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

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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

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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

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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

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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

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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

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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

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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

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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

