

Vitrinite reflectance and Raman spectra of carbonaceous material as indicators of frictional heating on faults

FURUICHI, Hiroyuki^{1*} ; UJIIE, Kohtarō¹ ; KOUKETSU, Yui² ; SAITO, Tsubasa¹ ; TSUTSUMI, Akito³ ; WALLIS, Simon⁴

¹University of Tsukuba, ²The University of Tokyo, ³Kyoto University, ⁴Nagoya University

Vitrinite reflectance (R_o) and Raman spectra of carbonaceous material (RSCM) have been used as geothermometers to estimate maximum temperature recorded in sedimentary and metamorphic rocks. We experimentally examined whether these geothermometers can be applied for the detection of temperature increases associated with fault slip. Friction experiments were conducted on a mixture of powdered clay-rich fault material and carbonaceous material (CM) at slip rates of 0.15 mm/s and 1.3 m/s in nitrogen (N_2) gas with or without distilled water. After the experiments, we measured R_o and RSCM and compared to those in starting material. The results indicate that when fault material suffers rapid heating and comminution in ~9 seconds at 1.3 m/s, R_o and the intensity ratio of D1 and D2 Raman bands of CM (I_{D2}/I_{D1}) markedly increase. Comminution with very small temperature rise in ~32 minutes at 0.15 mm/s is not responsible for changes in R_o and I_{D2}/I_{D1} . Our results demonstrate that R_o and RSCM can be useful for the detection of frictional heating on faults. However, the conventionally used R_o and RSCM geothermometers are inadequate for the estimation of peak temperature during seismic fault slip. The reaction kinetics considering rapid heating and comminution at high slip rates and the investigation of original microtexture and composition of CM are required to establish a thermometer of friction heating on faults.

Keywords: frictional heating, vitrinite reflectance, Raman spectra, carbonaceous material, friction experiments

Blackening of fault gouge by pyrolysis of carbonaceous mineral

KANEKI, Shunya^{1*} ; HIRONO, Tetsuro¹

¹Department of Earth and Space Science, Graduate School of Science, Osaka University

Earthquake slip induces frictional heating and comminution of mineral grains on the fault and interseismic physicochemical process produces the fault gouge. The fault gouges sometimes exhibit various colors (white-pink-green-gray-black), and in particular those developed in sedimentary rocks show gray to black. However, the origin of the change in color was not fully understood, and its relationship to slip parameters such as friction work and heat was not also revealed. Therefore, in this study, we focus on the blackening of the fault gouge originated from the sedimentary rocks. We first performed frictional and milling experiments on the mixture samples of clay mineral (montmorillonite) and coal (bitumen), and then investigated the spectroscopic feature by using visible, infrared, and Raman spectroscopies. We recognized blacker sample after friction experiment with higher initial content of coal, and confirmed the Raman G and D bands on the surface of clay mineral. Thus, we inferred that frictional heating induced thermal decomposition of carbonaceous material and the pyrolytic gases adsorbed on the surface of mineral grains resulting in the blackening. Furthermore, black-fault gouges in natural might have experienced high temperature at >300 °C.

Keywords: carbonaceous material, pyrolysis, frictional heating, fault gouge

Characteristics of frictional heating related thermal maturation of CM: Raman analysis of CM in the fault rocks

MUKOYOSHI, Hideki^{1*} ; HIRONO, Tetsuro²

¹Interdisciplinary Graduate School of Science and Engineering, Shimane University, ²Department of Earth and Space Science, Graduate School of Science, Osaka University

Determination of frictional heating effects along faults provides key insight into the dynamics of earthquakes and faulting. Raman spectroscopy has recently been used to estimate the thermal metamorphic grade of organic matter in sedimentary rocks and applying the method in order to estimate the temperature of fast heating like frictional heating during earthquake. We conducted Raman spectroscopic analysis of CM in the fault rock of three major thrusts [2.5-5.5 km depth of ancient mega-splay fault (an out-of sequence thrust in the Shimant accretionary complex), 1-4 km depth of a thrust in the Emi group, Hota accretionary complex and the Chelungpu fault, which slipped at the 1999 ChiChi earthquake]. Heating experiment of CM in the host rock of faults described above were also conducted and these Raman spectrum were analyzed in order to investigate the effects of fast heating rate like frictional heating.

Evolution of Raman spectrum of the short time matured experimented CM was differ from the diagenetic matured CM. This result shows that the existing Raman CM geothermometer is not applied for temperature estimation of short time matured CM in the fault rock.

In this presentation, we introduce the difference of characteristic of Raman spectrum of short time matured CM and diagenetic matured CM. To evaluate the levels of friction, Raman spectrum of the short time matured experimented CM is useful as calibration tool.

Keywords: Raman spectroscopy, carbonaceous material, frictional heat

Changes in carbonaceous materials from the fault rock detected by IR-Raman spectroscopies and Py-GC/MS

HIRONO, Tetsuro^{1*} ; YABUTA, Hikaru¹

¹Department of Earth and Space Science, Graduate School of Science, Osaka University

To understand the mechanism of fault lubrication during the 1999 Taiwan Chi-Chi earthquake, we developed a new temperature proxy for carbonaceous materials by using infrared and Raman spectroscopies together with heating and friction experiments. We found marked anomalies in the infrared and Raman spectra of carbonaceous materials retrieved from the primary slip zone of the earthquake: the infrared spectra exhibited very weak aliphatic CH₂ and CH₃ peaks and aromatic C=C absorbance peaks, and the Raman spectra exhibited very weak disordered and graphitic bands and a high ratio of disordered band area to graphitic band area. Those weak peaks and bands and the band area ratio were reproduced by heating carbonaceous materials from the nearby host rock to 700 C. These results suggest that the frictional heat in the slip zone reached approximately 700 C. We characterized the host rock carbonaceous materials by means of elemental analysis, pyrolysis-gas chromatography-mass spectrometry, and simultaneous thermogravimetry-differential scanning calorimetry and found that the H/C and O/C ratios were 0.108 and 0.400, respectively (which are close to the ratios for lignin) and that the volatile fraction was as high as 48 wt %. The pyrolysates obtained by heating from 100 to 400 C were dominated by phenols, fatty alcohols, and n-alkanes. When the residue from pyrolysis at 100-400 C was rapidly heated to 700 C, the resulting pyrolysate was dominated by phenols, aromatic compounds, heterocyclic compounds, and n-alkenes. This information suggests that changes in the infrared and Raman spectra with increasing temperature may have been due to decomposition and aromatization reactions during pyrolysis. Rapid heating during earthquake slip may promote reactions of carbonaceous materials that are different from the reactions that occur during long-term metamorphism.

Keywords: carbonaceous material, IR spectroscopy, Raman spectroscopy

Effects of morphology of minerals and adsorbed water on the friction in faults

SAKUMA, Hiroshi^{1*} ; KAWAI, Kenji² ; KATAYAMA, Ikuo³ ; SUEHARA, Shigeru¹ ; TAMURA, Kenji¹

¹National Institute for Materials Science, ²University of Tokyo, ³Hiroshima University

Friction among rocks and minerals is critical for understanding fault slip and landslide. The maximum friction coefficients of common minerals can be described by a constant value (0.85 for the normal stress $\sigma < 200$ MPa and 0.6 for $\sigma > 200$ MPa) [1]. However, certain mica and clay minerals have lower friction coefficients [1] and the friction coefficients were reduced under the presence of adsorbed water [2]. Since these mica and clay minerals are common constituents of fault-forming minerals, it is important for understanding the physics and chemistry of the low friction coefficients of these layered minerals.

Interlayer bonding energy (ILBE) of these layered minerals has been believed to have a linear relationship with the friction coefficients [2, 3]. However, this hypothesis is controversial due to the inconsistency of experimental results among researchers [4]. In this study, the ILBEs of several common mica and clay minerals were estimated by using the first-principles electronic state calculations for discussing whether the ILBE cited in the papers [2, 3] were correct or not. The hypothesis stands for that the major sliding plane should be localized on the flat (001) planes. This condition was discussed by comparing the sliding experiments of muscovite single crystal and powder samples.

Adsorbed water has been believed to have effects on the friction sliding by dry and humidity-controlled experiments. The effect of adsorbed water on the maximum friction was investigated by Morrow et al. (2000) [2]. However the direct evidence of the presence of adsorbed water was not obtained. In this study, the effect of adsorbed water on a muscovite surface was directly measured by using two salt solutions. The stability of adsorbed water was estimated by using the first-principles electronic state calculations.

In this talk, we discuss the factors describing the low friction coefficients of these layered minerals.

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Keywords: Interlayer bonding energy, maximum friction coefficient, clay minerals, mica, water

Formation process of a silica gel layer along a fault in chert

TSUTSUMI, Akito^{1*}; MIYAKE, Akira¹

¹Graduate School of Science, Kyoto University

Previous experimental studies have demonstrated that fault weakening in siliceous material occurred at relatively low slip velocities ($V > 0.01$ mm/s) [Goldsby and Tullis, 2002; Di Toro et al., 2004; Hayashi and Tsutsumi, 2010], under which conditions transformation reactions (e.g., melting, decomposition, etc) are unable to proceed because of low temperatures. Formation of a silica gel (hydrated amorphous silica) layer within a siliceous rock has been suggested for a possible cause of the weakening behavior [Goldsby and Tullis, 2002]. However, there exists only limited information on the frictionally generated material on faults in quartz-rocks. To get a better understanding of fault zone process in siliceous material, we have performed intermediate-velocity friction experiments on chert samples and have performed transmission electron microscope (TEM) studies of the fault surface material.

Friction experiments were performed on chert at intermediate velocity ($V = 104$ mm/s) and at low normal stress of 1.5 MPa. As has been reported preliminary in Hayashi and Tsutsumi (2010), fault weakening in chert samples occurred in association with the formation of a 0.1-mm-thick fault gouge layer. SEM observations on the fault surfaces revealed that the fault surfaces consisted of smooth and rough parts, with the smooth parts probably corresponding to the area with vitreous luster. On the smooth part of the surfaces, rod-shaped particles (1 to 5 μm long with a diameter of ~ 0.5 μm), aligned perpendicular to the sliding direction, probably indicating that they were rolled during the experiment [Hayashi and Tsutsumi, 2010]. These particles have been termed "rolls".

The samples for TEM studies were prepared with an application of a focused ion beam (FIB) system. Cross-sections of the fault surface were prepared so that rolls and the substrata interface could be observed using TEM. During the preparation, we paid attention to the cutting direction; rolls were cut perpendicular to their long axes. TEM observations revealed the following characteristics of the experimentally generated fault surface material in chert: (1) the smooth fault surface consist of several hundred-nm-thick amorphous silica layer. (2) Rolls exist on the smooth fault surface and are in contact with the amorphous silica layer. (3) Rolls are made of amorphous silica. The result from TEM observation implies that the rolls observed on the smooth fault surface are formed via a process of consuming the thin amorphous silica layer.

Hayashi and Tsutsumi (2010) showed that the fault gouge consists of a mixture of hydrated amorphous silica and quartz grains. The thin, several hundred-nm-thick amorphous silica layer formed on the fault surface would be a likely candidate for the source of the hydrated amorphous gouge material (silica gel layer).

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Keywords: silica gel, amorphous silica, rock friction, chert

Experimental study on frictional properties of biogenic sediments entering the Costa Rica subduction zone

NAMIKI, Yuka^{1*} ; TSUTSUMI, Akito¹

¹Graduate School of Science, Kyoto University

Various seismic behaviors such as large earthquakes, episodic slow slip events, or silent earthquakes are observed in subduction zones. This variation likely reflects spatial variations in frictional properties along the seismogenic portion of plate-boundary megathrusts (e.g., Bilek and Lay 1998). A number of studies have been performed to reveal the frictional properties of subduction-zone material. However, available experimental data have thus far been limited mostly to clayey materials (e.g., Brown 2003). Recently, Namiki et al. (2014) have reported that the frictional properties of silicic to calcareous ooze collected from the Costa Rica subduction zone were different from those of clay as the following: (1) the steady-state μ values of the silicic to calcareous ooze are high, measuring 0.6 to 0.8; and (2) the steady-state μ values of the silicic to calcareous ooze samples show negative dependence on velocity at velocities of 0.0028 to 0.28 mm/s and positive dependence at velocities of 0.28 to 2.8 mm/s. The second property is important because velocity-weakening behavior implies potentially unstable fault motion. In this study, to understand the mechanism of generating such characteristic frictional properties of the silicic to calcareous ooze, a series of friction experiments was performed on biogenic amorphous silica, a possible end-member component of the silicic to calcareous ooze.

We dissolved calcite by acid treatment to extract amorphous silica from the ooze, whose particle size and shape are expected to be similar to natural sediments. The extracted biogenic amorphous silica shows the following frictional properties: (1) the steady-state μ value is high, measuring ~ 0.6 ; (2) the steady-state μ value of the biogenic amorphous silica shows negative dependence on velocity at velocities of 0.0028 to 2.8 mm/s; and (3) as slip velocities increase, the values of D_c become larger.

The experimental results suggest that the frictional velocity dependence of the biogenic amorphous silica is intrinsically negative at a range of velocities tested in this study. The observed negative velocity dependence of the amorphous silica suggests that mixing of a second phase material such as calcite to amorphous silica probably influences the bulk frictional properties of the ooze, of which friction showed positive dependence on velocity at velocity of several mm/s.

Homogeneously sheared deformation texture was observed in the silicic to calcareous ooze sample after it showed positive friction velocity dependence. The homogeneous deformation textures are consistent to the previously reported diagnostic textures of positive frictional velocity dependence (e.g., Ikari et al., 2011).

Keywords: subduction zone, frictional experiment, CRISP

Verification of unstable frictional behavior for smectite as elevated temperature

KUBO, Tatsuro^{1*} ; KATAYAMA, Ikuo¹

¹Hiroshima University

Introduction: Subduction thrust faults are known to generate earthquakes over a limited depth range (Hyndman et al., 1993; Shimamoto et al., 1993; Tichelaar and Ruff, 1993). The seaward up-dip limit of seismicity is important for tsunami generation, and the total seismogenic width can be related to the maximum magnitude of great earthquakes along the interface of a subducting plate. Therefore, an understanding of the factors controls the updip and downdip limits of the seismogenic zone is important for seismic hazard assessment. There are various factors that possibly control the updip limit of the seismogenic zone. We focus on transition from unsolidated to solidated sediments because of dehydration of clays, which leads to coincidence with transition from aseismic frictional behavior to seismic frictional behavior. Along plate boundary subduction thrusts, the transformation of smectite to illite within fault gouge at temperatures around 100~200C is one of the key mineralogical changes thought to control the updip limit of seismicity. Clay in the fault gouge has been suggested as an explanation for the general lack of earthquakes in the upper 5-10 km of continental fault zones (Marone and Scholz, 1988). Frictional coefficient and velocity dependence is depending on humidity (Ikari et al., 2007). However, previous works were limited at room temperature although the updip limit of seismogenic zone is thermally controlled that occurs at temperature around 150C. Moreover, there is no verification for the effect on dehydration under rising temperature. Therefore, in this study, we determined the effect of temperature of frictional properties of smectite and discuss whether the dehydration for clay minerals as elevated temperature accounts for the updip limit of seismogenic zone along subduction thrust.

Experimental methods: Frictional experiments were performed using a biaxial frictional testing machine at Hiroshima University. The powder materials of clays were placed on the simulated fault surface and two side blocks were placed together to produce a double-direct shear configuration. Normal stress was applied via a hydraulic ram on the side block with 60 MPa, and then, shear stress was applied by advancing the central block downward at a constant velocity. The sample assembly was heated by an external furnace up to 200oC that is monitored by thermocouples located close to the central block. Mechanical data were recorded continuously with a sampling rate of 10 Hz and the frictional coefficient was calculated from the shear force divided by the normal force assuming zero cohesion.

Results and Discussion: Our experiments showed three phase change as elevated temperature. 1. Decreasing frictional strength, 2. Increasing frictional strength, and 3. Appearance of persistent stick-slip behavior. At phase 1, expansion of interlayer water due to rising temperature may open interlayer of clays, weakening adhesion. At phase 2, dehydration leads to healing adhesion and frictional strength. At phase 3, we observed persistent stick-slip behavior. This frictional behavior implies to have a potential of velocity weakening behavior, and temperature has significant influence on frictional behavior of clay minerals.

Keywords: frictional experiments under rising temperature, the updip limit along subducting plate, smectite-illite transformation, frictional property for clays, the effect of temperature, the effect of interlayer water

Frictional heating causes high-velocity weakening of gouge; inference from specimens with different thermal conductivity

SHIMAMOTO, Toshihiko^{1*} ; YAO, Lu¹ ; MA, Shengli¹ ; NIEMEIJER, Andre²

¹Institute of Geology, China Earthquake Administration, ²Department of Earth Sciences, Utrecht University

Various mechanisms such as (1) temperature rise in slip zones due to frictional heating, (2) powder lubrication, and (3) formation of weak materials like silica gel have been proposed as mechanisms for dramatic weakening of fault gouge at high slip rates. In friction experiments using rocks as host specimens on both sides of gouge, slip rate and/or normal stress had to be changed to produce different temperature conditions. However, different test conditions may change deformation mechanisms making it difficult to separate the effects of temperature rise in causing high-velocity weakening of gouge. We show in this presentation that different temperature conditions in gouge can be attained by using host specimens with different thermal conductivities, and our results indicate that the frictional heating plays an important role in causing the high-velocity weakening of gouge.

Uniaxial strength of rocks reduces by several hundred times due to thermal fracturing during high-velocity friction experiments with host rocks, making it difficult to conduct high-velocity friction experiments at normal stresses higher than several MPa. Experiments can be done at normal stresses up to about 30 MPa with host rocks reinforced with aluminum rings, but metal-metal friction or frictional melting of aluminum is involved with the experiments. We have been seeking for designing a sample cell that can sustain much higher normal stresses, but finding materials that exhibit similar frictional behaviors to those of rocks has been a difficult task. One of the coauthors (AN) found that TiAlV alloy has a thermal conductivity as low as those of rocks, and we decided to perform a series of high-velocity friction experiments on Longmenshan fault gouge from Hongkou outcrop (illite 47%, quartz 41%, smectite 3%, kaolinite 3% and chlorite 2%) using host specimens with different thermal conductivities. Experiments were done with a rotary-shear low to high-velocity friction apparatus at Institute of Geology, China Earthquake Administration, at slip rates of 0.5, 1.0, 2.1 m/s and at a normal stress of 1 MPa. Host specimens were made with gabbro (thermal conductivity of 3.3 W/mK), TiAlV alloy (5.8 W/mK), stainless steel (15 W/mK) and brass (123 W/mK). Both gabbro and TiAlV alloy exhibits marked slip weakening and their behaviors are quite similar. Whereas weakening is suppressed dramatically with brass, and stainless steel shows intermediate behaviors between gabbro/TiAlV alloy and brass. Temperature measurements in the stationary host specimens and FEM analysis with COMSOL software revealed that an average temperature in slipping zones in the outer-half of the gouge ranging from 90 to 300 degrees Celsius was attained by using those materials. Friction coefficient at the end of runs decreases from 0.65 to about 0.1 with an increase in the average temperature, and the results indicate that the temperature rise is important in causing the high-velocity weakening of gouge. Powder lubrication cannot explain the results. We have started to compare the results with modified flash heating theories (Rice, 2006, JGR; Noda, 2008, JGR; Proctor et al., 2014, JGR; Platt et al., 2014, AGU). TiAlV alloy is an ideal material for making sample cells for high-normal stress experiments.

Keywords: fault gouge, friction of fault, high-velocity weakening of fault, high-velocity friction experiments

Thin shear localization in matured mylonitic rock

TAKAHASHI, Miki^{1*} ; VAN DEN ENDE, Martijn² ; NIEMEIJER, Andre² ; SPIERS, Chris²

¹IVGE, GSJ, AIST, ²HPT Lab., Faculty of Geosciences, Utrecht University

Textures of deformation in fault rock are the results from every history of deformation they had been conducted, and the textures correspond to these deformation conditions, such as pressure, temperature and strainrate. In nature, deformation mechanism at earthquake preparation (aseismic) stage is of ductile forming the mylonite. Therefore, to reproduce more realistic fault behavior at the brittle-ductile transition regime, we carried out large jump experiment in the sliding velocity on brine saturated halite (80 wt.%) - muscovite (20 wt.%) mixed gouges after making the mature mylonitic texture in the gouges, using a rotary shear testing machine set at Utrecht University, Netherlands.

In mylonite, one of the fault rocks formed under ductile deformation condition (high temperature and low strainrate), we often found narrow strain localized zones, such as pseudotachylite with mm-scale of width. Our question from the nature is how to generate the strain localization in the mylonite, in order to know how deformation style changed from ductile (aseismic) to brittle (co-seismic). Here we experimentally investigated the strain localization process in rocks having ductile, matured mylonitic structure. We carried out rotary shear experiments on brine saturated halite - muscovite mixed gouges (5 g in weight, c.a. 1 mm in thickness) under 5 MPa in normal stress, room-temperature and various strainrate (from $3 \times 10^{-5} \text{ sec}^{-1}$ to 0.1 sec^{-1}) conditions, which were well-known analog of the fault rock consisting of quartz and phyllosilicate (e.g., Bos and Spiers, 2002; Niemeijer and Spiers, 2006). Additionally, deformation features on the mixed gouges were well-known to show very various on both the strength and the texture, depending on the strainrate. At lower strainrate ($< 1 \times 10^{-3} \text{ sec}^{-1}$), the deformation feature was characterized by velocity-strengthening and mylonitic texture. On the other hand, at higher strainrate ($> 1 \times 10^{-3} \text{ sec}^{-1}$), that showed velocity-weakening and chaotic texture.

In our experiments, we gave a large jump in sliding velocity after forming matured mylonitic texture on the mixed gouge. That large jump of 2.5- or 3.5-digit increases in the sliding velocity simulated earthquake nucleation or propagation in the mylonite. Microstructural observations on the experimental products indicated possible evidences of the strain localization caused by the high-speed rotation. The strain localization occurred only at $10 \mu\text{m}$ zone near a boundary surface of the ring shear. In that thin localized zone, grains of halite were crushed. Except the thin localized zone, the mylonitic texture has been completely remained. It was similar to the natural mylonite associated with narrow zones of the pseudotachylite.

We also measured changes in frictional strength after the velocity jump, showing abnormally large increase in the strength at instantaneous response and some delay to start evolutionally-weakening in the strength. It means that the rate and state friction law (RSF law) could not hold for a case changing the deformation style from the ductile to the brittle.

The strainrate during long term aseismic period is very low. Therefore domestic texture controlling mechanical behavior in a seismic-aseismic cycle is "mylonite" at the brittle-ductile transition regime. We revealed, in this experiment, that the matured mylonite texture never be completely broken (not chaotic), but localizes the deformation in one or several narrow shear zones at earthquake nucleation or rupture propagation. This feature is consistent with the natural observation, narrow pseudotachylite zones developed in the mylonite. The mechanical behavior of the mylonite at the earthquake would not obey the RSF law.

Viscoelasticity of the Nankai accretionary prism: Indentation test on sediments from NanTroSEIZE Expedition 348

KITAMURA, Manami^{1*} ; SONE, Hiroki² ; KITAJIMA, Hiroko³ ; HIROSE, Takehiro⁴

¹Hiroshima University, ²German Research Centre for Geosciences, ³Department of Geology and Geophysics, Texas A&M University, ⁴JAMSTEC/Kochi

We have investigated the viscoelastic properties (stress-strain curve, Young's modulus, yield stress, and stress relaxation modulus) of sediments collected from the Nankai trough during IODP Expedition 348. To determine the evolution of viscoelastic properties in the Nankai accretionary prisms, we conducted spherical indentation experiments on the hand-picked intact cuttings retrieved from 870 to 3058 meters below seafloor (mbsf) at Site C0002. We used a spherical sapphire indenter with a diameter of 4 mm to deform the cuttings sample of >2mm thickness saturated with brine at room temperature and pressure conditions with a constant loading/unloading rate of 0.5 N/sec and maximum load of 180 N.

The load/unload-displacement curves indicate that the sediments above ~1200 mbsf show plastic behavior while the sediments below 2000 mbsf show brittle behavior accompanied by a sudden drop in stress due to the formation of radial fractures. The yield stress increases with depth from a few MPa at 870 mbsf to ~40 MPa at 3000 mbsf. The Young's modulus of the sediments increases from ~0.1 GPa at 870 mbsf to ~1.5 GPa at 2000 mbsf, then it becomes nearly constant at ~1.5 GPa below 2000 mbsf. The change of mechanical behavior most likely reflects the sediment consolidation because porosity gradually decreases from ~60% at seafloor to ~30% at 1500-2000 mbsf, then reaches to ~18% at 3000 mbsf. The plastic-brittle transition may appear between 1500 mbsf and 2000 mbsf. The strain energy for the Nankai earthquakes could be accumulated mainly in the sediments below 2000 mbsf.

Keywords: Viscoelasticity, accretionary prism, Indentation, IODP, Expedition 348

Crustal deformation and stress accumulation process in and around the Atotsugawa fault system

TAKADA, Youichiro^{1*}

¹Disaster Prevention Research Institute, Kyoto University

I introduce recent two extensive surveys conducted in and around the Atotsugawa fault system. First is the joint seismic observation by university group during 2004 to 2008. With this seismic data, I have estimated the focal mechanisms of small earthquakes and tectonic stress field by using stress inversion methods. Second is to estimate the inter-seismic crustal deformation with very high spatial resolution using GNSS and InSAR time series analysis. The estimated stress rotation can be explained by a viscoelastic dislocation model assuming cumulative slip deficit relative to surrounding part up to several tens of meters. On the other hand, the geodetic data indicate strain concentration near the fault trace, which may require a minor change of the fault model. However, the velocity fields still include systematic error coming from atmospheric and/or tropospheric disturbances. Farther noise reduction is required to constrain the physical model.

Keywords: Atotsugawa Fault, Stress Field, GNSS, InSAR

An abrupt seafloor water-temperature increase in the epicentral region of the 2011 Tohoku earthquake

INAZU, Daisuke^{1*} ; ITO, Yoshihiro² ; SAFFER, Demian³ ; HINO, Ryota⁴

¹The University of Tokyo, ²Kyoto University, ³The Pennsylvania State University, ⁴Tohoku University

We reported in the previous JpGU meeting that an abrupt seawater temperature increase observed just after the 2011 Tohoku earthquake (Inazu et al. 2014 JpGU). The temperature anomaly started several hours after the earthquake, reaching up to 0.1 deg.C above background temperature with another hours, and last for a few weeks. The temperature anomaly was observed at the sea depth of 3000-6000 m, and not observed at shallower sea depth. In the present meeting, we suggest a sequence of a couple of geophysical models to explain the temperature anomaly. We first estimate a heat content required for the temperature increase, being 4×10^{16} J. Since the heat content was loaded with several hours, the estimated heat flux is to be 2×10^{12} J/s. These heat properties are comparable to those of "mega plumes" at hydrothermal vent systems typically found at plate spreading axes. We consider that a similar explosive event occurred during the Tohoku earthquake, and adopt a hydrothermal plume model (Wilcock 1997 JGR) for the temperature anomaly. The branch normal fault (Tsuji et al. 2013 EPSL) is assumed as a heat (fluid) path. The heat temperature is estimated to be about 200 deg.C at the seafloor. We next adopt a two-dimensional (vertical and east-west direction) advection-diffusion model. The temperature of 200 deg.C is successfully modeled if the heat source in the model (Kano et al. 2006 GRL) is given by the coseismic frictional heat at the plate boundary during the Tohoku earthquake. A portion (~10 %) of the frictional heat probably migrated through the branch normal fault, and was released in the seawater, referring the JFAST temperature observation in the plate boundary (Fulton et al. 2013 Science).

Keywords: Tohoku earthquake, seafloor, water temperature

Large-scale earthquake cycle simulations with Hierarchical Matrices Method

OHTANI, Makiko^{1*} ; HIRAHARA, Kazuro¹

¹Sci., Kyoto University

Recently, the inland and offshore seismic and geodetic observations have revealed a variety of slip events in the wide-range of spatiotemporal scale on the plate interface at subduction zones. These slip events are densely populated on the plate interface, and interact to each other. For example, Ariyoshi et al. (2014), assuming the plate interface along the Nankai Trough, showed the possibility that the activities of the shallow and deep low frequency earthquakes increase before the occurrence of the Nankai and Tonankai earthquakes, in the simulation. Their result shows the possibility that evaluating the interaction of multiple slip events may leads to getting the information of the next large earthquakes. For the evaluations, ECS (Earthquake Cycle Simulation) will be useful. In ECSs, we assume the friction on the plate interface, and simulate the earthquake cycle, i.e., the iterative stress accumulation during the interseismic period and the stress release as slip events on the plate interface. As we simulate the whole period of earthquake cycles, we can simultaneously consider the slip events with various scales in space and time and with the timing of occurrence. In this talk, we discuss the problem of performing large-scale ECS for the actual large earthquakes.

For considering the multi-scale slip behaviors, we need to model the large region with fine resolution. Then, the model becomes large, leading to much computational cost. For such large-scale ECSs, we often use the boundary integral element method (BIEM) and the quasi-dynamic scheme that approximates the inertial term. Then, the computational amount is $O(N^2)$, where N represents the number of discretized fault cells. To realize large-scale ECSs with large N , further reduction of computational time and memory is essential.

In this study, for the strategy of fast computation, we use the Hierarchical Matrices (H-matrices) method, developed by Hackbash (1999). This method compresses the dense matrix into H-matrix, consisted of submatrices which are approximated to be low rank. We can apply this method to the matrix that has large values in its diagonal and takes smaller values as being apart from the diagonals. In quasi-dynamic ECSs, we perform the multiplication of the slip response matrix and the slip vector to get the stress on the plate interface. When we order the series of the fault cells as the neighboring cells to have neighboring numbers, we can apply the H-matrices method. Applying this method enables us to reduce of the computational memory and time to $O(N) \sim O(N \log N)$. In this study, we use the library HLib for constructing the H-matrices.

There is also another problem. There are some effects which are not considered in the existing BIEM quasi-dynamic cycle simulations. For the ECSs of actual large earthquakes, we need to evaluate these effects and examine to what extent the models should be realistic. In this study, we focus on the geometry of the fault system. The existing ECSs consider the problems only in homogeneous full-space medium or half-space medium with flat Earth's surface, where analytic solutions for the slip response matrix exist. However, actual subduction zone has the non-flat Earth's surface. For example, in the region off Miyagi, Tohoku, in northeast Japan, where the 2011 Tohoku earthquake occurred, the seafloor topography close to the Japan Trench where the Pacific plate subducts has an amplitude of 7 km. Therefore, in this study, we developed the efficient way of taking into account the topography of the Earth's surface into quasi-dynamic ECS, following Hok and Fukuyama (2011) which takes into account the free surface into dynamic rupture model, and examined its effect.

Finally, we note that our developed method for the actual Earth's surface enables us to simulate the whole Japan Island-scale cycle simulations, which include both inter-plate earthquakes along the Japan Trench and the Nankai Trough with different trench depths.

Keywords: quasi-dynamic, earthquake cycle, Hierarchical Matrices method

Numerical model of slow slip events with plate configuration -A tentative application of the Nankai model to Cascadia-

MATSUZAWA, Takanori^{1*} ; SHIBAZAKI, Bunichiro²

¹National Research Institute for Earth Science and Disaster Prevention, ²Building Research Institute

Slow slip events (SSEs) and non-volcanic tremor are found in various subduction zones, for example, Nankai, and Cascadia. We have modeled and successfully reproduced SSEs in the Nankai region (e.g., Matsuzawa et al., 2013). However, to validate the model, it is important whether our model can explain SSEs in the other region. In this study, we show a result of a tentative application of our model to SSEs in the Cascadia region.

In our numerical model, a rate- and state- dependent friction law (RS-law) with a cutoff velocity is assumed to model frictional stress on the plate interface, as in the previous studies (e.g., Shibazaki et al., 2012; Matsuzawa et al., 2013). SSE regions are given by the actual distribution of tremor which is located by the monitoring system of Wech (2010). Low effective normal stress and a low cutoff velocity are assumed at the depth where SSEs occur. Negative and positive (a-b) value in the RS-law is assumed within and outside of the SSE region, respectively. Subducting plate interface is modeled by about 200,000 triangular elements, based on the configuration in McCrory et al. (2004).

In our numerical result, SSEs recur at the intervals of about 1 year. In addition, SSEs are relatively active between the south of Vancouver island and the Olympic Peninsula. These characteristics are similar to observations. In this region, minor tremor activities at the down-dip portion occur between the occurrences of major tremor activities both in the up-dip and down-dip portion. Such a feature is also reported in the actual tremor in Cascadia (Wech and Creager, 2011) and Nankai (Obara et al., 2011). The feature is more clearly found in the result of Cascadia SSEs than that in the Shikoku region (Matsuzawa et al., 2013). This may be attributed to wider tremor region with curved plate interface in Cascadia. In this study, it is suggested that our model can explain some features of SSEs.

Keywords: Slow slip event, Cascadia, Numerical simulation, Rate- and state-dependent friction law

Raman spectroscopic analysis of carbonaceous material in Longmenshan fault zone at Shexigou

KOUKETSU, Yui^{1*} ; SHIMIZU, Ichiko¹ ; YAO, Lu² ; MA, Shengli² ; SHIMAMOTO, Toshihiko²

¹Graduate School of Science, The University of Tokyo, ²State Key Laboratory of Earthquake Dynamics Institute of Geology, China Earthquake Administration

On 12th May 2008, Wenchuan M_W 7.9 earthquake occurred along the Longmenshan thrust belt between the Tibetan plateau and the Sichuan basin. Shexigou area is located at the western end of the coseismic faults during the Wenchuan earthquake. The fault zone consists of fault gouge, fine fault breccia, and fault breccia. The gouge zone consists of grayish gouge (GG) and blackish gouge (BG). The breccia zone consists of grayish breccia (GB), blackish breccia (BB), and mixtures (Mix) of GB and BB. The concentrations of organic carbon are reported as less than 1 wt.% in GG and GB, while those in BG and BB are 28 and 36 wt.%, respectively (Wang et al. 2014; Earthquake Science) . In the present study, we performed the Raman spectroscopic analysis of carbonaceous material (CM) included in these fault rocks and host sedimentary rocks. In addition to the natural samples, we also analyzed the gouge samples after high-velocity frictional experiment to detect the structural change of CM by frictional heating.

Raman spectroscopic analysis was carried out using 532 nm Nd-YAG laser. The laser power was limited to 0.2 mW to avoid the damage to CM. The CM Raman spectrum was fitted using four peaks (D1, D2, D3, and D4 bands) following the method of Kouketsu et al. (2014; Island Arc). The Raman spectra of CM in GG, BG, GB, BB, and Mix were similar, and all Raman spectra indicated that the structure of CM corresponds to amorphous carbon. This result suggests that the carbons were originated from the organic materials in the host rocks and not concentrated by hydrothermal precipitation. The Raman band width (full width at half maximum; FWHM) of these fault rocks was larger than that of the host rock, and it means that the degree of coalification of CM in the fault rock is lower than the host rock. The estimated metamorphic temperatures using Raman CM geothermometer proposed by Kouketsu et al. (2014) are around 200-230 °C in the fault rocks and 280-300 °C in the host rock. The Raman spectra of CM in the sample conducted on the frictional experiment that was carried out at constant slip rate of 1.4 m/s and normal stresses 0.8 MPa under room humidity conditions using BG also showed no obvious change compare to those of CM before the experiment. In the present study, frictional heating was not detected by the Raman spectroscopy in natural and experimental fault samples. These results indicate that the heating duration of the coseismic slip was insufficient for the studied CM to mature enough.

Keywords: Wenchuan earthquake, Longmenshan fault system, Carbonaceous material, Raman spectroscopy, Frictional heating

Detection of past frictional heating on fault from Raman spectra of carbonaceous material

TABATA, Hiroki^{1*} ; UJIIE, Kohtaro¹ ; KOUKETSU, Yui² ; KAGI, Hiroyuki²

¹University of Tsukuba, ²Graduate School of Science, The University of Tokyo

Raman spectra of carbonaceous material (RSCM) systematically change with increases in temperature and thus have been used as a geothermometer in sedimentary and metamorphic rocks. We examined whether RSCM can be useful to detect increased temperatures associated with frictional heating on fault. The studied fault constitutes the thrust sheet boundary in the coherent chert-clastic sequence of the Jurassic accretionary complex in central Japan. The fault includes a few millimeters-thick, chert-derived pseudotachylyte and the 50-cm-thick cataclasite defined by the fragments of black chert in the carbonaceous clay matrix. We analyzed RSCM with a 514.5 nm Ar⁺ laser across these fault rocks and obtained characteristic Raman bands. The results show that the intensity ratio of D1-band and D2-band (I_{D1}/I_{D2}) and the full width at half maximum (FWHM) of the D1-band markedly decrease in the pseudotachylyte and the host rocks (gray chert) of less than ~2 mm from upper and lower boundaries of the pseudotachylyte, representing the localized progress in carbonization. In contrast, there are no changes in I_{D1}/I_{D2} and FWHM of the D1-band across the boundaries of the cataclasite. The spatial distribution of the decreased I_{D1}/I_{D2} and FWHM of the D1-band and the presence of pseudotachylyte are consistent with the localized heating during frictional melting along a few millimeters-thick slip zone. We conclude that RSCM is useful to detect increased heating associated with seismic slip on faults.

Keywords: carbonaceous material, Raman spectra, pseudotachylyte, cataclasite, chert-clastic sequence

Effect of humidity on frictional healing of montmorillonite

TETSUKA, Hiroshi^{1*} ; KATAYAMA, Ikuo¹

¹Department of Earth and Planetary Systems Science, Hiroshima University

According to time-predictable model for characteristic earthquakes, a stress increases at a constant ratio in interseismic period, and an earthquake occurs when the stress reaches a certain constant stress (Shimazaki and Nakata, 1980). This model has been applied for long-term forecasts for the Tokai earthquake, the Nankai earthquake. The ratio of stress increasing depends on the frictional healing effect which is the effect of the strength recovery with logarithm of hold time. In subduction-zones, smectite plays a key role for frictional behavior in surfaces of oceanic plates, and which has shown very low coefficient of friction (Ikari et al., 2007; Ujiie et al., 2013). Moreover, water distribution, hence humidity, contribute to the non-uniform clay minerals and its saturation along subduction-zones (Zhao et al., 2009). Previous studies investigated the effect of humidity on frictional healing of bare quartzite and quartz, alumina and soda-lime glass powders, which results that the frictional healing increases with increasing relative humidity (Dieterich and Conrad, 1984; Frye and Marone, 2002; Scuderi et al., 2014). However, the effect of humidity on the frictional healing of smectite has not well understood, therefore, we examined the effect of humidity on frictional healing of montmorillonite (a type of smectite) with comparison to quartz.

We conducted slide-hold-slide test (10, 30, 100, 300, 1000, 3000s) at 15MPa normal stress and 3 μ m/s shearing velocity. The experiment are carried out at four humidity conditions, 1) in deionized water with a water tank at room temperature, 2) at room temperature and humidity, 3) at room temperature and humidity after having been dried samples at 100 °C for 24 hours, 4) at 100 °C with a heater after having been dried samples at 100 °C for 24 hours.

We found the result that the frictional healing of montmorillonite decreases with increasing relative humidity, which is opposite to that observed in the experiments for quartz. The negative correlation between frictional healing effect and relative humidity on montmorillonite can be explained by the weakness of interlamellar cohesion due to expanding distance between layers in montmorillonite.

The smaller the frictional healing effect, the smaller stress recover in interseismic period. Assuming that the time-predictable model is correct, the smaller stress recover in interseismic, the longer recurrence time of earthquakes. Therefore, it is expected that the recurrence time of earthquakes is long in areas are wet and in which montmorillonite abound.

Keywords: smectite, frictional healing, humidity

Sample preparation condition for SEM-EBSD: An example of quartz minerals in granite

KANAI, Takuto^{1*}; MUKOYOSHI, Hideki²; TAKAGI, Hideo³

¹Graduate school of creative science and engineering, Waseda University, ²Interdisciplinary Graduate School of Science and Engineering, Shimane University, ³Faculty of Education and Integrated Arts and Sciences, Waseda University

Electron Backscatter Diffraction (EBSD) is used to determine a crystallographic orientation of the mineral in the Scanning Electron Microscope (SEM). For rock samples, thin section is generally used for EBSD analysis. Mechanical polishing of thin sections with diamond paste cause damages to the lattices of minerals at the specimen surface. Thus, additional processes of vibratory chemical-mechanical polishing with colloidal silica suspension is required to remove the mechanical damage (e.g., Prior et al., 1999; Lloyd, 1987). Although a number of study of EBSD for rocks are published, there is little report of detailed procedure or optimum conditions for thin section preparation with colloidal silica vibratory polishing. The objective of this study is to examine the optimum conditions of rock sample preparation, especially time and normal load of vibratory polishing, for EBSD analysis using quartz crystals in granite.

Vibratory polishing were conducted using VibroMetTM 2 vibratory polisher (BUEHLER Inc.) with colloidal silica suspension (Model No.: 5904-S-64, pH: 9.8, particle size: 40 nm) (PRECISION SURFACES INTERNATIONAL Inc.).

Examined conditions of vibratory polishing with colloidal silica suspension were as follows:

Time: 0, 60, 120, 180 minutes

Normal load: weight (200 g)×1, weight (200 g)×3

The EBSD analyses were performed at the Waseda University with an automated electron back-scattered diffraction system (Channel5, HKL) attached to a SEM (HITACHI S-3400N) with a tungsten filament, an accelerating voltage of 25 kV, a working distance of 30 mm, and with the specimens tilted 70°. Coating the specimen with a conductive material such as carbon removes the problem of charge build-up, but reduces the quality of Electron Backscattering Patterns (EBSPs). To eliminate the problem, EBSD analyses were performed under low-vacuum condition (30Pa) without coating. We selected 20 quartz grains per samples under the BSE image and 70×70 μm area with 2 μm step size (total 1225 points) were measured for each grains. To evaluate the effects of the different vibratory polishing steps on EBSD pattern quality, hit rate which is percentage of value of correctly indexed points to total measured points was used.

The results of 0 minute vibratory polished sample (only diamond polishing) shows less than 55% of hit rate. After 60 minutes of colloidal silica polishing, 70% of the points are correctly indexed, while after 180 minutes this value increases to around 80%. Significant difference of effect of weight was not found. This result shows 60 minutes vibratory polishing is enough for EBSD analysis of quartz grain in granite. For another minerals or rock type, further examination might be required.

Keywords: SEM-EBSD, colloidal silica, vibratory polishing, thin section

Fault Lubrication and Billow-like Wavy Folds in a Seismic Slip Plane of Nojima Fault Gouge: Rock Magnetic Perspective

FUKUZAWA, Tomohiko^{1*} ; NAKAMURA, Norihiro¹

¹Graduate School of Science, Tohoku University

An earthquake can occur only if friction decreases rapidly as slip proceeds and the shear stress on its fault planes surpasses the frictional strength of faults, indicating frictional coefficients significantly decrease ($0.7 \rightarrow 0.1$) in proportion to a displacement. High-velocity friction experiments have proposed thermal pressurization and fluidization as weakening mechanism of a frictional strength of faults, but few geological traces for this mechanism are left behind in a natural fault zone. Asymmetric folding and fluttering structures have been found in a natural fault zone, such as in Nojima active fault and in Kodiak accretionary prism. In Nojima fault gouge, it is well known that there are billow-like wavy folds along slip planes, being similar to the pattern of Kelvin Helmholtz (KH)-instability which normally occurs in fluid. This instability generates at the interface between two fluids of different densities shearing at different velocities (Thorpe, 2005). Therefore, the presence of billow-like wavy folds in Nojima fault gouge suggests the fluidization of gouge materials. If a temperature range for the generation of such billow-like folds could be determined, one can give a constraint to the weakening mechanism of frictional strength of faults. Here I show rock magnetic studies to prove the temperature rise in the generation of billow-like folds in cohesive blackish gouges, using a custom-made scanning magneto-impedance magnetic microscope. The results showed the billow-like folds and the sharp slip zones experienced at least a 375 °C heating during its formation from the incohesive grayish gouges, because of the magnetite formation through thermal decomposition of siderite in the grayish gouge. The upper limit of temperature rises can be constrained as at maximum 800 °C by the preservation of microfold textures because high viscosity fluid, such as melt, can't generate a shear flow forming KH-instability. Based on these results, these two zones had been experienced a frictional heating (375 °C ~800 °C). From the temperature condition and the one-dimensional diffusion model, I estimated the frictional coefficient of a fault zone in Nojima fault gouge is approached to be 0.02~0.04 during coseismic slip. These results indicate that thermal pressurization-induced fluidization occurred in the fault slip.

The fragmentation and alteration history of fault rocks in the Byobuyama fault, Gifu Prefecture, central Japan.

KATORI, Takuma^{1*} ; KOBAYASHI, Kenta¹ ; YASUE, Ken-ichi² ; NIWA, Masakazu² ; KOMATSU, Tetsuya² ; HOSOYA, Takushi³ ; SASAO, Eiji²

¹Department of Geology, Faculty of Science, Niigata University, ²Japan Atomic Energy Agency, ³Chuo Kaihatsu Corporation

The Chubu region is one of the most concentrated area of active faults. These are roughly classified into two orthogonally-oriented fault sets of NE-SW and NW-SE strikes. The Byobuyama fault, 32 km in length, is NE-SW strike and located in the boundary of the Mikawa and Mino plateaus. It displaces perpendicularly the Pliocene Toki Sand and Gravel Formation by 500 m. This fault's northeastern edge has contact with the southern edge of the Atera fault of NW-SE strike and offset their displacements each other. It is clear that the activity of the Byobuyama fault has affected topographical development in this area and also plays a role of the development of the complicated fault geometry system in the Chubu region. In this study, we performed structural and chemical analyses of fault rocks of the Byobuyama fault, as a case study for improving research technique to reveal the history of active faults.

Studied outcrop is located in Rontochi area in Mizunami city, Gifu Prefecture. This is a newly discovered outcrop of the Byobuyama fault. Wide brittle fracture zone along the boundary of the Toki Sand and Gravel Formation and Inagawa Granite is identified in this outcrop. Strike and dip of the fault plane is N42E50SE. This outcrop can include the master fault of the Byobuyama fault based on the fault trend, scale of the fracture zone, the relationship dividing the Toki Sand and Gravel Formation and Inagawa Granite, and with the location along the active fault trace. The fracture zone consists of light brown fault breccia (>30 cm thick) derived from the Toki Sand and Gravel Formation, brown fault gouge (about 30 cm thick) derived from the Toki Sand and Gravel Formation, reddish brown fault gouge (about 5 cm thick) derived from the Toki Sand and Gravel Formation, white foliated cataclasite (about 40 cm thick) derived from the granite, white cataclasite (about 30 cm thick) derived from the granite, and weak crushed granite in order from footwall to hanging wall. Deep green fault gouge injects into the foliated cataclasite. At this outcrop, we collected samples for structural and chemical analyses. Samples of non-cohesive fault rocks are fragile because of abundant swellable clay minerals. We referred to Takagi & Kobayashi (1996) and Oohashi et al. (2008) for suitable sample collection, solidification, cutting and polishing. As a chemical analysis, we performed XRD and XRF analyses.

Based on these structural and chemical analyses, the Byobuyama fault has experienced activities of several stages under different stress field. The fault rocks contain smectite, illite and kaolinite as a whole. Especially, the fault rocks derived from the granite also contain zeolite. In addition, we can see a trend that increasing Mg, Ca and LOI, and decreasing Na of the fault rocks. Degree of variability of elements is highest in the fault core.

In this presentation, we discuss the fragmentation and alteration history of fault rocks through the development of the Byobuyama fault.

This study was carried out under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

Keywords: Byobuyama fault, fault rocks, fragmentation, alteration, clay mineral

Permeability evolution of oceanic basalt at Nankai subduction zone: implication from on shore basalt at Shimanto belt

TANIKAWA, Wataru^{1*}; YAMAGUCHI, Asuka²; HAMADA, Yohei¹; KAMEDA, Jun³; TADAI, Osamu⁴; HATAKEDA, Kentaro⁴

¹JAMSTEC/KCC, ²Tokyo University, ³Hokkaido University, ⁴Marine Works Japan. LTD

A large slip displacement was observed at shallow portion of the plate boundary fault during 2011 Tohoku earthquake, and this slip has contributed to cause a huge tsunami disaster. One of possible mechanisms that caused the large slip is a formation of excess pore pressure zone, which can reduce the fault strength for a long period of time, at middle to deeper portion of subduction zone. The excess pore pressure can be generated by chemical dehydration, fluid influx from deeper crust and pore volume reduction which associates with permeability reduction at a large subduction plate boundary. The same process would be caused at the Nankai Subduction zone as well. Fluid transport properties (i.e. permeability, porosity) and their changes during subduction can strongly influence on the pore pressure generation. In the present study, the evolution of fluid transport properties for oceanic basalt at Nankai Subduction zone are investigated by measuring the transport properties for basaltic rocks from the on shore Shimanto belt, South-western Japan.

We collected basalt brocks in the Cretaceous Shimanto accretionary complex of Japan from Okitsu-Kozurutsu, Kure, Mugi (Upper and Lower), and Makimine sites in the southeast Japan. Vitrinite reflectance value, Ro, that is the indicator of the maximum experienced temperature, ranges from 1 to 4.5 in our samples. The basalt from Lower Mugi site shows the lowest value, and the largest value is observed in Makimine site. We measured porosity, elastic wave velocity, and rock electric resistivity of each basalt at atmospheric pressure and room temperature. Permeability was measured at room temperature and under confining pressure from 1 to 160 MPa. The steady state gas flow method was applied to evaluate the permeability by using N₂ gas as a pore fluid. Pore pressure at the upper end of the specimen was kept at constant pressure from 0.05 to 2 MPa to apply constant differential pressure, and mass flow rate at atmospheric pressure that flows out from the lower end of the specimen was measured.

The permeability testing results show gas permeability was proportional to the inverse of the pore pressure at the same confining pressure. This trend agrees with the Klinkenberg effect, therefore most of the gas permeability data were transformed to 'water' permeability using the relationship between gas permeability and pore pressure. Permeability of all samples decreased with an increase of confining pressure, and permeability decreased three orders of magnitude by increasing confining pressure from 5 to 120 MPa. Permeability was lower for more matured basalt, and permeability of the Lower Mugi basalt was $7 \times 10^{-18} \sim 9 \times 10^{-19} \text{ m}^2$ and that of Makimine basalt showed the lowest value of $2 \times 10^{-22} \text{ m}^2$. Variation of permeability in the same unit varied from 1 to 2 orders of magnitude. Pore diameters for all samples showed less than $0.01 \mu\text{m}$, which is the lower limit of the machine.

Permeability reduction by the diagenesis is consistent with the reduction of porosity, and this indicates that a reduction of pore diameter and pore volume induced by a mechanical and chemical compaction during subduction caused gradual permeability reduction. Internal structure of basalt observed from the μX -ray CT image suggests the variation of the permeability in the same unit is influenced by the variation of fracture density for the basalts.

Our results suggest that both pore volume and permeability reductions can significantly contribute to pore pressure generation. Therefore, timing and area of high pore pressure generation can be controlled by the evolution of permeability and porosity with subduction.

Keywords: permeability, diagenesis, pore pressure, Nankai earthquake, Shimanto belt, basalt

Lithology and fluid transport property of the topmost part of the oceanic crust subducting into the Nankai Trough

YAMAGUCHI, Asuka^{1*} ; TANIKAWA, Wataru² ; TADAI, Osamu³ ; KAMEDA, Jun⁴

¹Atmosphere and Ocean Research Institute, the University of Tokyo, ²Japan Agency for Marine-Earth Science and Technology, Kochi Institute for Core Sample Research, ³Marine Works Japan, ⁴Earth and Planetary System Science Department of Natural History Sciences, Graduate School of Scienc

Fluids in subduction plate boundaries play important roles for both mechanical and chemical aspects. Recently, oceanic crust has been recognized as a source of water along seismogenic subduction plate boundary (Kameda et al., 2011). For documenting hydration state of topmost part of subducting oceanic crust, we performed visual, optical and Electron Probe Micro Analyzer (EPMA) observations and powder X-ray Diffraction (XRD) analyses of basaltic rocks retrieved from the Site C0012 of Integrated Ocean Drilling Program (IODP) Expedition 333. We also measured porosity and permeability of samples selected from each lithology. We further interpreted Logging-while-drilling (LWD) data of Hole C0012H obtained during the IODP Expedition 338 to estimate the thickness of seafloor alteration.

The IODP Site C0012 is located at the top of Kashinozaki Knoll, tectonically uplifted topographic high on the Philippine Sea Plate coming into the Nankai Trough. Basaltic rocks in Holes C0012A, E, F, G occurring below 520 mbsf, are mainly composed of upper pillow basalts and lower massive basalts. The pattern of alteration is lithology-dependent: in pillow basalts, volcanic glasses and vesicles were replaced by clay minerals; while alteration of massive basalt showing doleritic texture is characterized by red-colored Fe-oxyhydroxide veins with alteration halos. Potassium-bearing alteration minerals (K-feldspar and celadonite) occur in places.

Permeability measurement of representative samples of each lithology was performed at JAMSTEC-Kochi, under the room temperature conditions with effective pressures of 5 to 120 MPa. Permeability was measured by using N₂ gas as a pore fluid, and calculated by steady-state gas flow method. Gas permeability decreases with increasing effective pressures and pore pressures, following the Klinkenberg equation. Klinkenberg-corrected permeability of pillow basalt ranges 10-19 to 10-20 mD at effective pressure of 5 MPa, while that of massive basalt ranges 10-17 to 10-19 mD. Permeability contrast between the two lithologies would reflect microtextural difference between two lithologies, because of the absence of significant difference in porosity.

LWD data of basaltic rocks were obtained from Hole C0012H of the IODP Expedition 338. Low resistivity and velocity intervals are corresponding to pillow basalts, whereas high resistivity and velocity intervals are corresponding to massive basalts. Contrastingly, gamma ray trend is independent from resistivity and velocity trends: positive at around lithological boundaries. Positive peaks of gamma ray would reflect potassium-bearing alteration caused by permeability contrast between each lithology. Below 680 mbsf, all logging data become constant and non-fluctuated, suggesting that lithology become homogeneous below this depth without strong alteration. Therefore the thickness of hydrated part of oceanic crust at Site C0012 is roughly estimated to be ~100 m.

Laboratory experiments on dynamic rupture propagation using rocks

MIZOGUCHI, Kazuo^{1*}

¹Central Research Institute of Electric Power Industry

Around pre-existing geological faults in the crust, we have often observed off-fault damage zone where there are many fractures with various scales, from $\sim\mu\text{m}$ to $\sim\text{m}$ and their density typically increases with proximity to the fault. One of the fracture formation processes is considered to be dynamic shear rupture propagation on the faults, which leads to the occurrence of earthquakes. Although much work on such off-fault damage associated with dynamic rupture in homogeneous material (ex. polymers) have been done in the past decades (Rosakis et al., 2007), the rupture-induced damaging behavior of rocks, that constitute the faults in nature and of which frictional properties controlling the dynamic rupture might be different from the polymers, is still experimentally unexamined.

Recently, I have worked on laboratory experiments on dynamic rupture propagation along contacting surfaces of two metagabbro blocks from Tamil Nadu, India, simulating a fault of 30 cm in length. For the experiments, the similar uniaxial loading configuration to Rosakis et al. (2007) is used. Axial load σ is applied to the fault plane with an angle θ to the loading direction. Changing the angle makes the ratio of shear to normal stress on the fault a critical level close to the maximum static frictional strength beyond which the fault begins to slip spontaneously. For the critically stressed fault, the triggering of rupture is archived by striking the one edge of the fault with a hammer and the subsequent increase in shear load for a short duration. The load cell attached to the tip of the hammer head can provide us the magnitude and time duration of the impact stress. In this presentation, I introduce the experimental set-up and some preliminary results for the dynamic rupture propagation on rocks. This work is supported by the JSPS KAKENHI (26870912).

Keywords: Dynamic rupture propagation, Rock, Fault, Experiment

Temperature-dependent frictional strength of dolerite in a nitrogen atmosphere

TANAKA, Nobuaki^{1*} ; WADA, Jun-ichi² ; KANAGAWA, Kyuichi¹

¹Graduate School of Science, Chiba University, ²OYO Corporation

Since mid-1990's, high-speed (up to several m/s; equal to coseismic slip rate) friction experiments on variable rocks have revealed that frictional strength significantly decreases with increasing slip rate ≥ 10 cm/s. However, frictional strength possibly decreases due to increased temperatures because the past high-speed friction experiments have not controlled temperatures increased by frictional heating. In fact, friction experiments on dolerite at a normal stress of 1 MPa, a slip rate of 1 cm/s, controlled temperatures up to 1000 °C and in air showed that the decrease in frictional strength at fast slip rates is possibly due to increased temperatures (Noda et al., 2011, JGR). These experiments also showed that the temperature-dependent frictional strength of dolerite has a negative correlation with the amount of amorphous wear material as well as a positive correlation with the amount of iron oxides formed by oxidation of iron-bearing minerals. However, oxidation of iron-bearing minerals as observed in the experiments is unrealistic in fault zones at depths due to the paucity of oxygen there.

We therefore have conducted similar friction experiments on dolerite as Noda et al. (2011) in a nitrogen atmosphere with an oxygen concentration of 0.1 %, and investigated the dependence of steady-state frictional strength on temperature and its relation to the amount of amorphous wear material and the ratio of wear material cover on the slip surface. The steady-state friction coefficient was ~ 0.52 at room temperature, while it was ~ 0.7 being roughly constant at 100-500 °C and ~ 0.76 at 600 °C. The amount of amorphous material ranged within 60 ± 6 wt% from room temperature to 500 °C and ~ 38 wt% at 600 °C. The ratio of wear material cover on the slip surface was ~ 0.78 at room temperature, while it was ~ 0.9 being roughly constant at 100-600 °C. The steady-state friction coefficient of dolerite in a nitrogen atmosphere is significantly lower than that in air (~ 0.77) at room temperature, while it is larger than the latter (0.61 ± 0.03) at temperatures from 100-600 °C. It shows a negative correlation with the amount of amorphous material as observed in air at 100-600 °C, while it also shows a positive correlation with the ratio of wear material cover at room temperature to 500 °C. However, the former and latter correlations become unclear at room temperature to 100 °C and at 500-600 °C, respectively.

The frictional strength of dolerite at room temperature significantly lower in a nitrogen atmosphere than in air is likely due to the lack of moisture-adsorbed strengthening. However, the reason for higher frictional strength in a nitrogen atmosphere than in air at 100-600 °C is unknown at present. It is also unknown at present what are responsible for the correlations among temperature-dependent frictional strength, the amount of amorphous material and the ratio of wear material cover. These are the subjects of our future study.

Keywords: Dolerite, Nitrogen atmosphere, Rotary shear experiment, Temperature dependency, Amount of amorphous wear material, Ratio of wear material cover

Relation between mainshock rupture and aftershock sequence based on highly resolved hypocenters and focal mechanisms

YUKUTAKE, Yohei^{1*}; IIO, Yoshihisa²

¹Hot Springs Research Institute of Kanagawa Prefecture, ²Disaster Prevention Research Institute, Kyoto University

To understand a generation process of aftershock following a large earthquake, it is essentially important to elucidate whether an aftershock reflects re-rupture of mainshock fault plane or rupture of damage zone surrounding it. Liu et al. (2003) found that only a small portion of the aftershocks occurred on the rupture fault planes of the 1992 Landers Earthquake. However, since the location errors of the aftershock hypocenters in their study were up to 1 km, discussion based on more precisely determined hypocenters is essential.

A dense seismic observation network composed of 59 temporary stations was installed, immediately after the 2000 Tottori-Ken Seibu Earthquake (Mw 6.8). The high quality observation data gives us an excellent opportunity to clarify the above issue. To obtain highly resolved hypocenter locations, we used the Double Difference relocation method (Waldhauser and Ellsworth, 2000). Then, we used the differential travel time data determined from manually picked arrival times and cross-correlation analysis. We could determine the hypocenters of approximately 4,100 events that occurred during the period from October, 15 and November, 31, 2000. We also could obtain the focal mechanisms of 3,300 events, by using absolute amplitude data of P and SH waves, as well as P wave polarities.

Since surface faulting were not immersed above the aftershock region of the Tottori-Ken Seibu Earthquake (Ueta et al., 2002), we estimated subsurface structure of the mainshock fault planes on the basis of the relocated hypocenter and focal mechanisms distributions. Since we could see several 'earthquake clusters' that possess similar characteristic of focal mechanism, we divided the aftershock distribution (except the northern part of the aftershock region) into 5 earthquake clusters. We estimated the best-fit plane in each earthquake cluster, by using principal component analysis (e.g. Shearer et al., 2003).

We could obtain 5 best-fit planes. Trends of the best-fit planes near the mainshock hypocenter and southern part of the aftershock region are consistent with those of mainshock focal mechanism obtained from P wave polarities and CMT analysis, respectively. On the other hand, in the northern part of the mainshock hypocenter, the best-fit planes suggesting conjugate fault were estimated. We found that most of the aftershocks in each earthquake cluster were distributed within zones of approximately 1.2 km width, rather than aligned on a single plane. We also evaluated the variety of focal mechanisms by using the Kagan angle (Kagan, 1991) from reference focal mechanisms that were estimated based on the best-fit planes. We found that the focal mechanisms of the aftershocks have wide range of the Kagan angle ($\leq 100^\circ$). These results suggest that many aftershocks represent rupture within fault damage zone around the mainshock rupture planes. The wide variations of focal mechanisms probably reflect the complicate structure in the fault damage zone.

Keywords: Aftershock, Hypocenter distribution, Focal mechanism, Mainshock fault

Earthquake sequence simulations using measured frictional properties for JFAST core sample

NODA, Hiroyuki^{1*}; SAWAI, Michiyo²; SHIBAZAKI, Bunichiro³

¹JAMSTEC, ²Hiroshima University, ³Building Research Institute

Parameters in a rate- and state-dependent friction law (RSF) are often determined by velocity-step tests in which the slip rate V is stepped typically by a factor of 3 to 10. The test may yield a set of parameter values such as a , b , and d_c , but it is often the case that those determined parameters depend on V if a logarithmically wide range of V is investigated. At this point, the originally assumed constitutive law is shown to be invalid, strictly speaking, and thus need to be modified. For example, the experiments by Dieterich [1978] show that the rate-dependency $\partial f_{ss}/\partial \ln(V)$ increases as V increases, which can be explained by introduction of a cut-off time for healing [Okubo, 1989]. Such a proposal of a new constitutive law with a corresponding microphysical interpretation is a great advance in technology which enables us to implement a complex rate-dependency into earthquake sequence simulations, as well as in understanding of physics of rock friction and earthquake generation process. However, not all experimental data showing complex rate-dependency have been digested and implemented in a rate- and state-dependent framework. In this study, we propose a simple modification to the logarithmic RSF which enables implementation of rate-dependencies ($\partial f/\partial \ln(V)$ and $\partial f_{ss}/\partial \ln(V)$) that change with $\ln(V)$.

Sawai et al. [2014, AGU fall meeting] conducted a series of velocity-step tests with a core sample obtained in JFAST project at 50 MPa effective normal stress σ_e , 50 MPa pore water pressure, various temperatures T from 20 °C to 200 °C, and V from 0.3 to 100 $\mu\text{m/s}$. They found that with increasing V , the rate-dependency $\partial f_{ss}/\partial \ln(V)$ increases from negative to positive at $T = 20$ °C, decreases from positive to negative at $T = 100$ °C and 150 °C, and decreases more remarkably but stays positive in the studied range of V at $T = 200$ °C. In order to account for these complex rate-dependencies, we modified the logarithmic RSF to a quadratic form:

$$f = f_0 + F_1 L_V + F_2 L_V^2 + G_1 L_W + G_2 L_W^2$$

where $L_V = \ln(V/V_0)$ and $L_W = \ln(d_c/V_0\theta)$, f_0 is a reference friction coefficient at a reference slip rate V_0 , F_1 , F_2 , G_1 , and G_2 represent rate-dependencies which are assumed to be given by quadratic functions of ambient temperature T , and θ is the state variable representing recent slowness which evolves with a characteristic slip d_c :

$$d\theta/dt = 1 - V\theta/d_c.$$

Note that at a steady-state, $L_V = L_W$ and

$$f_{ss} = f_0 + (F_1 + G_1)L_V + (F_2 + G_2)L_V^2.$$

This is a generalization of the aging law, the original version corresponding to $F_1 = a$, $F_2 = 0$, $G_1 = -b$, and $G_2 = 0$. We determined the rate-dependency functions by least-squares method from the experimental data by Sawai et al. [2014], and investigated the consequence by means of dynamic earthquake sequence simulations [e.g., Lapusta et al., 2003].

In preliminary simulations, we simulated earthquake sequences on a planer fault in 2-D (mode II) problems with depth-dependent T , depth-dependent σ_e , and a rotation axis to mimic intersection of the fault plane and the surface. Distributions of T and σ_e are determined to be consistent with the heat-flow measurement and modeling by Gao and Wang [2014].

Without additional complexity such as patch-like asperities and high-velocity weakening (e.g., thermal pressurization of pore fluid [Noda and Lapusta, 2013]), earthquakes are nucleated at about 30-50 km down-dip from the trench where $\partial f_{ss}/\partial \ln(V)$ is negative regardless of V , and rupture only the shallowest part of the plate interface. The nucleation is preceded by slow slip in the shallower part of the plate interface where $\partial f_{ss}/\partial \ln(V)$ changes its sign with increases V and thus spontaneous acceleration to coseismic slip rate cannot occur. Effect of thermal pressurization and interaction of the system with embedded rate-weakening patches generating earthquakes shall be discussed in the presentation.

Keywords: Earthquake cycle, Friction constitutive law, Numerical simulation, Friction experiment

Relations between wide-area gravity changes and earthquake activity

YAMADA, Kyohei¹ ; MITSUI, Yuta^{2*}

¹Faculty of Science, Shizuoka University, ²Institute of Geosciences, Shizuoka University

We made gravity time series over the world every one month from 2002 to 2014 based on data of the satellite gravity mission GRACE (Gravity Recovery and Climate Experiment). To investigate relations between gravity change and seismic activity, four observation areas (Red Sea, Chile, Tibet and Alaska) were selected. Using seismic activity data of these areas, We counted the earthquake occurrence numbers every one month. A correlative analysis of the gravity changes and the earthquake number of times enabled us to find out that there is a weak correlation between the gravity changes and the earthquake number of times only for the Alaska area. We owed the correlation to some mechanisms of the gravity change leading to the earthquake occurrence in Alaska. Referring to a preceding study about induced earthquakes (Ellsworth, 2013), We investigate two typical mechanisms (fault stress changes due to surface loads by fluid mass increases or reduces in fault friction due to fluid pressure injection). As a result, we consider that the reduction of fault friction by the fluid pressure injection caused the earthquakes, particularly in the northern area of Alaska ($>63^{\circ}\text{N}$) where strike-slip fault mechanisms dominate.

Keywords: Gravity, Seismicity, Induced earthquake, Surface load, Pore fluid pressure

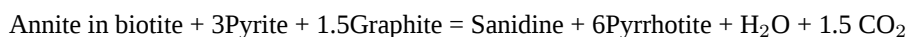
Dynamic fluctuation of redox state during frictional melting and crystallization of graphite-bearing pseudotachylites

NAKAMURA, Yoshihiro^{1*}; MADHUSOODHAN, Satish-kumar²; TOYOSHIMA, Tsuyoshi²

¹Graduate School of Science & Technology, Niigata University, ²Department of Geology, Faculty of Science, Niigata University

We carried out a stable carbon isotopic study of graphite-bearing pseudotachylites to characterize the origin, role and behavior of different forms of carbon during frictional melting. The study area, located in the Hidaka Metamorphic belt, exposes metasedimentary rocks and various magmatic intrusions and are extensively deformed as evidenced by the presence of various types of fault rocks such as graphite-bearing cataclasite, ultracataclasite and pseudotachylites. In particular, graphite-bearing pseudotachylites are observed in the brittle shear zones, which are a few mm to maximum 5 cm in width. They are mainly divided into two types (Pst-I and Pst-II) based on the occurrences, microstructures and mineral assemblages of lithic fragments and secondary minerals. The graphite in each domain of Pst-I and Pst-II were separately analyzed for carbon isotopic composition. Disseminated graphite in protolith has a narrow range of $\delta^{13}\text{C}$ values between -23.6 and -25.8 ‰ (n = 13), and cataclasite, ultracataclasite and Pst I also have similar values between -24.1 and -27.0 ‰ (n = 25). On the other hand, the graphite separated from Pst II matrix on slab sections show values between -18.2 and -23.6 ‰ (n = 16), shifting the carbon isotope values to 2-3 ‰ higher from host metamorphic graphite. In particular, there is a clear correlation between stable carbon isotope composition and volume fraction of lithic fragments in each domain.

Our data indicate that metamorphic graphite in fault rocks were converted into $\text{H}_2\text{O}-\text{CO}_2$ or $\text{H}_2\text{O}-\text{CH}_4$ fluids under very-high temperature condition of frictional melting. Subsequently, a part of the COHS fluid re-precipitated as fluid-deposited graphite and the remaining was expelled as COHS fluids into fault zones during quenching stage. On the basis of chemical compositions and mineral assemblages in the pseudotachylites, we attempt to estimate the P-T- $f\text{O}_2$ - $f\text{S}_2$ phase diagram during frictional melting and crystallization of pseudotachylites. The thermal decomposition of biotite coexisting with graphite and sulfide minerals are deduced by following reaction;



The dehydration and decarbonation processes in this reaction are mainly driven by temperature, $f\text{S}_2$, and $f\text{O}_2$, and the breakdown of biotite that is ferromagnesian mineral change the redox state to the more oxidation state at ranges between $\Delta\text{FMQ} +0.5$ to $+3.0$. Such high $f\text{O}_2$ and $f\text{S}_2$ environments are only observed in the domains which show relatively low-temperature condition (Pst I matrix) during frictional melting. On the other hand, in the domains which show high temperature conditions (>1200 degree C) biotite microlite are observed in pseudotachylites instead of pyrrhotite. This suggests the negative jump to biotite stable field of ASM buffer by lowering $f\text{S}_2$ under high-temperature condition. In addition, we tried to estimate the redox state at precipitation stage using graphite-fluid fractionation model. The difference between disseminated graphite and fluid deposited graphite show the positive 2-3 ‰ shifting by carbon isotope fractionation, suggesting the presence of CH_4 -rich COHS fluid during precipitation stage. Under CH_4 - H_2O dominant fluid in COH diagram, we can explain the carbon isotope variation of fluid deposited graphite at around $\Delta\text{FMQ} -3.0$ by hydration reactions during the crystallization of titanite and hydroxyapatite. Such reducing conditions are only observed in the high temperature frictionally melted domains (Pst II matrix).

Thus, oxidation and precipitation processes of graphite are mainly controlled by the breakdown of ferromagnesian minerals and we revealed that the redox state and TOC values dynamically changed within each pseudotachylite matrix. In addition, our data imply that redox state in pseudotachylite sensitively change in melting domains at ranges of $\Delta\text{FMQ} -3.0$ to $+3.0$ as a function of melting temperature and bulk chemistry.

Keywords: Graphite, stable carbon isotope, pseudotachylite, redox state

Thermal and pressure effect on frictional property of smectite: application to the plate boundary earthquakes of Nankai

MIZUTANI, Tomoyo^{1*} ; HIRAUCHI, Ken-ichi¹ ; LIN, Weiren² ; SAWAI, Michiyo³

¹Department of Geosciences, Graduate School of Science, Shizuoka University, ²Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, ³Department of Earthsciences, Graduate School of Science, Hiroshima University

Along subduction thrust faults, the transformation from smectite to illite at 100-150 °C plays a key role to define the updip limit of the seismogenic zone. If this hypothesis is correct, it is required that smectite exhibits velocity strengthening behavior at in-situ effective normal stress (σ^{eff}) and ~100-150 °C. Here we report results of friction experiments on gouges of pure Na-montmorillonite at σ^{eff} of 10-70 MPa, a pore fluid pressure of 10 MPa, at temperatures of 25-150 °C, and sliding velocities of 0.03-3 $\mu\text{m/s}$, using an oil-medium triaxial testing machine. We found that the coefficient of friction (μ) ranges from 0.056 to 0.120. At temperatures of 20 to 60 °C, μ systematically decreased with increasing σ^{eff} , while at 90-120 °C, it increased with increasing σ^{eff} . With increasing σ^{eff} , the velocity dependence of friction ($a-b$) became negative at 25-90 °C and positive at 120 °C. Therefore, we suggest that smectite friction promotes stable slip along the decollement at the shallow Nankai subduction zone.

Keywords: subduction thrust fault, decollement, aseismogenic zone, smectite, laboratory experiment, velocity dependence of friction

Dependences of pore pressure on elastic wave velocities and Vp/Vs ratio for thermally cracked gabbro

NISHIMURA, Kaya^{1*}; UEHARA, Shin-ichi¹; MIZOGUCHI, Kazuo²

¹Graduate School of Science, Toho University, ²Central Research of Electric Power Industry

Marine seismic refraction have found that there are high Vp/Vs ratio regions in oceanic crusts at subducting oceanic plates. For example, Cascadia subduction zone (2.0~2.8) (Audet *et al.*, 2009), Nankai Trough subduction zone (≥ 2.03) (Kodaira *et al.*, 2004), Chile subduction zone (>1.8) (Marcos *et al.*, 2012). Christensen (1984) conducted laboratory measurements of compressional and shear wave velocities (Vp and Vs, respectively) of basalt and dolerite, which are ones of major rocks in oceanic crust, and the results of Vp/Vs ratio were high enough to explain the observation for basalt, while for the measurements of dolerite, the results of the Vp/Vs ratio were not high enough. This difference may reflect the difference on porosity; porosities of the basalt and dolerite specimens were approximately 4% and 1%, respectively. Peacock *et al.*, (2011) also indicated that Vp/Vs ratio is high when porosity and pore pressure is high. But relationships between of fracture distribution and Vp and Vs for gabbro have not investigated in detail. This study reports the results of measurements of Vp and Vs at controlled confining and pore pressure and estimation of Vp/Vs ratio for thermally cracked gabbro, which is one of major rocks in oceanic crust and can mainly distribute in the high Vp/Vs ratio zone.

To prepare specimens with various fracture distribution, the rock specimens were heated at 500 °C and 700 °C for 24 hours. We also did measurement with an intact rock specimen. We measured Vp and Vs by using transmission method, with putting piezoelectric elements on the specimen. Before measuring Vp and Vs at confining and pore pressure, we did measurements under atmospheric pressure, and revealed the anisotropy of the velocities of up to 10 %. We measured Vp and Vs for four directions at confining and pore pressure. Confining pressure was constant, 50 MPa, and pore pressure was decreased from 49 to 0.1 MPa and then increased to 49 MPa. For the specimen thermally cracked under 500 °C, when pore pressure was 49 MPa, Vp/Vs ratio was 2.0~2.1. This is close to the value of Vp/Vs which was obtained by marine seismic refraction. On the other hand, the Vp/Vs ratio of intact rock did not change as pore pressure changed and were almost constant, approximately 1.5.

At the presentation, we will also show the results of measurements of fracture distribution such as fracture densities or apertures, and reveal the relationship between them and the results of the experiment.

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Keywords: Gabbro, Vp/Vs ratio, Elastic wave velocity, High pore pressure