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

*Ali Pinar[1]

1.Bogazici University, Kandilli Observatory and Earthquake Research Institute, Department of Earthquake Engineering, Cengelkoy, Istanbul, Turkey

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

*Takahiro Shiina[1], Junichi Nakajima[2], Toru Matsuzawa[1]

1.Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, 2.Graduate School of Science and Engineering, Tokyo Institute of Technology

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

*Moeto Fujisawa[1], Dapeng Zhao[2], Genti Toyokuni[2]

1.JAPEX, 2.Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University

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.

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Keywords: 2015 Bonin deep earthquake, seismic tomography, Pacific slab

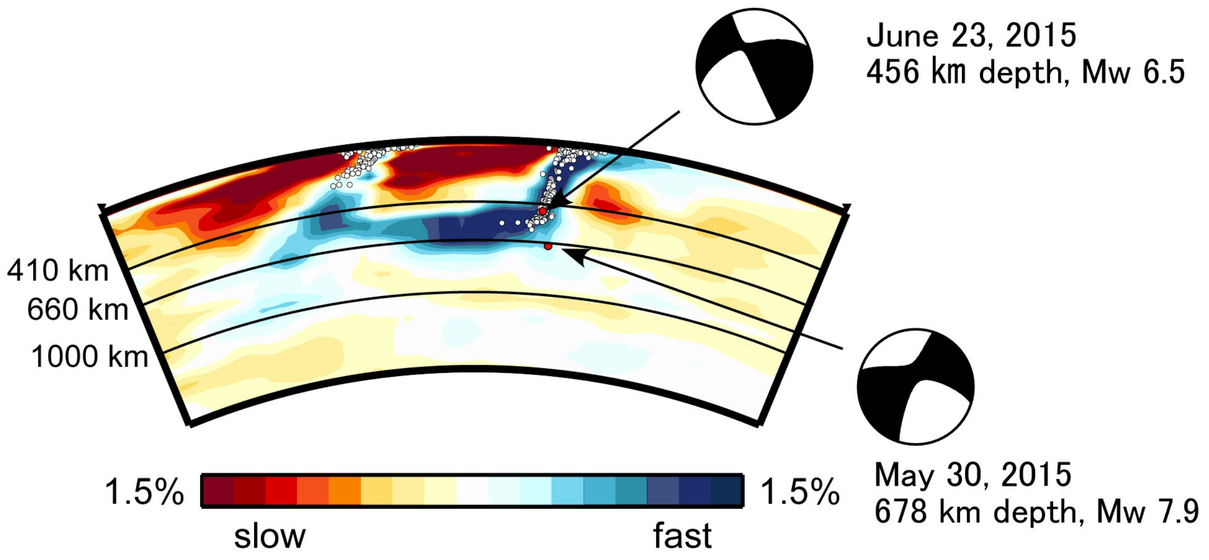
Unusually deep Bonin earthquake (M7.9) of May 30, 2015 near the junction of the northern and southern Bonin slabs

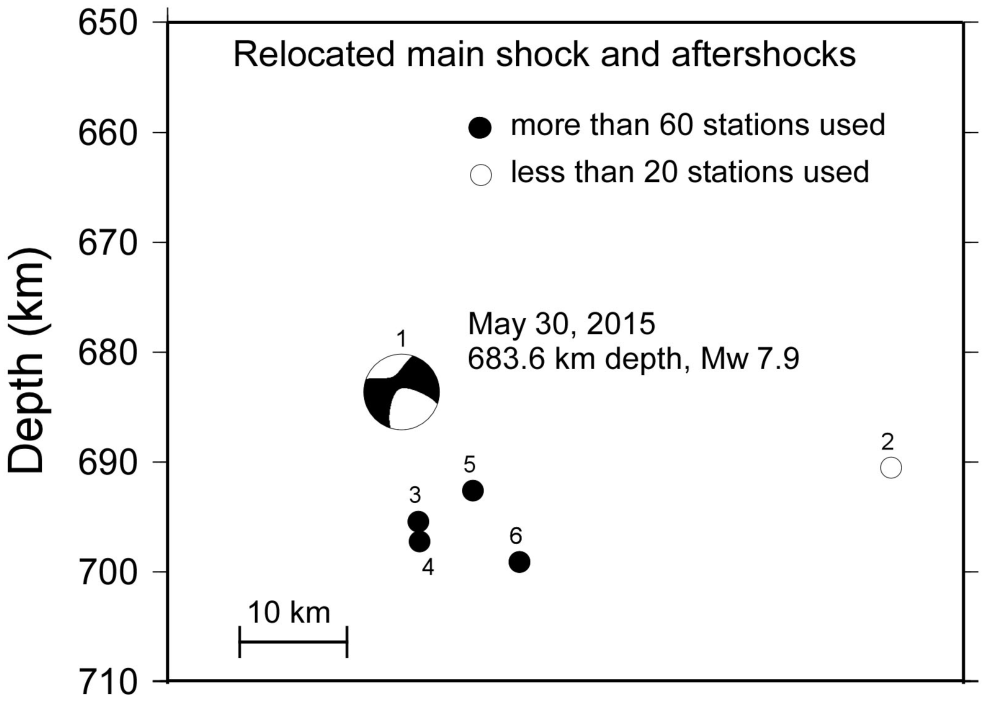
*Masayuki Obayashi[1], Yoshio Fukao[2], Junko Yoshimitsu[1]

1.D-Earth, Japan Agency for Marine-Earth Science and Technology, 2.CEAT, Japan Agency for Marine-Earth Science and Technology

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

*Takashi Tonegawa[1], Yasushi Ishihara[1]

1.Research and Development center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology

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

*Keiko Kuge[1]

1.Department of Geophysics, Graduate School of Science, Kyoto University

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

*Keiko Kuge[1]

1.Department of Geophysics, Graduate School of Science, Kyoto University

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

*Yasushi Ishihara[1]

1.R&D Center for Earthquake and Tsunami, JAMSTEC

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

*Alexandre Schubnel[1], Nadège Hilairet[2], Thomas Ferrand[1], Sarah Incel[1], Julien Gasc[8], Loic Labrousse[7], Fabrice Brunet[6], Joerg Renner[3], Harry W. Green[5], Yanbin Wang[4]

1.Laboratoire de géologie, Ecole Normale Supérieure, Paris, France, 2.UMET, U. Lille, France, 3.Ruhr Universität Bochum, Germany, 4.GSECARS, University of Chicago, USA, 5.UC Riverside, USA, 6.Isterre, U. Joseph Fourier, Grenoble, France, 7.ISTEP, UPMC, Paris, France, 8.Geosciences Montpellier, France

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

