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

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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?

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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

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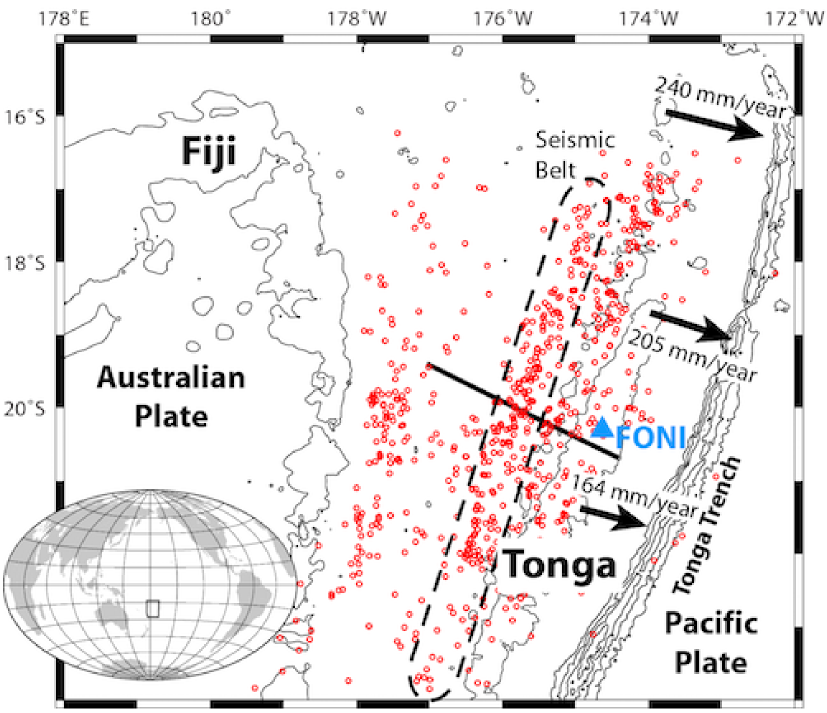
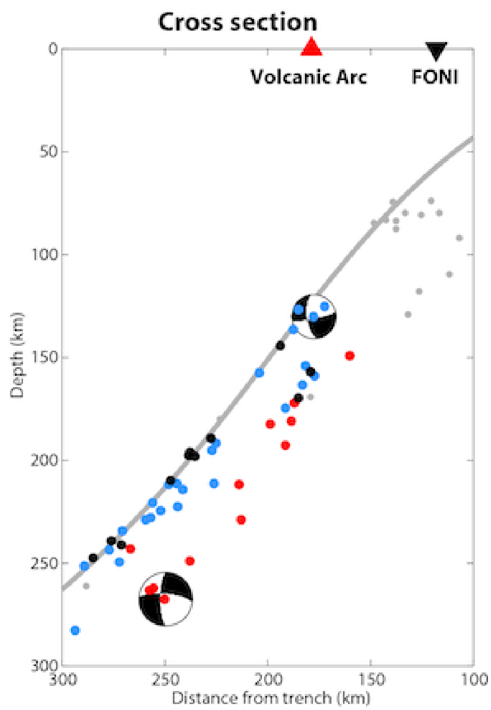
We present precise hypocenters of intermediate-depth earthquakes in the Tonga subduction zone obtained using data from local island-based, ocean bottom, and global seismographs. The results show a clear double seismic zone, with a downdip compressional upper plane and a downdip tensional lower plane 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

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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

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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

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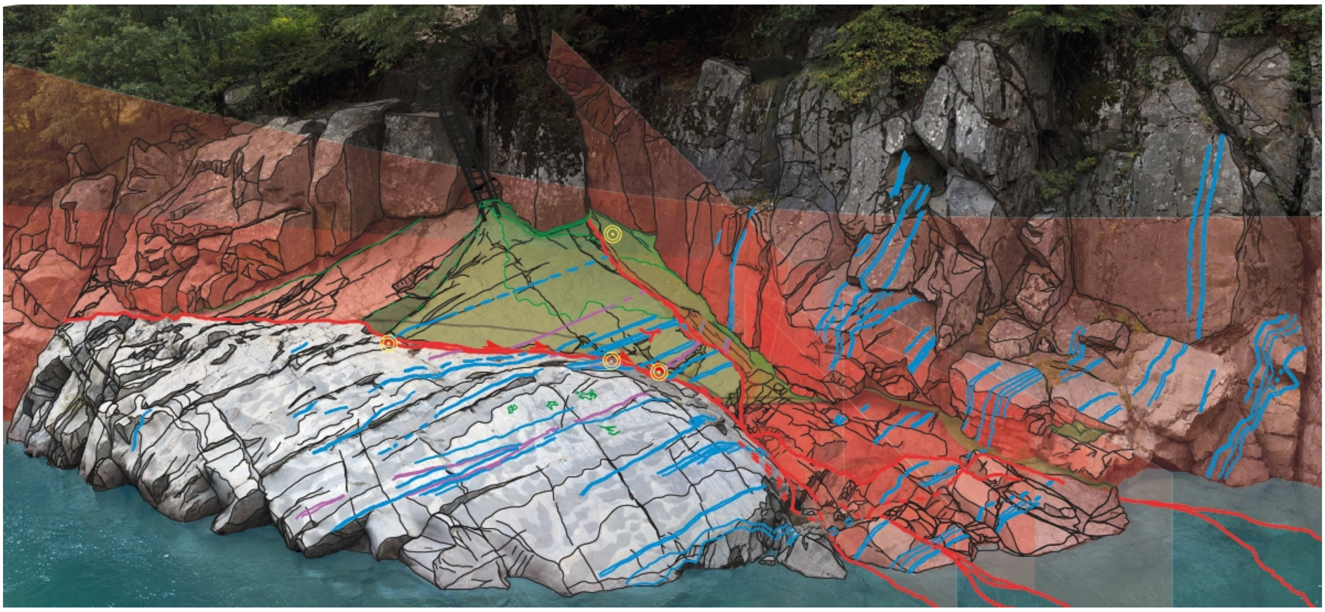
In the Balmuccia massif (NW Italy), pseudotachylytes (PST) are found within a spinel lherzolite. Coming from the solidification of the melt generated during seismic rupture, these rocks constitute a geological record of fossilized earthquakes. Here, combining field observations, Raman spectrometry and 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

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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

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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

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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

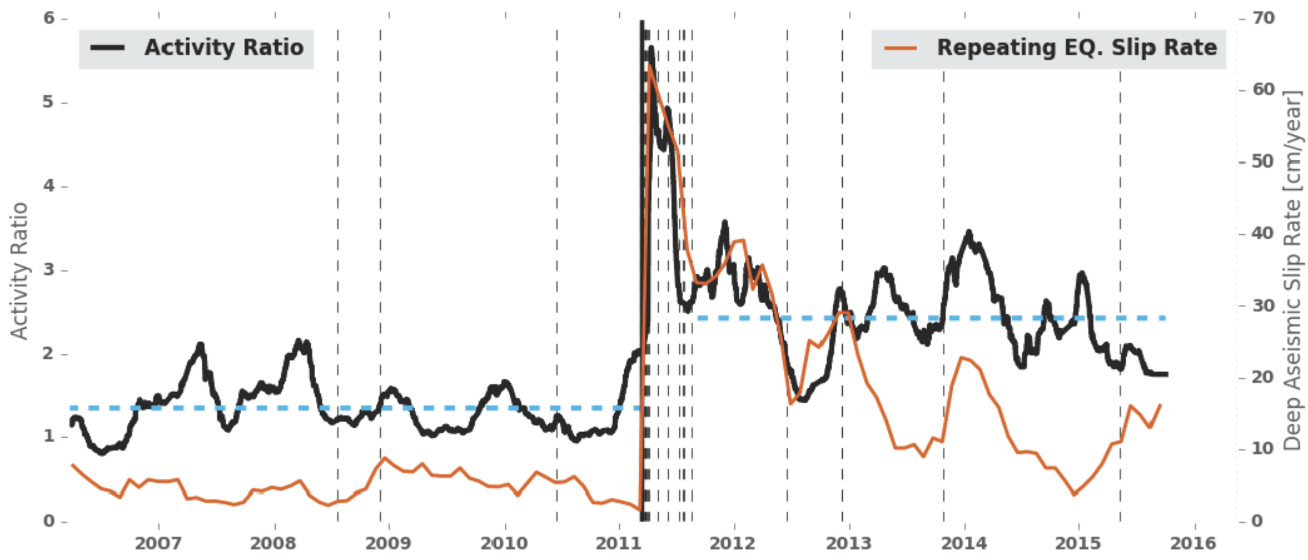

Fig 1. Intermediate-depth earthquake rates near the rupture area of the 2011 M9.0 Tohoku-oki Earthquake estimated from the ETAS model using M>2 events and deep aseismic slip rates. The ratio of the background rates of the upper and lower planes, termed the activity ratio, is shown by the black line. 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

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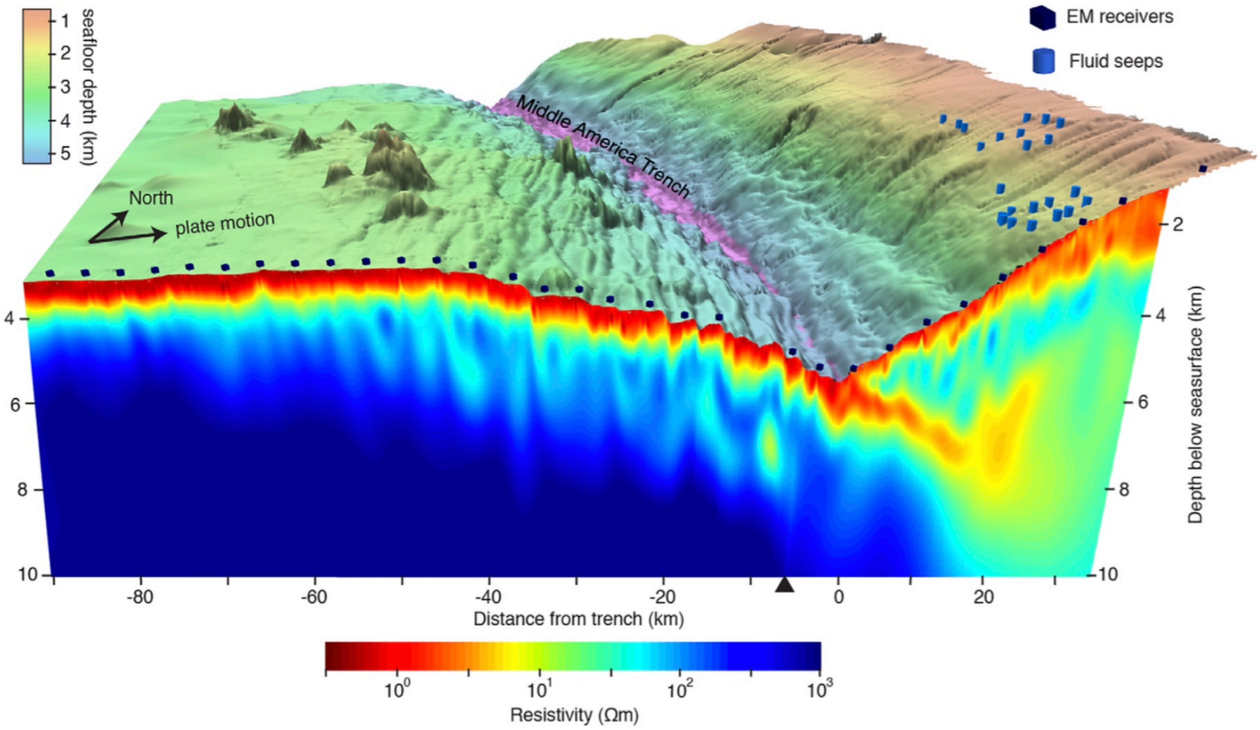
Controlled-source electromagnetic (CSEM) soundings provide important constraints on the electrical structure of the uppermost oceanic lithosphere. Since the conductivity signature of porous media is strongly dependent on the presence of saline fluids, CSEM data can be used to quantify porosity. Here, 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

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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

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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