Systematics of intermediate-depth earthquakes: what have we learned recently?

*Geoffrey A Abers[1]

1. Cornell University

Since their discovery by Wadati in the 1920’s the physics responsible for intermediate-depth earthquakes (IDEs) have remained problematic. Common explanations require either dehydration reactions to reduce effective stresses or otherwise weaken subducting plates, or ductile shear instabilities to localize in slab conditions. Despite the seemingly large difference between these two processes it has been difficult to identify clear observations that differentiate them. Several systematics of IDEs are robustly observed, particularly with the advent of high-precision hypocenters from dense networks. IDEs occur almost exclusively in subduction zones where cold and hydrated material descends, and form a plane or planes subparallel to the slab surface. High-precision hypocenters show a primary zone that is 10 km thick or much less –in many cases limited by the accuracy of hypocenters –and generally decrease in abundance with increasing depth. IDEs almost always show double-couple focal mechanisms, often on fault planes at high angles to the seismic zone. They exhibit rupture duration scaling (stress drops) within the range of crustal earthquakes, once shear modulus variations are accounted for. The largest IDEs reach M8 and exceed M7 in many subduction zones, and require rupture on planes of tens of km length to generate the source durations. Thus the conditions for rupture propagation persist outside of the thin regions in which IDEs typically nucleate. Converted-wave studies provide high-resolution information on slab locations independent of the seismicity, and show that IDEs sometimes take place in subducting crust and sometimes in subducting mantle; earthquakes in subducting crust are only seen in cold subduction zones. Analysis of metamorphic reaction systematics suggests that the volume changes associated with dehydration can regulate the occurrence of IDEs, such that IDEs only occur in crust where net volume of fluid produced exceeds the production of porosity (reduction in solid volume). This behavior is evidence that fluid pressure plays an important role in creating IDEs. However, the process remains enigmatic in mantle rocks because serpentine does not exhibit velocity-weakening instability in most conditions. Local maxima in earthquake abundance have been observed beneath well-instrumented volcanic arcs, again indicating a role for metamorphic dehydration, but they are modulated by incoming plate structure in complex ways. The existence double seismic zones indicate that temperature may be most important in the mantle, since many zones lie 25-40 km below the plate interface where hydration is hard to observationally confirm.

Keywords: subduction, wadati-benioff zone, earthquakes

Is serpentine dehydration a viable mechanism for intermediate-depth earthquakes?

*Bruno Reynard[1]

1. CNRS Ecole Normale Superieure de Lyon 69364 Lyon cedex 07 France

Serpentines and magnesian chlorites are major components of ultramafic rocks that interacted with aqueous fluids released at depths in convergent margins. They play an especially important role at subduction interface where the presence of thin layers with high seismic anisotropy suggests intense deformation. Their rheology suggests that they play a role in the brittle to ductile transition by allowing plastic deformation at low temperatures where anhydrous rocks are brittle. When they decompose, the release of aqueous fluids may trigger brittle failure, and coincidence of the lower seismicity plane in double Wadati-Benioff zones with the dehydration temperature of serpentine is taken as good evidence for the validity of this mechanism (Peacock, 2001). I discuss here geophysical evidence in contradiction with this conclusion and potential geophysical observations necessary to resolve this issue.

Peacock, S.M. (2001) Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle? Geology 29, 299-302.

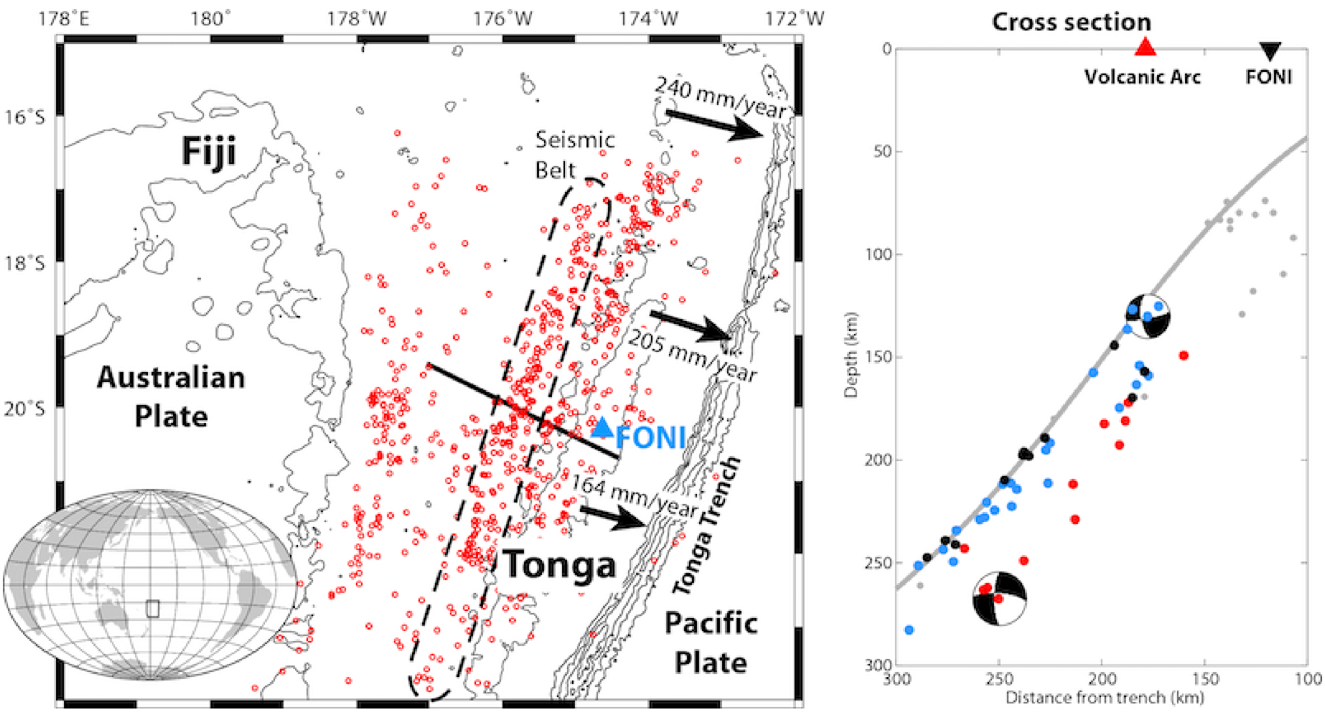
Slab temperature controls on the Tonga double seismic zone and slab mantle dehydration

*Songqiao Shawn Wei[1], Douglas Wiens[2], Peter van Keken[3], Chen Cai[2]

1. Scripps Institution of Oceanography, UC San Diego, 2. Washington University in St. Louis, 3. Carnegie Institution for Science

We present precise hypocenters of intermediate-depth earthquakes in the Tonga subduction zone obtained using data from local island-based, ocean bottom, and global seismographs. The results show a clear double seismic zone, with a downdip compressional upper plane and a downdip tensional lower plane with a separation of about 30 km. The double seismic zone in Tonga extends to about 300 km depth, deeper than in any other subduction system. This is due to the lower slab temperatures resulting from faster subduction, as indicated by a global trend towards deeper double seismic zones in colder slabs. Additionally, a line of high seismicity in the upper plane (“seismic belt”) is observed at 160–280 km depth, which shallows southwards as the convergence rate decreases. Thermal modeling shows that the earthquakes in this seismic belt occur at various pressures but a nearly constant temperature, which highlights the important role of temperature in triggering intermediate-depth earthquakes. This seismic belt may correspond to regions where the subducting mantle first reaches temperatures of ~500°C, implying that metamorphic dehydration of mantle minerals in the slab provides water to enhance faulting.

Keywords: Tonga subduction zone, Double seismic zone, Fluid-related embrittlement, Slab dehydration



Fracturing Behaviors of Unfavorably Oriented Faults Investigated Using an Acoustic Emission Monitor

*Xinglin Lei[1]

1. National Institute of Advanced Industrial Science and Technology

Reactivation of pre-existing unfavourably oriented faults is an important issue in earthquake seismology, particularly in the cases, in which high pressure fluid has a role. Researching of favourably oriented faults provides the lower limiting bound to overpressures, which is a key parameter in the design and management of injection applications. At the same time, unfavourably oriented faults are also important because they are stable and show very low levels of background seismicity under regional stress conditions, but might be reactivated by pore pressure increasing.
In order to shed light on the mechanism and characteristics of the reactivation of unfavourably oriented faults due to natural or man-made stress changes, we investigated the stick-slip behaviour of pre-cut faults having different angles to the greatest principal stress in granite rock samples using an acoustic emission (AE) technique under well-controlled laboratory conditions. The results show that the friction coefficient of a pre-cut fault depends only on its stick-slip history, being independent of fault angle. In all cases, the fault friction drops from ~0.75 to 0.6 after a few stick-slip iterations. Many AE events preceding each stick-slip event were observed. We mapped both on-fault and off-fault microcracks in detail with their AE hypocenters. A tendency toward decreased AE activity was observed. Experimental results suggest that there are two competing mechanisms governing the evolution of the frictional properties and the damage zone characteristics of such faults. On one hand, the fault plane is smoothed by fault slippage as a result of asperities failing on the fault plane and a fault gauge is created. On the other hand, the fault plane is roughened by new damage. As a result, both AE activity and fault friction tend to decrease, but with significant fluctuations.

Keywords: Acoustic emission, Stick-slip, Unfavourably oriented faults, Laboratory experiment

Eclogitization of granulite can trigger instability in deep continental crust: the case of Southern Tibet

Feng Shi[1,4], *Yanbin Wang[1], Tony Yu[1], Lupei Zhu[2], Julien Gasc[3], Junfeng Zhang[4], Zhenmin Jin[4]

1. Center for Advanced Radiation Sources, University of Chicago, 2. Department of Earth and Atmospheric Sciences, Saint Luois University, 3. Laboratoire de Géologie de l'ENS -PSL Research University - UMR8538 du CNRS, 4. State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan)

Intermediate-depth earthquakes (IDEQs) occur at focal depths from about 50 km to 300 km. Their physical mechanism has been enigmatic, because as pressure and temperature increase with depth, brittle failure should be suppressed, and rocks tend to flow plastically. IDEQs have been recorded down to depths of 80 - 100 km in Southern Tibet, where the lower crust is considered hot and dry [1]. It is questionable whether such seismicity can be produced by unassisted brittle shear fracture or frictional sliding. Pseudotachylytes that formed under conditions corresponding to the eclogitic facies are ubiquitously observed in western Norway [2], demonstrating that faulting took place in granulite, which is the main constituent of lower continental crust at pressures approaching 3 GPa. These observations suggest strongly that eclogitization is potentially involved in the seismicity in the deep continental crust. Here we conduct deformation experiments on natural and nominally dry granulite in a deformation-DIA (DDIA) apparatus and Griggs apparatus within the thermal stability fields of both granulite and eclogite, to investigate the mechanism of intermediate earthquake. The D-DIA, installed at the synchrotron beamline of GSECARS, is interfaced with an acoustic emission (AE) monitoring system, allowing in-situ detection of mechanical instability along with the progress of eclogitization based on x-ray diffraction. We found that granulite deformed within its own stability field (< 2 GPa and 1000 C) behaved in a ductile fashion without any AE activity. Unstable fault slip, on the other hand, occurred during deformation of metastable granulite in the eclogite field above 2 GPa. Numerous AE events were observed. Microstructural observation on recovered samples shows conjugated macroscopic faults. Strain is highly localized along the fault, and microcracks observed along grain boundary likely involve with eclogitization products. The fault zones consist of fine-grained (<1 micron) angular fragments likely to be eclogitic phase transformation products. However, no pseudotachylyte has been found in these samples so far. Therefore, we conclude that eclogitization of deforming metastable dry granulite can produce mechanical instability. No formation of pseudotachylytes is required for brittle failure. We suggest that syn-deformational eclogitization of dry granulite may be responsible to the lower crustal seismicity in Southern Tibet.

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Keywords: intermediate-depth earthquakes, lower crust, Southern Tibet, high-pressure deformation, acoustic emission, nano-seismology

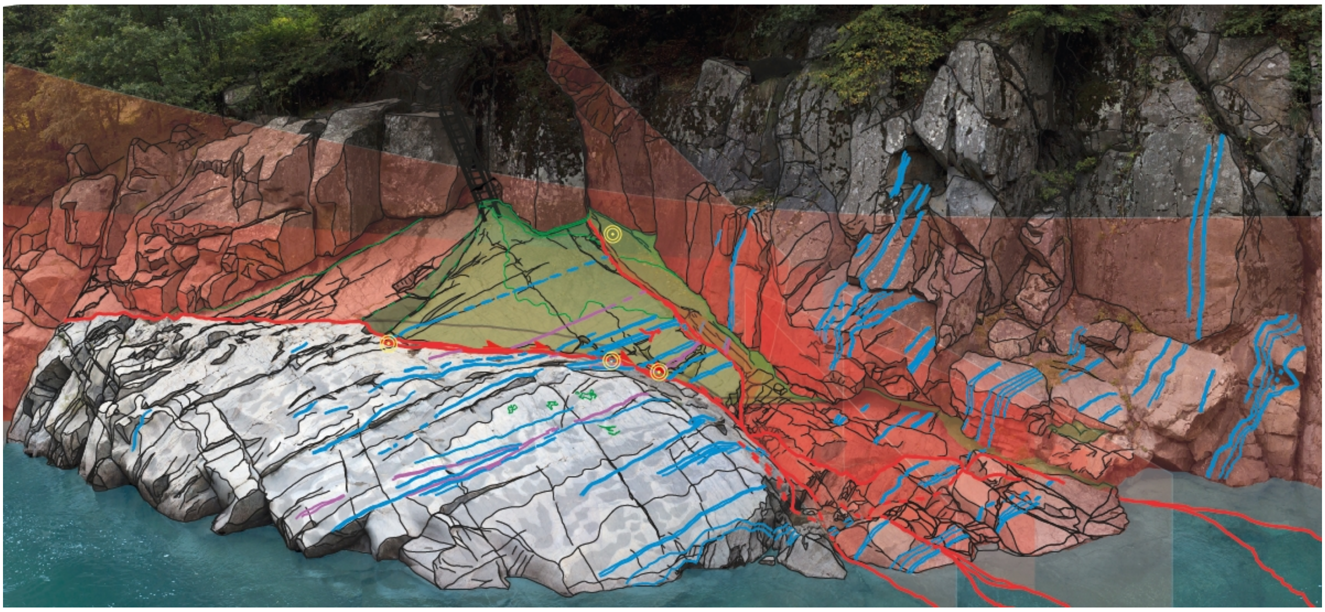
Sliding history and energy budget recorded in a frozen mantle earthquake in Balmuccia, Italian Alps

*Thomas Pascal Ferrand[1], Loïc Labrousse[2], Nadège Hilairet[3], Alexandre Schubnel[1]

1. Laboratoire de Géologie, CNRS UMR 8538, ENS, PSL Research University, Paris, France, 2. ISTeP, CNRS UMR 7193, UPMC, Sorbonne Universités, Paris, France, 3. UMET, CNRS UMR 8207, Univ. Lille 1, Villeneuve d'Ascq, France

In the Balmuccia massif (NW Italy), pseudotachylytes (PST) are found within a spinel lherzolite. Coming from the solidification of the melt generated during seismic rupture, these rocks constitute a geological record of fossilized earthquakes. Here, combining field observations, Raman spectrometry and Electron Back-Scattered Diffraction (EBSD), we decipher the sliding history of an ancient Mw >6 earthquake.
The earthquake fault displays a 1-1.2 m strike-slip component. The average width of the principal fault plane is about 5 mm. A dense network of thin (20-200 μm) faults and injection veins decorates this principal slip surface. Ultramylonitic faults, filled with olivine (0.2-2 μm), pyroxenes and Al-spinel exhibit strong olivine fabric, with (010) planes parallel to the sliding of the fault and [100] direction parallel to the slip direction. The EBSD pole figure for the [100] direction shows an angle of about 40° with respect to Z-axis, indicating a non-negligible dip-slip component of 1.2-1.5 m, i.e. a probable total relative displacement of 1.6-1.9 m. The olivine fabric is consistent with partial melting and/or high temperature (>1250 °C) diffusion-accommodated grain boundary sliding, which proves: 1) that the ultramylonite originates from a recrystallized melt; 2) that the earthquake occurred at a depth greater than 35 km (stable Al-spinel, no plagioclase). Raman spectrometry in micrometric injectites reveals amorphous material, with water content of 1-2 wt%, structurally bounded. Assuming a peak temperature of 1600-1800°C during sliding, the melt viscosity was < 1 Pa s.
Fracture surface energy and thermally dissipated energy are estimated from fracture density and melt volume (including injected volume) around 5.10^4 and 5.10^7 J m^{-2} respectively. Considering a metric displacement, an average melting width of 1 cm and high normal stress, > 1 GPa, this yields a dynamic friction coefficient << 0.1, which demonstrates that complete fault lubrication occurred during co-seismic sliding. We argue however, that lubrication is transient, as the melt could rapidly flow (2-10 m s^{-1}) into tensile fractures. Melt injection within the fracture led to rapid cooling and may have promoted strength recovery and sliding arrest. Post-seismic slip is nevertheless recorded in the main PST axes, which are mylonitized, contrary to the thin fault network. Finally, the finding of water fossilized in a frozen mantle earthquake strongly suggests that fluid and/or hydrous minerals were present and emphasizes the need for a better understanding of their role in the mechanics of earthquakes.

Keywords: Earthquakes, Péridotite, Pseudotachylyte, Intermediate-depth, Mantle, Water



Relation between slab-bending-related hydration and earthquake swarms in subduction zones

*Tomoaki Nishikawa[1], Satoshi Ide[1]

1. Graduate School of Science, Universiy of Tokyo

Slab-bending-related faults and their hydration are known to strongly influence fluid distribution in subduction zones [Worzewski et al., 2011]. Recent studies have shown that slab-bending-related hydration also has a strong influence on seismicity in subduction zones. For example, Ranero et al. [2005] found that intermediate-depth (70—350 km) intraplate earthquakes are especially active in subduction zones with well-developed bending-related faults. Nishikawa and ide [2015] and Shillington et al. [2015] found positive correlations between the curvature of incoming plate before subduction, the pervasiveness of bending-related faults, and the seismicity rate of interplate earthquakes in subduction zones. These correlations suggest that expelled fluid from hydrated bending-related faults reduce the strength of intraplate faults and plate interface, and increase the seismicity rates.

An earthquake swarm, which is an increase in seismicity rate without a clear mainshock and does not follow the Omori’s law [Utsu, 1961], also may be related with slab-bending-related hydration. Poli et al. [2017] found that a spatial clustering of earthquake swarms in central Chile trench shares similar orientation with slab-bending-related faults, and suggested that expelled fluids from hydrated bending-related faults might facilitate earthquake swarms. Therefore, it is also possible that variations in earthquake swarm activity in world’s subduction zones [Holtkamp and Brudzinski, 2011] are related with variations in slab-bending-related hydration. Here we detected earthquake swarms in world’s subduction zones and compared the swarm activity with the curvature of incoming plate before subduction, which is known to correlate with the pervasiveness of slab-bending-related faults and the intensity of slab-bending-related hydration [Faccenda, 2014].

We divided world’s subduction zones into 100 half-overlapping study regions. Each region is bordered by a trench section of about 500 km and extends 200 km in the direction of plate motion [Ide, 2013]. In each region, we extracted earthquakes with M 4.5 during 1995-2009 in the ANSS catalog. We applied the space-time ETAS model [Zhuang et al., 2002] to seismicity in each region and detected anomalous increases in seismicity rates that do not follow the Omori’s law as earthquake swarms. Then, we compared the swarm activity and the curvature of incoming plate before subduction. Here we fitted cubic functions to the topography of outer-rise regions (< 100 km from trench) [Smith and Sandwell 1997] and calculated the curvature of incoming plate before subduction. As a result, we found that the number of swarm events, the number of swarm events per 1-m plate motion, and the ratio of the number of swarm events to all observed events positively correlate with the curvature of incoming plate. The swarm activity is especially high in subduction zones with a large plate curvature and thus strong bending-related hydration.

These results are consistent with the interpretation of Poli et al. [2017]. Expelled fluids from hydrated bending-related faults may facilitate earthquake swarms in subduction zones with a large plate curvature. Furthermore, slow slip events (SSEs), which often trigger earthquake swarms in subduction zones [e.g, Sagiya, 2004], are known to occur in regions with abundant fluid [e.g., Kodaira et al., 2004]. It might be possible that slab-bending-related hydration also has some relation to SSE activity at seismogenic depths in subduction zones. In fact, expelled fluids from hydrated bending-related faults can facilitate decoupling and aseismic slip on the plate interface [Moreno et al. 2014].

Our results reveal the relation between slab-bending-related hydration and earthquake swarm activity in world’s subduction zones. To understand variations in the characteristics of seismicity among world’s subduction zones, it is important to further clarify the role of slab-bending-related hydration in seismicity.

Keywords: Slab-bending-related fault, Earthquake swarm, ETAS model, Hydration, Slow slip, Seismicity

Constraint on the yield strength envelope of subducting oceanic plate from stress neutral surface depth and bending moment

*Ryohei Sasajima[1], Takeo Ito[1]

1. Graduate School of Environmental Studies, Nagoya University

1. Introduction

Many previous studies attempted to estimate the yield strength envelope (brittle strength and ductile flow law) of the oceanic plate from flexural topography and gravity anomalies in outer rise [e.g., Goetze and Evans, 1979; Hunter and Watts, 2016]. Their approaches can constrain the bending moment, which reflects depth-integrated yield strength envelope. Estimated bending moments of world outer rise are consistent with the standard yield strength envelope estimated from rock experiments [Hunter and Watts, 2016].

In addition, recent seismic studies succeeded to constrain stress neutral surface depth (SNSD) in the oceanic plate around the trench and double seismic zone in intermediate depth slab, in few km of precision. The SNSD reflects relative strength between shallower-half brittle part and deeper-half ductile part, while bending moment reflects integrated absolute strength. Thus, combining these two independent observed parameters enables us to constrain the yield strength envelope in more detail, which will contribute to understand rheology, magnitude of stress, and pore-fluid pressure in the oceanic plate and slab.

This study attempted to constrain the yield strength envelope of the oceanic plate around outer rise and intermediate depth slab from observed SNSD and bending moment. The target is the Pacific plate subducting from the Japan Trench and the Kuril Trench.

2. Bending moment

We estimated the bending moment at the outer rise from topography and gravity anomalies following the study of Hunter and Watts [2016]. In addition to their study, we considered the effect of thermal stress on estimating the bending moment. We estimated the bending moment of subducting, intermediate depth slab from gravity anomalies [Sasajima and Ito, 2016, *SSJ fall-meeting*] and corner flow stress in the mantle wedge.

3. Stress neutral surface depth (SNSD)

We used observed SNSD around the Japan Trench that is 30-35 km from the plate upper surface based on Hino *et al*. [2009] and Obana *et al*. [2012]. We used observed SNSDs of intermediate-depth double seismic zone that are 22 km from the slab upper surface under the Tohoku region, and 10 km from the slab upper surface under the Hokkaido region based on Kita *et al*. [2010b].

4. Modeling stress evolution in subducting oceanic plate

In order to connect observed SNSDs and the bending moment to the yield strength envelope, we conducted a model simulation of stress evolution of the oceanic plate. The model describes differential stress of 1D column of the oceanic plate in the Lagrangian description by time integral of elastic stress changing, brittle stress release, and ductile stress relaxation.

The factors controlling SNSD are (1) brittle strength, (2) ductile flow law, (3) thermal structure, and (4) net-horizontal force. We tested to change them within conceivable range and compared the resulting modeled SNSD and bending moment with observed them.

5. Results
Observed SNSD (30-35 km) and bending moment around the trench are explained by standard ductile flow law with moderate pore-fluid pressure for brittle strength. On the other hand, observed SNSD (22 km) at intermediate depth under the Tohoku region requires further higher pore-fluid pressure than around the trench. This is because the compressional brittle strength in the intermediate depth without high pore-fluid pressure is extremely strong and it shifts the SNSD to too shallow. This high pore-fluid pressure in the intermediate depth slab is consistent with many previous studies. On the other hand, much shallower SNSD (10 km) at intermediate depth under the Hokkaido region may be caused by both of relatively low pore-fluid pressure than Tohoku region [Shiina *et al.*, 2017] and extensional net-horizontal force [Kita *et al.*, 2010b].

Keywords: Stress neutral surface depth, Yield strength envelope

Temporal variation of intermediate-depth earthquakes around the time of the M 9.0 Tohoku-oki earthquake

*Brent G Delbridge[1], Saeko Kita[2], Christopher Johnson[1], Naoki Uchida[3], Toru Matsuzawa[3], Roland Bürgmann[1]

1. UC Berkeley, 2. Hiroshima Univ. , 3. Tohoku Univ.

The temporal evolution of intermediate depth seismicity before and after the 2011 M 9.0 Tohoku-oki earthquake reveals interactions between plate interface slip and deformation in the subducting slab. We investigate seismicity rate changes in the upper and lower planes of the double seismic zone beneath northeast Japan using both a beta-statistic approach and a temporal epidemic type aftershock sequence(ETAS) model. We do not observe an anomalous precursory increase in intermediate-depth earthquake activity preceding the mainshock, however, following we observe a rate increase for the intermediate-depth earthquakes in the upper plane. The average ratio of upper plane to lower plane activity and the mean deep aseismic slip rate both increased by factor of two. An increase of down-dip compression in the slab resulting from coseismic and postseismic deformation enhanced seismicity in the upper plane, which is dominated by events accommodating down-dip shortening from plate unbending.

Keywords: intermediate-depth , seismogenesis, intraslab, Tohoku-oki

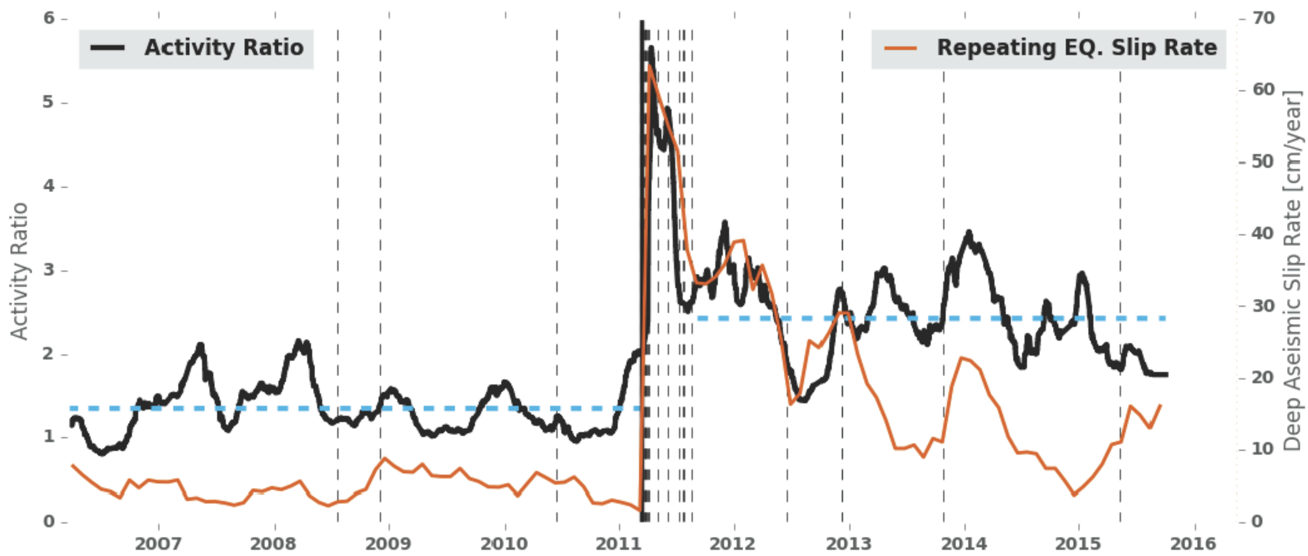


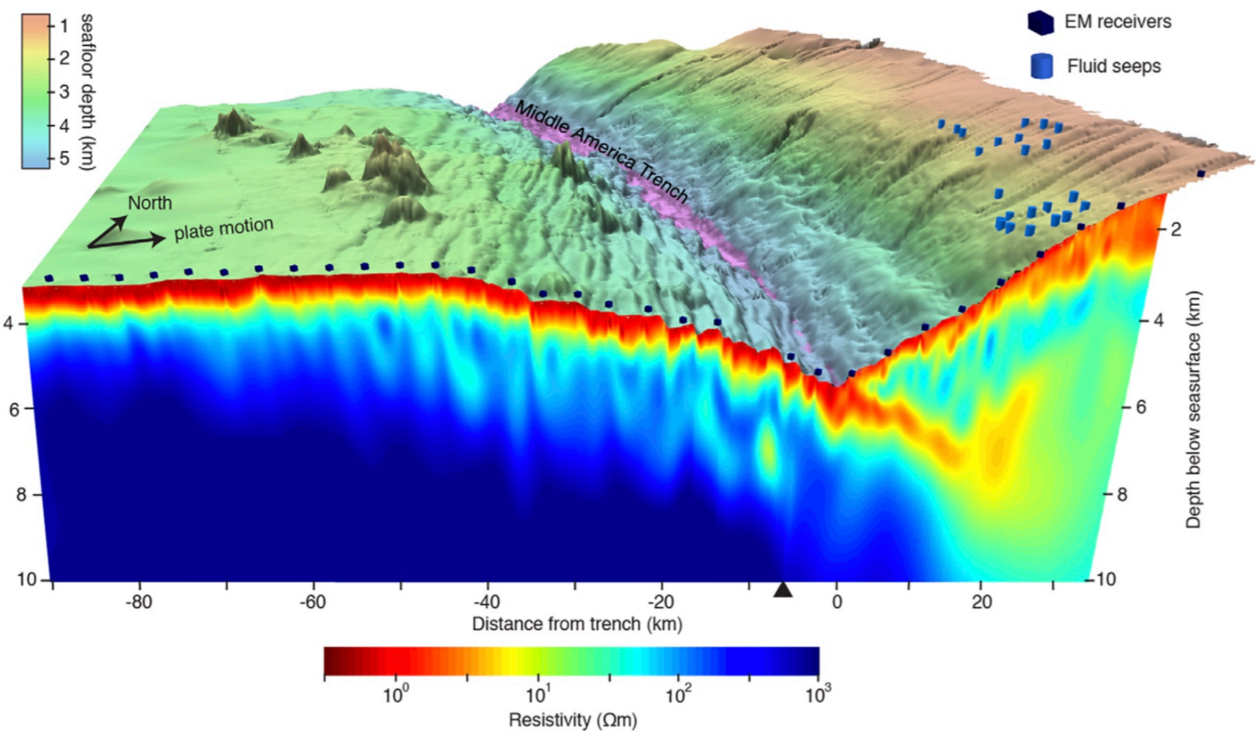
Fig 1. Intermediate-depth earthquake rates near the rupture area of the 2011 M9.0 Tohoku-oki Earthquake estimated from the ETAS model using M>2 events and deep aseismic slip rates. The ratio of the background rates of the upper and lower planes, termed the activity ratio, is shown by the black line. The deep aseismic slip rate estimated from repeating earthquakes is shown by the orange curve. The vertical black dashed lines show the origin times of large magnitude earthquakes (M>6.0). The solid black line shows the time of the M9.0 March 11 Tohoku-oki mainshock.

Controlled-source EM data constrain porosity and fluid budget of the outer rise and forearc slope offshore Nicaragua

*Samer Naif[1], Kerry Key[2], Steven Constable[2], Rob L Evans[3]

1. Lamont Doherty Earth Observatory, 2. Scripps Institution of Oceanography, 3. Woods Hole Oceanographic Institution

Controlled-source electromagnetic (CSEM) soundings provide important constraints on the electrical structure of the uppermost oceanic lithosphere. Since the conductivity signature of porous media is strongly dependent on the presence of saline fluids, CSEM data can be used to quantify porosity. Here, we present results from the Middle America Trench offshore Nicaragua, the first CSEM survey across a subduction margin. The results document the capacity of CSEM observations to image a variety of relevant convergent margin processes, including fluid pathways associated with faulting and subducted sediments along the plate interface. In the outer rise, several sub-vertical conductive channels occur along the trace of bending faults. This suggests localized hydration and the development of a heterogeneous pattern of crustal alteration. Our porosity estimates constrain the fluid budget of the incoming crust, indicating significantly more pore fluids are subducted than previously thought. Seismic implications will be discussed.



Subduction of buoyant oceanic plateaus and intraslab high-angle normal-fault earthquakes

*Ryuta Arai[1], Shuichi Kodaira[1], Tomoaki Yamada[2], Tsutomu Takahashi[1], Seiichi Miura[1], Yoshiyuki Kaneda[3], Azusa Nishizawa[4], Mitsuhiro Oikawa[4]

1. Japan Agency for Marine-Earth Science and Technology, 2. Earthquake Research Institute, University of Tokyo, 3. Kagawa University, 4. Japan Coast Guard

Shallow normal-fault earthquakes at subduction zones usually occur either in the forearc of overriding plates, in the outer rise region of incoming plates or within deeply subducting plates. These normal-fault events are typically induced by plate bending and/or volume reduction (densification) associated with metamorphic dehydration and tend to avoid a source region of megathrust earthquakes along the plate interface at typical seismogenic depths (e.g., 10-30 km). This spatial relationship between reverse-fault and normal-fault events reflects the fundamental stress regime caused by plate subduction and thus seems true for most of the subduction zones worldwide. In that sense, an earthquake sequence that occurred in 1995 in the northern Ryukyu (Nansei-Shoto) subduction zone seems weird. This activity was initiated by the main shock with a moment magnitude of 7.1 and was followed by several large aftershocks with a magnitude greater than 6.0 within 24 hours. Surprisingly, aftershock distributions constrained by ocean bottom seismograph data indicate that conjugate faults with very high dip angles of up to 80° ruptured the subducting slab (Yamada et al., 1997). The source region is characterized by collision/subduction of the Amami Plateau, a large-scale oceanic plateau developed on the incoming Philippine Sea plate. Based on the spatial coincidence, previous studies hypothesized that a subducting seamount in the flank of the Amami Plateau played a role in generating the large intraslab normal-fault earthquakes (Kasahara and Sato, 1997), but fine-scale structural information was necessary to test this hypothesis.

Based on active source seismic imaging, we present structural evidence for large normal-fault events almost vertically intersecting the subducting slab. The seismic reflection images reveal that the plate interface is a few kilometers displaced along one of the faults of 1995 events and that a large seamount with a relative height of 1-2 km is located updip of their source region. These results suggest that a lateral variation in buoyancy force acting on the slab can sufficiently produce an extensional stress regime in a semi-vertical direction leading to large near-vertical normal-fault earthquakes within the subducting plate.

In the study area, another large earthquake with magnitude of around 8 named the Kikai-jima earthquake occurred in 1911. The previous study proposed that this event may have been a shallow interplate earthquake (Goto, 2013), but its potential source region may overlap the regions with large-scale structural heterogeneities along the plate interface including the seamounts and vertical displacements, which are likely to inhibit stress accumulation leading to a high-speed rupture. Alternatively, we point out another possibility that the Kikai-jima earthquake was also a high-angle normal-fault earthquake within the subducting slab similar to the events in 1995.

Keywords: Seamount subduction, Normal-fault earthquakes, MCS reflection

Plate bending-related faulting just prior to subduction and subduction zone seismicity in NE Japan

*Gou Fujie[1], Shuichi Kodaira[1], Koichiro Obana[1], Yuka Kaiho[1], Yojiro Yamamoto[1], Tsutomu Takahashi[1], Tomoaki Yamada[2]

1. Japan Agency for Marine-Earth Science and Technology, 2. Earthquake Research Institute, Univ. of Tokyo

Water transported by the subducting oceanic plate plays key roles in various process in the Earth's interior, including generation of intermediate depth earthquakes. The amount of transported water is accounted for by the hydration of the oceanic plate before subduction. Many factors, such as hydrothermal circulation at the spreading ridge, fracture zones, and the plate bending-related faulting near the subduction trench, can affect the hydration of the oceanic plate. Of these, plate bending-related faulting (hereafter, bending faulting) recently comes to draw attentions because it has a potential to promote the hydration of the oceanic mantle as well as the crust. However, the actual contribution of the bending faulting to the plate hydration is still poorly understood, because it is not easy to separate the contribution of bending faulting from other factors.

In this presentation, we show results from controlled-source seismic survey around a junction of Japan and Kuril trenches. This is a good place to investigate the impact of the bending faulting because the same oceanic plate have experienced different bending faulting at both trenches. We modeled seismic velocities (Vp and Vs) by a traveltime inversion and observed reduction of seismic velocities and increase of Vp/Vs ratio toward trench, suggesting fracturing and water penetration (hydration) caused by the bending faulting. Although the same oceanic plate is subducting into both subduction zones, structural changes are more remarkable in the Japan trench than that in the Kuril trench, suggesting more hydration in the Japan trench than in the Kuril trench. This observation is consistent with the distribution of the dehydration induced intermediate depth earthquakes; intermediate depth earthquakes are much more active in the subduction zone of the Japan Trench than that in the Kuril Trench (Kita et al, 2006). If the difference in the activities of the intermediate depth earthquakes between both trenches is mainly dependent on the hydration of the subducting oceanic plate, the development of the bending faulting is the primary controlling factor on the oceanic plate hydration here.

The difference in the seismic structure changes can be attributed to the difference in the bending faulting. Generally, the bending faulting can be divided into two types dependent on the angle between the strike of the trench axis and the abyssal-hill fabrics, which represents the strike of the ancient ridge axis. When the trench-ridge angle is small (less than about 30 degree), the abyssal-hill fabrics are reactivated as the bending faults, otherwise, bending faults are newly formed crossing the abyssal-hill fabrics (Billen et al., 2007). In the outer slope of the Kuril trench, the abyssal-hill fabrics are reactivated as the bending faults. In contrast, new faults are formed in the outer slope of the Japan trench. Our observations suggest that the trench-ridge angle might be a controlling factor of the plate hydration, at least, in this old plate subduction zone.

Keywords: plate bending-realted faulting, controlled-source seismic survey, hydration

Characteristics of the stress drops for intralslab earthquakes beneath Tohoku and Hokkaido, northeastern Japan

*Saeko Kita[1], Takahiro Shiina[2]

1. School of science, Hiroshima University, 2. Institute of seismology and volcanology, school of science, Hokkaido Univerisity

1. Introduction

Kita and Katsumata [2015] estimated the stress drops of ~2000 small-to-middle magnitude events in the Pacific plate at intermediate-depths and examined the spatial variation of stress drops of them. Some previous studies reported some degree of dependence of the stress drop on the focal mechanism of earthquakes. Kita et al. [2010] revealed that stress regime in the slab beneath Hokkaido is quite different that beneath Tohoku. In order to understand the characteristics of nature of the intermediate-depth intraslab earthquakes and relationship of stress drops and stress field, I examined characteristics of stress drops for ~5000 intraslab earthquakes beneath Tohoku and compared the results with that beneath Hokkaido.

2. Data and method

I adopted method and analysis procedure from Kita and Katsumata [2015, G-cubed]. In the estimation of stress drops of the events, I used corner frequencies of 5094 events from 70 to 200 km (August 2003 to July 2014) estimated by S-coda wave spectrum ratio method [e.g., Mayeda et al., 2007].

3. Results and Discussion

The stress drops of events generally increased with depth at depths of 70 to 200 km, which corresponds to results beneath Hokkaido. In the oceanic crust, we also found a decrease of median stress drops at depths of 70 to 110 km (6.8 to 3.6 MPa) and an increase with depth at depths of 110 to 170 km (3.6 to 8.6 Mpa). This depth variation also corresponds to that beneath Hokkaido. Depth change of rigidities due to eclogite-forming phase change with dehydration causes the depth variation of stress drops in the oceanic crust. At the depth of 70 to 170 km, median stress drops for events in the oceanic crust (3.6 to 8.6 MPa) are smaller than those in the oceanic mantle (7.2 to 13 Mpa). Differences of rigidities and/or rupture mechanisms of events could induce the difference between the stress drops of events in the oceanic crust and those in the oceanic mantle. In the oceanic mantle, median stress drops of events between the double seismic planes, which yields downdip compression stress field, is larger than those of the lower plane event, which yield downdip tension. This characteristics beneath Tohoku is different from that beneath Hokkaido, which implies that difference of stress field could cause the difference of the stress drops.

Keywords: Intraslab earthquakes, stress drops, Dehydration due to the eclogite formation process in MORB, Stress field in the subducting slab

Mechanisms and distribution of deep Earthquakes in the subducting Pacific slab beneath Japan

*Ayako Tsuchiyama[1], Junichi Nakajima[1], Toru Matsuzawa[2]

1. Tokyo Institute of Technology, 2. Tohoku University

The number of earthquakes in slabs decreases with depth to a depth of ~300 km, but increases again around a depth range of 400–500 km. The mechanism of this phenomenon has not been understood, even though many hypotheses for the origins of deep earthquakes have been proposed, which include dehydration-embrittlement hypothesis, shear instability and transformational faulting. In this study, we selected 93 deep earthquakes (M3.0) that occurred at depths of >300 km beneath Tokai area in Japan and analyzed waveform data to understand factors that control the high seismic activity in the mantle transition zone.
First, we read P-wave polarities and determined focal mechanism solutions of the earthquakes. Next, we relocated hypocenters by using picked arrival times of both P and S waves with double-difference earthquake relocation algorithm (Waldhauser and Ellsworth, 2000). The relocated hypocenters did not show a double-planed seismicity as that observed in Iidaka and Furukawa (1994). In the next step, we will relocate the earthquakes with differential travel-time data derived from waveform cross correlations to constrain hypocenter locations with much higher accuracy. We will present detailed hypocenter distributions together with focal mechanism solutions, and discuss a plausible mechanism that facilitates deep earthquakes in the mantle transition zone.

Keywords: deep earthquake, slab

Relation of seismicity with age in stable oceanic plates and its implication for the mechanism of intraplate earthquakes

*Kazuya Ueyama[1], Yukitoshi Fukahata[1]

1. Disaster Prevention Research Institute, Kyoto University

It is considered that the main cause of oceanic intraplate earthquakes is thermal stress due to plate cooling. Thermal stress increases with age of an oceanic plate. On the other hand, it is shown that seismicity in oceanic plates tends to decrease with age until 40 Ma (e.g., Wiens and Stein, 1983). In this research, we investigated the seismicity in stable oceanic plates to reveal this apparent contradiction.
We used the seismic data catalog provided by IRIS (Incorporated Research Institutions for Seismology). Earthquakes that happened in stable oceanic plates are plotted on a world-wide map with the seafloor age, and counted the number of seismic events for each age range. In this analysis, we removed the earthquakes which occurred in tectonically active regions, such as near plate boundaries, marginal seas, Arctic sea, and the hotspot in Hawaii. In order to remove the effect of the difference of areas in oceanic ages, we normalized the number of events by the area of the analyzed region for each age range.
As a result, we found that seismicity in stable oceanic plates decreased with the seafloor age until 50 Ma, which was consistent with the result of previous studies. This result suggests that not the absolute value of thermal stress but the change of it mainly controls the seismicity. We also investigated the difference of seismicity in areas (the Pacific, Indian, and Atlantic oceans), and found that the seismicity was the highest in the Atlantic ocean, where the spreading rate is the slowest, and the seismicity was the lowest in the Pacific ocean, where the spreading rate is the fastest. The difference in the accumulation rate of elastic strain in the direction parallel to the ridge axis would be the cause of this difference.

Keywords: oceanic intraplate earthquakes, thermal stress, oceanic sea floor age

The depth variations in seismic velocity and intermediate-depth seismicity in the subducting crust of the Pacific slab

*Takahiro Shiina[1], Junichi Nakajima[2], Toru Matsuzawa[3], Genti Toyokuni[3], Saeko Kita[4]

1. Institute of Seismology and Volcanology, Graduate School of Science, Hokkaido University, 2. Graduate School of Science and Engineering, Tokyo Institute of Technology, 3. Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, 4. Graduate School of Science, Hiroshima University

It is well known that active and localized seismicity called as the double seismic zone (e.g., Hasegawa et al., 1978) occurs in the Pacific slab. Additionally, Kita et al. (2006) discovered a concentrated seismicity at depths of 70-100 km associated with the upper plane of the double seismic zone in the Pacific slab beneath northeastern Honshu and Hokkaido, Japan. Dehydrated fluids from hydrous minerals in the subducting oceanic lithosphere are considered to play significant roles in these seismic activity in the slab (e.g., Kriby et al., 1996; Okazaki and Hirth, 2016). Therefore, revealing the dehydration depths of the hydrous minerals and presences of the dehydrated fluids would help us to understand seismogenesis of the intraslab earthquakes in detailed.
In this study, we investigated seismic velocity in the subducting crust located at the uppermost part of the Pacific slab beneath eastern Hokkaido, northern Japan, in order to reveal the distributions of fluids in the crust. At the eastern Hokkaido, guided waves propagating in the low-velocity subducting crust were often observed (Abers, 2005; Shiina et al., 2014). The guided waves are sensitive to the crustal heterogeneity because they propagate over a long distance in the crust. Thus, analyzing the guided waves could estimate seismic velocity in the crust with high accuracy. After we identified the guided-P and guided-S waves and visually picked those arrival times, we calculated Vp and Vs in the crust by using travel time differences of the guided waves and inter-event distances, as carried out by Shiina et al. (2014). In this study, 286 and 208 earthquake pairs for the guided-P and guided-S waves, respectively, are obtained from 315 intraslab earthquakes that occurred during from 2003 to 2011.
The obtained results show that Vp of 6.5-7.5 km/s and Vs of 3.6-4.2 km/s in the subducting crust at depths of 50-100 km beneath eastern Hokkaido. The Vp and Vs at depth of 50-70 km mark 6.5-6.8 km/s and 3.6-3.8 km/s, respectively, which are 10-15 % lower than those expected for the fully hydrated MORB materials (e.g., Kimura and Nakajima, 2014). The reductions in seismic velocity suggest that fluids of ~1 vol% are channeled in the subducting crust with the hydrous minerals beneath eastern Hokkaido, as well as beneath Tohoku, northeastern Honshu, Japan (Shiina et al., 2013).
At depths of ~80 km, on the other hand, increases in the Vp and Vs comparable to that values expected for the hydrated MORB (e.g., Kimura and Nakajima, 2014) are observed. The Vp of ~7.3-7.5 km/s at depths of 80-100 km is about 0.5 km/s faster than that estimated in Tohoku (Shiina et al., 2013). A straightforward interpretation for the regional variations in Vp, we consider that the change in the velocity would be proportional to the amount of fluids channeled in the crust. In this interpretation, the lower Vp in Tohoku implies that larger amount of fluids is trapped in the crust at the depths compare to that in eastern Hokkaido. According to Kita et al. (2006), crustal earthquakes that occurred at the depths of 80-100 km are more active in Tohoku than in eastern Hokkaido. These correlations between the seismic velocity and seismicity in the subducting crust suggest that the amount of fluids channeled in the crust closely links to the facilitation for activity of the crustal earthquakes at intermediate depths.

Keywords: oceanic crust, intermediate-depth earthquakes, fluid-related embrittlement, later phase

Experimental investigation of dehydration weakening and embrittlement of antigorite serpentinite and possible mechanisms to induce various fault slip behaviors in subduction zones

*Keishi Okazaki[1,2], Greg Hirth[2], Ikuo Katayama[3]

1. Japan Agency for Marine-Earth Science and Technology, 2. Brown University, 3. Hiroshima University

The frictional behavior of phyllosilicates dramatically changes during dehydration reaction due to phase change of minerals and increasing of pore fluid pressure. Especially, the presence of serpentinite has stimulated interest in their relationship to various slip behaviors in subduction zones such as regular/slow earthquake and creep along plate boundaries and intermediate-depth earthquakes within subducting slabs.
Recent high-pressure deformation experiments using Griggs apparatus and D-DIA on antigorite serpentinite at mantle conditions show a stable sliding with shear localization without acoustic emission (Proctor and Hirth 2016; Okazaki and Hirth 2016), while temperature ramping experiments on antigorite show dramatic weakening during dehydration reactions due to the build-up of the pore fluid pressure (Proctor and Hirth 2015). The weakening rate during the dehydration reaction is controlled by the temperature ramping rate and the strain rate. In contrast, low-pressure friction experiments on antigorite serpentinite under hydrothermal conditions demonstrated that slip behavior of antigorite varies from stable sliding to unstable stick-slip via slow stick-slip with increasing temperature (Okazaki and Katayama 2015).
We analyzed fault stabilities at natural and laboratory conditions assuming a spring-slider configuration based on the dehydration kinetics, the far field (i.e., the load point) sliding velocity, the pressure and the temperature with various stiffness values. Initial result indicates that the fault is more unstable if the dehydration reaction occurs at higher temperature and solid pressure-medium apparatuses (Griggs apparatus) is too stiff to induce an unstable slip by the dehydration weakening. Generally solid pressure-medium apparatuses tend to have very high stiffness to compare with the apparent stiffness of natural fault zones (orders of kPa/mm to MPa/mm). Such high stiffness may inhibit unstable slips in dehydrating antigorite layer in laboratories, while we need to conduct further analysis to evaluate whether dehydration weakening and embrittlement really induce seismicity in natural fault zones especially within the subducting slabs.

Keywords: subduction zone, dehydration embrittlement, serpentinite

Shear localization in peridotites and the occurrence of intermediate-depth earthquakes

*Tomohiro Ohuchi[1], Xinglin Lei[2], Hiroaki Ohfuji[1], Yuji Higo[3], Yoshinori Tange[3], Takeshi Sakai[1], Kiyoshi Fujino[1], Tetsuo Irifune[1,4]

1. Geodynamics Research Center, Ehime University, 2. National Institute of Advanced Industrial Science and Technology, 3. Japan Synchrotron Radiation Research Institute, 4. Earth-Life Science Institute, Tokyo Institute of Technology

The subduction zone produces a major fraction of the Earth’s seismic activity. The mechanisms of intermediate-depth and deep-focus earthquakes are fundamentally different from those of shallow earthquakes. This is because the frictional strength (and also fracture strength) of rocks exceeds the upper limit of the stress level in the upper mantle (< 600 MPa: Obata and Karato, 1995) at depths greater than 30 km. The cause of intermediate-depth intraslab seismicity have been attributed to dehydration of antigorite (Peakock, 2001) and lawsonite (Okazaki and Hirth, 2016), because the location of the double seismic zone in a slab corresponds to the pressure-temperature conditions for breakdown of these hydrous minerals (Omori et al., 2002). However, dehydration embrittlement has been reported at a unrealistically high stress (> 1 GPa) and does not account for the origin of earthquakes in the hydrous-mineral absent regions, such as ~40 km depth below the palaeo-sea floor and the lower seismic plane (Reynard et al., 2010). The effect of hydrous mineral breakdown on failure is questionable because microcracking does not occur through the dehydration of antigorite (Gasc et al., 2011). Therefore, we focus on the hypothesis of intermediate-depth earthquakes triggered by localized heating (Kelemen and Hirth, 2007).

To investigate the origin of intraslab earthquakes at intermediate depths, we conducted uniaxial deformation experiments on dry dunite and wet harzburgite at pressures from 1.0–2.6 GPa and temperatures from 860–1350 K with a constant displacement rate using a deformation-DIA apparatus. The dry dunite and wet harzburgite correspond to the strongest and the weakest peridotites, respectively. Wet harzburgite is the final form of the dehydration product of antigorite and the main constituent of the double seismic zone. Pressure, stress, and strain were measured in situ by using x-ray diffraction patterns and radiographies. Acoustic emissions (AEs) were also recorded continuously on six sensors, and three-dimensional AE source location were determined.

We observed the proceeding of plastic deformation followed by faulting accompanied by significant increments of AEs at temperatures lower than 950 degC. Flow strength was higher than 1 GPa in dry dunite but that was significantly low (down to 0.3 GPa). A sudden stress drop (up to 2 GPa) associated with faulting was observed. The throughgoing faults associated ultrafine-grained (10 nm) gouge layers in dunite and harzburgite samples. In the regions away from faults, formation of subgrain boundaries and recrystallized grains are frequently observed, showing the dislocation-creep controlled flow. AEs were recorded during sampled deformation at strains higher than 1E-4 s^{-1} and at temperatures below 1000 degC. Strain weakening was commonly observed due to grain size reduction, and strain weakening caused strain localization. The b-value was around 1 at the primary phase and it decreased to < 1 just before a mainshock (at < 950 degC). The b-values were anomalously high (between 3 and 6) at 1000 degC, and any AE ceased at temperatures higher than 1100 degC. Our results suggests that the seismicity is strongly related with temperature in the subducting slabs.

Keywords: intermediate-depth earthquake, harzburgite, shear localization, faulting

Study of deformation mechanism(s) of sandstones by parallel AE signal measurement and neutron diffraction technique

*Jun Abe[1], Kotaro Sekine[2], Harjo Stefanus[3], Takuro Kawasaki[3], Kazuya Aizawa[3]

1. Comprehensive Research Organization for Science and Society, 2. Japan Oil, Gas and Metal National Corporation, 3. Japan Atomic Energy Agency

Understanding the mechanical behavior of rock materials is essential if we are to utilize an underground environment as storage space (e.g., geological isolation of high-level nuclear waste). The macroscopic strain of rock samples may be associated with strains accumulated in mineral grains and a structural change caused by slip of mineral grains and /or crack initiation. Neutron diffraction technique can evaluate the lattice strain of crystal grains. AE (Acoustic Emission) signal measurements are useful way to identify dynamic phenomena, such as mineral grain slip and crack initiation. Therefore, to investigate deformation mechanism(s) of rock materials under uniaxial compression, measurements of neutron diffraction patterns have been undertaken in parallel with measurements of AE signal.

In situ neutron diffraction measurements were undertaken using the Engineering Materials Diffractometer “TAKUMI” at J-PARC (Japan Proton Accelerator Research Complex). AE signals were measured using a PCI-2 (PHYSICAL ACOUSTIC CORP.). Three types of sandstone were tested: Berea, Tomita, and Izumi. Macroscopic strain values were recorded using a strain gauge.

The macroscopic strain of each sandstone was larger than the lattice strain. The macroscopic strain exhibited plastic deformation behavior, whereas the lattice strain exhibited elastic deformation behavior. AE signals were detected as the applied load was increased. These AE events might be related to internal structural changes. These dynamic phenomena may also explain the discrepancy between the macroscopic and lattice strain values. The characteristics of the measured AE signals varied with rock type, indicating that the deformation mechanism is a function of rock type.

In this presentation, I will provide further details of the experimental methods and present some of the more interesting data obtained from these measurements.

Keywords: neutron diffraction, acoustic emission, rock, strain

Shear deformation experiments of two-phase aggregates of antigorite and olivine at high pressure: A preliminary study

*Mai Ikehara[1], Tomoaki Kubo[1]

1. Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University

Intermediate-depth earthquakes are observed to occur within subducting slabs at depths of about 60-300 km where most rocks exhibit plastic deformation rather than brittle failure, owing to high pressures and temperatures. Dehydration embrittlement of hydrous minerals, particularly antigorite serpentine, is one of the most popular hypotheses for explaining shear instability under such conditions (e.g., Raleigh and Paterson, 1965). Although there have been many experimental studies on this topic, the direct relationship between seismicity and serpentine dehydration remains unclear at high pressure conditions. Previous deformation experiments have often been conducted on a single-phase antigorite in axial compression at relatively low pressures (<2 GPa). However, it is also important to investigate effects of shear deformation on partially hydrated rocks at higher pressures for discussing intermediate-depth earthquakes. In this study, we are conducting shear deformation experiments on two-phase aggregates of antigorite and olivine, considering partially serpentinized peridotites within subducting slabs, in order to constrain how faults could be formed under high pressures and temperatures in the laboratory. Here we report preliminary results of these experiments.

High-pressure deformation experiments were conducted within antigorite stability field using a Deformation-DIA apparatus. We used a powder mixture of antigorite and olivine (3:7 in vol.) as a starting material. Firstly, the starting powder was compressed to 5 GPa at room temperature and, annealed at 400 ℃ for 1 h. The hot-pressed sample was recovered and cut into disks having thickness of 300 μm. The sintered disk was used for a shear deformation study by being assembled between two 45°-cut alumina pistons. In shear deformation experiments, the starting disk was annealed in the same steps (i.e., at 5 GPa and 400 ℃ for 1 h), and then deformed with an anvil displacement rate of 200 μm/h. Microstructures of the recovered samples were examined by an optical microscope and a scanning electron microscope. We also observed microstructures of a sample recovered just before the shear deformation and a sample deformed in uniaxial compression for comparison.

The sample deformed in shear showed brittle-plastic transitional microstructures and regional variations in shear strain (γ = 1.7-3.8), and has a through-going crack. A shear zone was formed in the middle of the entire sample along the crack, in which the plastic deformation of antigorite was significant. Whereas in small shear-strain regions, brittle failures within the olivine crystals were evident. This was also observed in the sample recovered just before the deformation stage (γ = 0.8), which indicates the brittle texture could be developed during the cold compression stage. Olivine also deformed plastically when shear strain was accommodated and localized during the deformation stage. On the other hand, the sample deformed in uniaxial compression (ε = 0.16) had a similar texture as observed in the small shear-strain regions, and the shear localization was not developed. Thus, the two-phase aggregates deformed in large shear strains showed unique microstructures involving shear zones and faults, which may provide important insights into shear instability at high pressure.

Keywords: intermediate-depth earthquakes, shear deformation, antigorite, olivine

