# 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 $^{o}$C (for lawsonite) and 400 $^{o}$C (for antigorite), and constant displacement rates of 0.16 to 0.016 μm/s (corresponding to equivalent strain rates of 8 x$10^{-5}$ to 8 x$10^{-6}$ $s^{-1}$). Samples were first loaded at conditions within the lawsonite/antigorite stability field. Next the temperature was increased to 600 $^{o}$C for lawsonite and 700 $^{o}$C for antigorite at temperature ramping rates of 0.5 to 0.05 $^{o}$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$^{o}$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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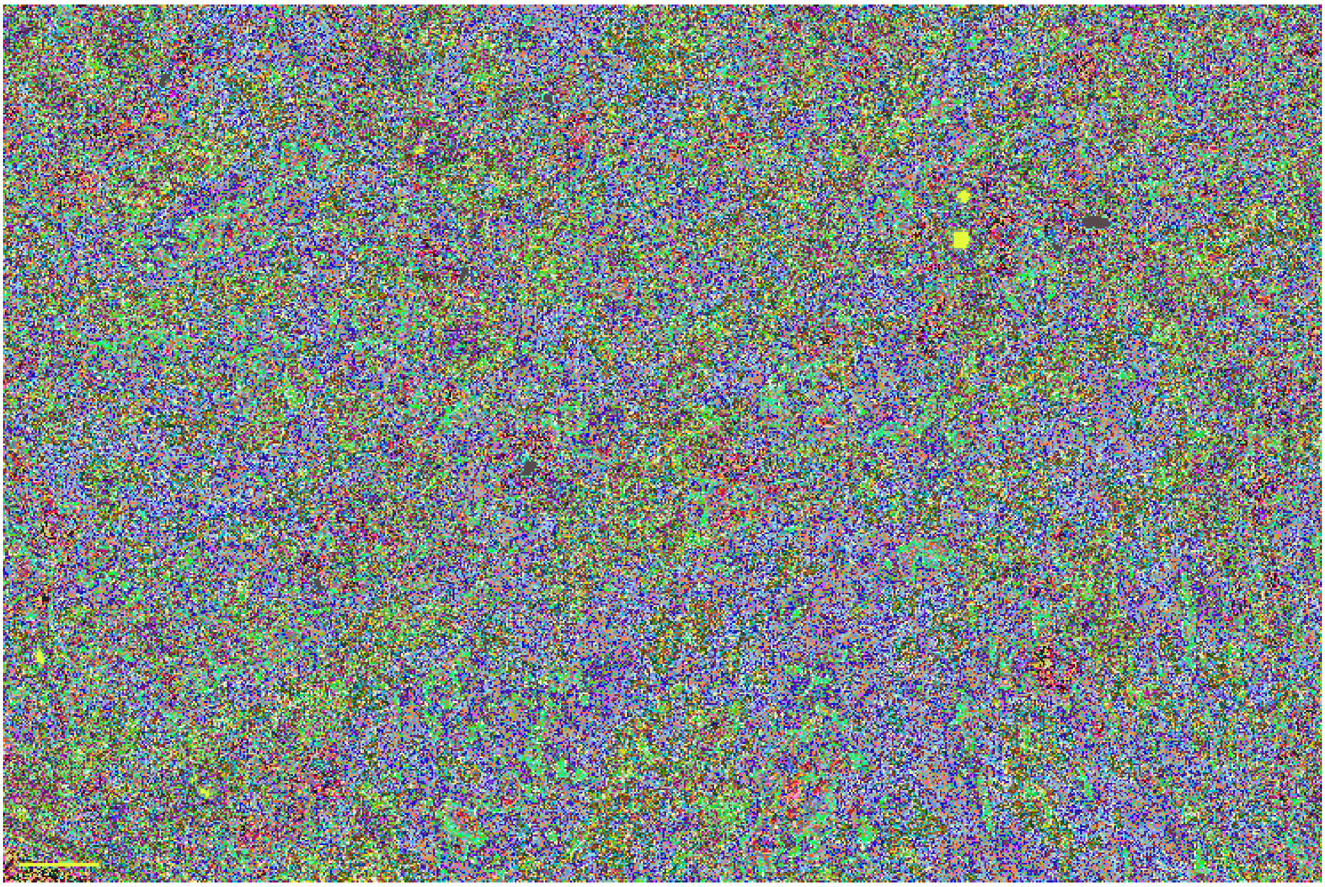
Although extensively documented, intermediate-depth earthquakes (40-400 km) within subducting oceanic slabs remain enigmatic. Here we reconcile more than a decade of apparently contradictory experimental studies on the possible link between these earthquakes and serpentine dehydration. We show that for 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

 