation of subgrain boundaries and recrystallized grains are frequently observed, showing the dislocation-creep controlled flow. Flow strength was higher than 1 GPa, and a sudden stress drop (1-2 GPa) associated with faulting was observed. AEs were recorded during sampled deformation at strains higher than 1E-4 s^{-1} and at temperatures below 1000 degC. The b-value was in the range of 1.2-4.3 at the primary phase and it decreased to < 1 just before a mainshock. The b-value tends to be higher at higher temperatures. At temperatures higher than 1100 degC, AEs were hardly recorded (i.e., ductile flow). Our results suggests that the brittle-ductile flow may play an important role in the seismicity in the subducting slabs.

Keywords: subducting slab, earthquake, olivine, acoustic emission

Interface and in-slab fragments along the Cyprean arc: a look at final stage of a subduction process

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The scope of this review study is to understand the lateral and depth variations of seismicity along the Cyprean Arc and outline the borders of an inteface and in-slab region along the Cyprean arc. In this respect; 1) the geodynamic evolution of the Bitlis–Hellenic subduction zone is examined, 2) the tomographic images of the subducting African slab are utiliazed 3) correlation between the tomograms and the seismic activity is done 4) differential motions between Cyprus and Anatolia derived from the nearby GPS stations is investiagetd 5) results from wide-angle seismic reflection data along a profile crossing Cyprus island and extending from Eratosthenes Seamount to Central Anatolia is correlated 6) gravite data profiles crossing the western, central and eastern parts of the Cyprus arc are used to trace the interface boundaries and 7) receiver functions derived from the CSS broadband seismic station deployed on the island are used to constrain the depth of the interface.
The seismic activity is not uniform along the subdcuting African plate. Iit terminates at 130-140 km depth along the western flank of the Cyprean arc. However, the seismogenic depth is getting shallower from west to east along the arc. In the central part of the Cyprean arc the seismic activity terminates at about 70 km and the region to the north along the slab no seismic activity is observed. Such a feature in seismicity along with the tomographics images suggest slab steepening, breakoff and slab tear. Westward tear propagation along the Cyprean arc suggested by the geodynamic models might be a causative for the systematic decrease in the depth of seismicity. Both CMT solutions and seismicity provide evidences on NE subduction in the western flank of the Cyprean arc, but no seismic evidences of subduction is present in the central and eastern part of the arc. Constraints from hypocenters, CMT depth, receiver functions, gravity data, wide-angle reflection data, and tomographic images are applied to plot the boundaries of the interfaces and in-slab portion of the slab. The following characteristic features are determined;
1.Break off between the interfaces in the central and western parts of the Cyprean arc
2.No evidances for an interface and in-slab in the eastern part of the arc
3.Interface exist in the central part of the arc
4.No in-slab in the central part of the Cyprean arc
5.Interface and in-slab exist in the western part of the Cyprean arc

Keywords: African plate, subduction , intermediate depth seismicity, slab tear

P-wave attenuation structure and seismicity in the Pacific slab beneath northeastern Japan

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Intermediate-depth earthquakes and arc magmatism in subduction zones are considered to be related to hydrous minerals and aqueous fluids dragged downward with a subducting oceanic plate (e.g., Kirby et al., 1996; Nakajima et al., 2013). The existence of fluid contributes to reduce seismic velocity reduction and enhance seismic attenuation (e.g., Karato, 2003). Therefore, the investigation of heterogeneous structures in the subducting oceanic plate is important to improve our understanding on genesis of intermediate-depth earthquakes.

In northeastern (NE) Japan, low P-wave velocities are observed in the subducting crust at a depths of 100 km (e.g., Shiina et al., 2013) and along the lower plane of the double-seismic zone (e.g., Zhan et al., 2004) at depths of 80-120 km, and they are interpreted as the existence of hydrous minerals and aqueous fluid. Although the fluids are likely to enhance seismic attenuation, detailed seismic attenuation structure of the Pacific slab have not yet been investigated because conventional methods are difficult to separate attenuation properties in the slab from that in the mantle wedge.

In this study, we adopted a spectral ratio technique for intraslab earthquakes beneath NE Japan to directly investigate seismic attenuation in the Pacific slab. By calculating a spectral ratio of velocity spectra for two earthquakes that are observed at common station and have identical ray paths from the shallower earthquake to the station, we obtained a spectrum that represents an intra-earthquakes average attenuation. We evaluated P-wave attenuation in the Pacific slab for 2,954 pairs from 1,135 earthquakes with assuming a source spectrum as w^2-model (Brune, 1970). Then, we estimated 3-D P-wave attenuation structure in the Pacific slab by the tomographic inversion method (Nakajima et al., 2013).

We obtained average P-wave attenuation (Q^{-1}) of 0.0016 in the Pacific slab beneath NE Japan, which is comparable to attenuation estimated in previous studies (e.g., Tsumura et al., 2000). The results show that P-wave attenuation is high near the subducting crust and in some areas beneath the coastline of the Pacific ocean. The high P-wave attenuation areas seems to be located at the upper plane seismic belt (Kita et al., 2006) and around source regions of large earthquakes, such as the 2003 Miyagi-oki intraslab earthquakes (M 7.1). As high attenuation in the subducting slab can be caused by the existence of fluid, these results suggest fluid-related embrittlement of intraslab earthquakes.

Keywords: Seismic attenuation, The Pacific slab, Spectral ratio, Intraslab earthquakes

P-wave tomography of the source zone of the 2015 Bonin deep earthquake

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On 30 May 2015, a distinct deep earthquake occurred to the west of the Ogasawara (Bonin) Islands with a focal depth of 682 km and a magnitude of 8.1 determined the Japan Meteorological Agency (JMA). Such a great deep event is very rare, and it is the deepest large earthquake occurring in Japan during the observational history of the JMA. The 2015 Bonin deep earthquake is an isolated event which is over 100 km deeper than the Wadati-Benioff zone seismicity recorded so far. It is very important to clarify the generating mechanism of this deep event, which will shed new light on the slab structure and subduction dynamics in the Izu-Bonin region.
Seismic tomography is a very powerful tool for investigating the 3-D structure of the Earth’s interior. Usually a dense local seismic network is required to obtain detailed tomographic images of an area. However, there are only a few seismic stations in the Bonin region where the 2015 deep event occurred. Thus, it is hard to image its source zone using the conventional methods of local earthquake tomography or teleseismic tomography. In this work, we have adopted a modified version of the global tomography method (Zhao, 2004, 2009). To express the 3-D seismic velocity structure, a denser 3-D grid with a grid interval of ~50 km is arranged at depths of 0-1000 km beneath the target area including the 2015 Bonin deep event, whereas a coarse grid with a grid interval of ~220 km is arranged in the whole crust and mantle of the Earth. We used over five millions P-wave arrival times of P, pP, PP, PcP and Pdiff waves from 39,323 earthquakes recorded by 9141 seismic stations in the world, which are selected from the ISC-EHB catalogue as well as the Annual Bulletin of Chinese Earthquakes. Thus our target Bonin area is well sampled by the up-going and down-going rays of both the direct P waves and later phases.
Our tomographic results show clearly that the 2015 Bonin deep event took place within the high-velocity subducting Pacific slab which is penetrating down to the lower mantle. In the Izu-Bonin region, the subducting Pacific slab is split roughly at 28 degree north latitude, i.e., slightly north of the hypocenter of the 2015 deep event. In the north, the slab becomes stagnant in the mantle transition zone, whereas in the south, the slab is directly penetrating down to the lower mantle. We have relocated the 2015 Bonin deep event using our 3-D velocity model. The relocated focal depth is 667.3 km with an uncertainty of 0.5 km. Previous study has revealed that the 670 km discontinuity is locally depressed down to more than 690 km depth in the Bonin area. Thus, the 2015 Bonin deep earthquake is certainly located above the upper-lower mantle boundary.
In summary, our results suggest that the generation of the 2015 Bonin deep event was affected by several factors, including the fast deep subduction of the Pacific slab, changes in the stress regime and phase transformation in the slab near the 670 km discontinuity, as well as complex interactions between the subducting slab and the ambient mantle.
References
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Keywords: 2015 Bonin deep earthquake, seismic tomography, Pacific slab

Unusually deep Bonin earthquake (M7.9) of May 30, 2015 near the junction of the northern and southern Bonin slabs

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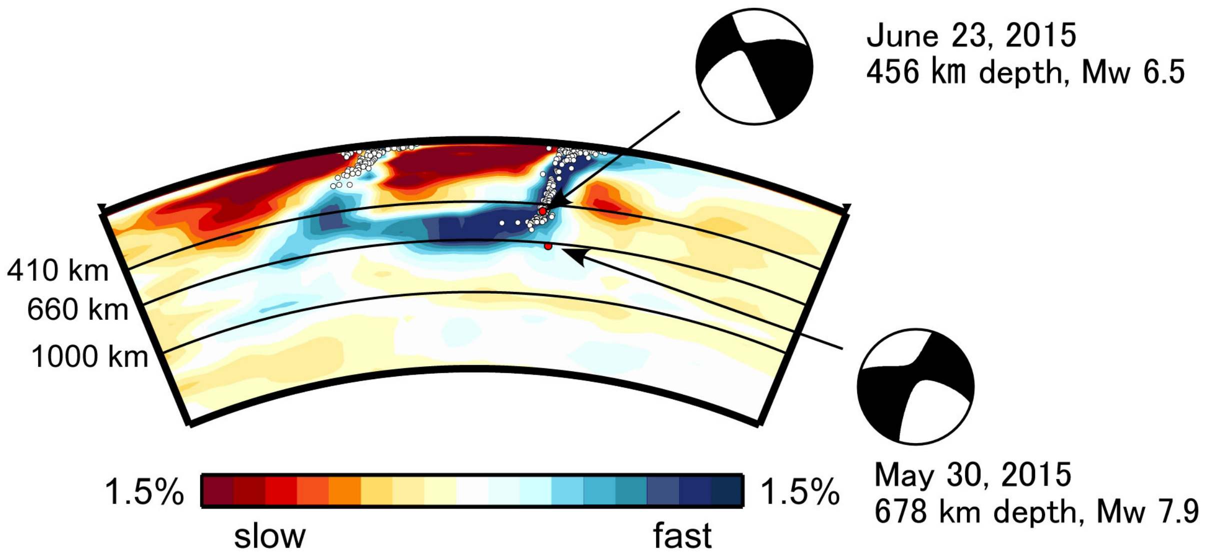
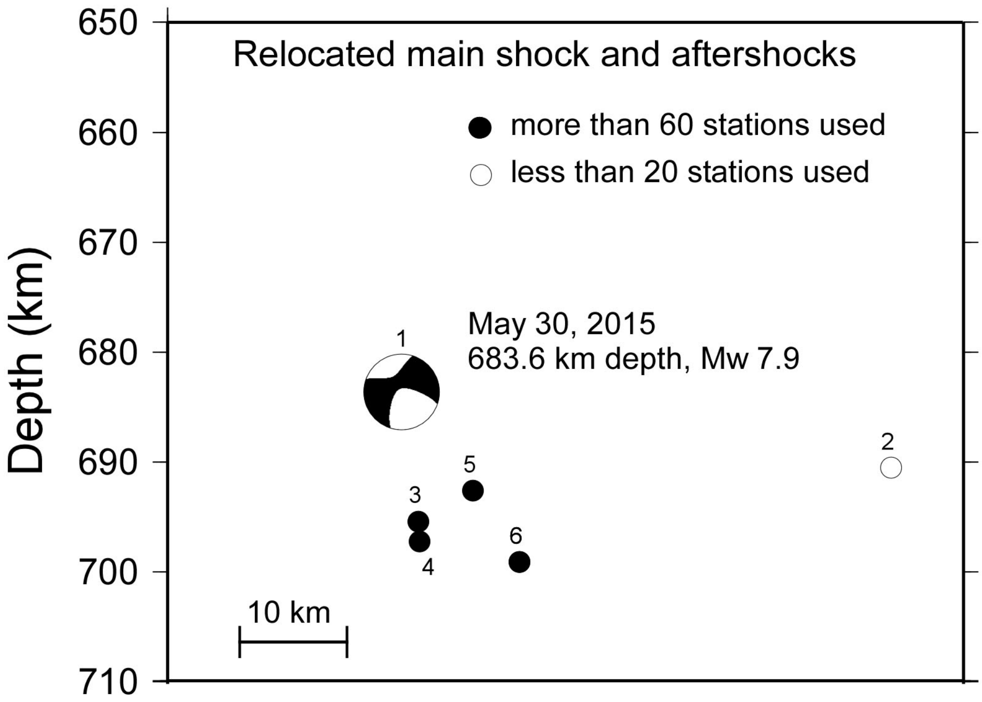
A great shock occurred at an unusual depth of 679.9 km (centroid depth of GCMT) far away from the well-defined Wadati-Benioff zone of the Izu-Bonin arc. To the north of this region the slab is stagnant above the 660-km discontinuity and to the south it penetrates the discontinuity. In this transitional region, the steeply dipping part of the slab bends sharply to horizontal and the great shock happened at the lowest corner of the bent portion. The CMT solution indicates pure normal faulting with the gently-dipping tensional axis and the steeply-dipping compressional axis, both approximately trench-normal. We suggest that this mechanism (Fig.1) reflects the stress environment of the lowest corner of the bent portion of the slab, where the slab is stressed near vertically by the negative buoyancy of the overlying slab and the positive buoyancy due to the phase boundary depression and near horizontally by the sharp bend of the slab upon its encounter to the discontinuity.

Among the reported 5 aftershocks, the first three occurred within 2 hours after the main shock and the remaining two, including the largest event with Mb 4.9 event (2 June 2015), occurred 3 to 5 days after the main shock. We relocated the main shock and aftershocks simultaneously using the absolute P-wave traveltime residuals and the differential travel time residuals between different events at the same stations to constrain the relative locations. The travel time residauls were calculated with respect to the three-dimensional P-wave velocity model GAP_P4 (Obayashi et al., 2013). The depth of the main shock is relocated at 683.6 km. The relocated aftershocks do not lie on ether of the nodal planes of the main shock but in deeper directions roughly along the axis of the principal compressive stress of the main shock (Fig.1). This situation may be compared to such a situation as observed further to the south where the downgoing slab buckles towards the Pacific side before its penetration into the lower mantle. We suggest that the slab portion in the relevant region begins to penetrate the 660, leaving the horizontally bent portion as a seismically inactive stagnant slab.

Because the occurrence of Wadati-Benioff zone earthquakes is fairly stationary in time and space, the resultant stresses give a measure of how stresses in the slab are perturbed by such earthquake occurrence. We calculated the cumulative stress perturbation due to 26 Wadati-Benioff zone earthquakes using their CMT solutions. The cumulative stress perturbation changes rapidly along a trench-normal profile at a depth of 680 km so that only the heel portion of the bent slab is stressed to enhance the occurrence of deep shocks of the type of the 2015 great shock. The occurrences of Wadati-Benioff zone earthquakes and the isolated 2015 great earthquake are mutually cooperative in terms of the resultant stress fields.

Keywords: Bonin Deep Earthquake, Tomography, Subducting slab, Focal mechanism, Aftershock distribution


June 23, 2015
456 km depth, Mw 6.5
410 km
660 km
1000 km
May 30, 2015
678 km depth, Mw 7.9
1.5%
1.5%
slow
fast


Relocated main shock and aftershocks
more than 60 stations used
less than 20 stations used
May 30, 2015
683.6 km depth, Mw 7.9
Depth (km)
650
660
670
680
690
700
710
10 km
1
2
3
4
5
6

A receiver function imaging of the 660-km discontinuity beneath the Ogasawara Islands

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A magnitude-8.1 earthquake occurred on 30 May 2015 at a depth of 681.71 km (determined from Japan Meteorological Agency (JMA)) beneath the Ogasawara Islands. The relative location of the deep earthquake to the 660 km seismic velocity discontinuity (the 660) is an interesting issue, because the 660 is the transition between the upper and lower mantle, and the hypocenter is located at a depth of the lower mantle. Indeed, the undulation of the 660 in the Izu-Bonin subduction zone has been investigated using S-to-P phases converted at the discontinuity (Collier and Helffrich, 1997; Castle and Creager, 1998). Castle and Creager (1998) showed a large depression of the 660, down to 745 km depth, at a distance scale of 2 degrees around the Ogasawara Islands, which is associated with the cold material of the subducting Pacific slab. In the map view, the epicenter of the deep earthquake is located inside the region of the depressed 660, which may imply that the earthquake occurs in the upper mantle. However, to determine a relative spatial location, the depth estimation of the deep earthquake and the 660 using the same velocity model would be necessary. In this study, we convert from the time-domain to depth-domain receiver function (RF) using a 1D JMA velocity model, which was used by JMA to determine hypocenter location of the deep earthquake, and compare their relative depths.
We calculate RFs using teleseismic records observed at two broadband stations, a station OGS in Ocean Hemisphere network Project (OHP) and another station OSW in F-net operated by National Research Institute for Earth and Disaster Prevention (NIED), deployed at the Chichijma Island in the Ogasawara Islands. The separation distance of the two stations is 4.6 km. The teleseismic events that occurred during 2006-2014 and 2005-2014 were used for OGS and OSW, respectively. The total number of the collected RFs is 267 (188 at OGS and 79 at OSW). We applied 0.16 Hz low-pass filter to the time-domain RFs, and converted them to depth-domain RFs using the 1D JMA velocity model.
We could image the depth-variation of the 660 from 660 km to 750 km. Most importantly, we found a RF that shows a peak of P660s, and the Ps converted point at a depth of 660 km of the RF is only ~20-30 km in horizontal distance away from the hypocenter of the deep earthquake, which allows us to compare the relative depths of the deep earthquake and the 660. As a result, is seems that the 660 is deeper than the focal depth at least by 50 km, and this fact indicated that the deep earthquake occurred in the upper mantle, but presumably deeper than the surrounding 660 km discontinuity.
We used seismic records observed by F-net operated by NIED, and thank K. Shiomi for kindly providing us teleseismic event data.

Keywords: receiver function, Ogasawara, 660 km discontinuity

The 30 May 2015 Bonin Deep Earthquake and the 660-km Discontinuity around its Source Region

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We model P and SH waveforms at regional and teleseismic distances from the 30 May 2015 Bonin deep earthquake (depth 664km, Mw7.8; USGS), investigating the rupture propagation and the depth of the 660-km discontinuity. The results suggest that seismic waves from a 660-km discontinuity below the source region cannot be needed. A significant, subhorizontal 660-km discontinuity could not be located below the source region. Seismic waves from the Bonin earthquake were recorded by a number of broadband stations in a wide range of distance around the world, which include many Japanese stations at regional distances. Along with data collected by IRIS DMC, we use data recorded by F-net in Japan. Because high-frequency waves, which could be associated with the descending Pacific slab, were observed in eastern Japan, we use F-net data only from western Japan. The P and SH waves in western Japan have an apparently long duration, consisting of pulses. Because the distance of the stations ranges from 7 to 16 degrees, the 660-km discontinuity may affect the waveforms, depending on its depth. Changing the depth in the velocity model iasp91, we perform waveform inversion for spatiotemporal distribution of moment release on a plane, based on the method of Kuge (2003, 2010). Results from P waves show that the waveform fit becomes worse when the 660km-discontinuity is assumed below the source region. This is consistent with the observation of a simple pulse for P and SH waves from an aftershock.

Teleseismic Peak Ground Accelerations from the 30 May 2015 Bonin Deep Earthquake

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We show that the characteristics of teleseismic peak ground accelerations (PGAs) from the 30 May 2015 Bonin deep earthquake (Mw7.9) are consistent with those of the 2013 Sea of Okhotsk deep earthquake (Mw8.3) and previous large deep earthquakes which were examined by Kuge (2015). PGAs from the Bonin deep earthquake decrease with distance up to 110 degrees, and have a peak at a distance of 150 degrees. PGA values at distances between 40 and 85 degrees are associated with vertical components of direct P waves, and the average values range from 0.37 to 0.90 times the values from the Sea of Okhotsk earthquake. The logarithm of the amplitude decreases by 13% with an increase in distance of 10°, which is smaller, compared to that of the Sea of Okhotsk earthquake (18%). The difference can be attributed to different radiation patterns that affect the decay curves of PGA with distance by changing the amplitude of P waves. The average decay of PGA with distance agrees with the decay of the P-wave amplitude predicted by the ray theory using lower-mantle attenuation in a range between the values predicted by PREM and Hwang and Ritsema (2011). This is consistent with the observations from the Sea of Okhotsk and previous large deep earthquakes (Kuge, 2015). Frequencies characterizing the PGA decay for the Bonin earthquake are between 1.0 and 1.8 Hz, which is similar to the range between 0.8 and 1.8 Hz for the Sea of Okhotsk earthquake. For the Bonin earthquake, we cannot see spatial variations of PGA characterized by the tectonic setting, which was observed for the Sea of Okhotsk earthquakes. This could be because Western Europe and North America, where dominant contrast in PGA was observed, are located near a node of P waves and at distances close to 90 degrees, respectively.

Source time function archive of deep earthquake: re-examination of hierarchy source model

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Rupture evolution process to large earthquake from its initiation is still hot topics in seismology. Many analysis and seismograms of major earthquakes show complexity of source process resulting from heterogeneous slip distribution on source fault and its time history. Smaller earthquake generally shows apparent simple rupture process. As one model to explain source evolution and size relation for smaller and large earthquake, hierarchy model was proposed (e.g. Fukao and Furumoto, 1985). In this study, we review last 20 years broadband seismograms excited by world-wide deep earthquakes and re-evaluate evolution model of rupture process.
Moment rate function of large size earthquake generally shows complexity of rupture process. As for shallow earthquake, body wave inversion are required including realistic earth’s shallow structure model to get source time function. Meanwhile moment rate function of deep earthquake is obtained relative easily and stably using P-wave form. By global seismic network, world-wide deep earthquakes are recorded in homogenous sensitivity and station coverage.
From earthquake catalogue, recent 20 years deep seismic events are searched and applied grouping in hypocenters’ area. From our broadband seismogram data base, we archived P wave waveforms that their magnitude is greater than 4.5. According to attenuation of seismic wave, source duration time of less than 2sec is undetectable. Source time functions of magnitude 5 class events are simple pulse functions. Around magnitude 6 to 6.5 events show also pulse shape function with significant width. Larger quakes than magnitude 6.6 have multiple functions in general and sometimes preceding to initial rupture process. Based on hierarchy model, it seems that an earthquake size locates on step between two hierarchy levels.
Earthquake catalogue shows that each area has apparent magnitude gap in its seismic activity. Now we have searched only last 20 years data, so that final conclusion should be done carefully. However the gap coincides with hierarchy step in some area and the magnitude gap may depend on area in this study. The regionality may be one of parameters that characterize deeply subducting plate, e,g, characteristic scale of heterogeneity in/on plate and occurrence potential of deep earthquake.

Keywords: deep earthquake, source time function, hierarchy model

The mechanics of intermediate and deep focus earthquakes: experimental evidences

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At least part of the subducting slab seismic activity could be triggered by phase transformations and mineral reactions. However, the way mineral reactions can modify the deformation regime of deep rocks, from ductile to brittle (embrittlement) is still poorly understood and remains one of the outstanding unsolved problems of geophysics and rock mechanics.Here, we provide experimental evidence that, under differential stress at high pressure and temperature conditions (3-5GPa/800-1000°C), shear fractures nucleate and propagate at the onset of the olivine -> spinel transition in the Mg_2GeO_4 analogue system. The propagation of these fractures is sufficiently rapid to radiate energy in the form of intense acoustic emissions (AEs). Using a similar set-up, a second set of experiments demonstrates that glaucophane and lawsonite mixtures, two of the principal mineral water carriers in the subducted oceanic crust, undergo dynamic fracture instabilities when deformed within the eclogite field (3GPa/400-800°C). This time, AEs are observed due respectively to the glaucophane breakdown into jadeite and talc under low temperature and lawsonite dehydration under higher temperature. Finally, deformation experiments performed on partially serpentinized peridotites at 2-4GPa, 500-700°C, demonstrate that 5% serpentine in sufficient to trigger dehydration embrittlement of the peridotite body. In this case, low serpentine contents may favor initiation of mechanical failure of the olivine “load bearing” network. In all these three cases, various post-mortem microstructural observations techniques (SEM, TEM, Raman, Microprobe, X-ray tomography) reveals that samples deformed under stress almost systematically present high presure (HP) faulting, to the contrary of samples transformed under isostatic conditions. In addition, AEs correspond to acoustic waves radiated by dynamic HP transformational faulting and follow the Gutenberg-Richter law over sometimes more than 4 orders of moment magnitudes.Put together, our observations provide strong experimental evidence of the role played by mineral reactions on earthquake triggering in mantle conditions, both in the Wadati-Benioff double plane of seismicity and the Earth mantle's transition zone.

Keywords: Phase transformation, Acoustic emission, rheology

