Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SSS29-01 Room:A05 Time:May 24 12:00-12:15

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

FURUICHI, Hiroyuki[1*] ; UJIIE, Kohtaro[1] ; KOUKETSU, Yui[2] ; SAITO, Tsubasa[1] ; TSUTSUMI, Akito[3] ; WALLIS, Simon[4]

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

SSS29-02 Room:A05 Time:May 24 12:15-12:30

Blackening of fault gouge by pyrolysis of carbonaceous mineral

KANEKI, Shunya[1*] ; HIRONO, Tetsuro[1]

[1]Department 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 ℃.

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

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SSS29-03 Room:A05 Time:May 24 14:15-14:30

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

MUKOYOSHI, Hideki[1*] ; HIRONO, Tetsuro[2]

[1]Interdisciplinary Graduate School of Science and Engineering, Shimane University, [2]Department 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 maturated 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 maturated CM in the fault rock.

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

Keywords: Raman spectroscopy, carbonaceous material, frictional heat

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SSS29-04 Room:A05 Time:May 24 14:30-14:45

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

HIRONO, Tetsuro[1*] ; YABUTA, Hikaru[1]

[1]Department 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

SSS29-05 Room:A05 Time:May 24 14:45-15:00

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

SAKUMA, Hiroshi[1*] ; KAWAI, Kenji[2] ; KATAYAMA, Ikuo[3] ; SUEHARA, Shigeru[1] ; TAMURA, Kenji[1]

[1]National Institute for Materials Science, [2]University of Tokyo, [3]Hiroshima 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 σ <200 MPa and 0.6 for σ >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

SSS29-06 Room:A05 Time:May 24 15:00-15:15

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

TSUTSUMI, Akito[1*] ; MIYAKE, Akira[1]

[1]Graduate 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 $\sim$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).

References

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

SSS29-07 Room:A05 Time:May 24 15:15-15:30

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

NAMIKI, Yuka[1*] ; TSUTSUMI, Akito[1]

[1]Graduate 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-srtate 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

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SSS29-08 Room:A05 Time:May 24 15:30-15:45

Verification of unstable frictional behavior for smectite as elevated temperature

KUBO, Tatsuro[1*] ; KATAYAMA, Ikuo[1]

[1]Hiroshima 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 ef-fect on dehydration under rising temperature. Therefore, in this study, we determined the effect of tempera-ture 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 ma-chine 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 ap-plied 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. De-creasing 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

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

SHIMAMOTO, Toshihiko[1*] ; YAO, Lu[1] ; MA, Shengli[1] ; NIEMEIJER, Andre[2]

[1]Institute of Geology, China Earthquake Administration, [2]Department 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 allow and brass. Temperature measurements in the stationary host specimens and FEM analysis with COMSOLE software revealed that an average temperature in slipping zones in the outer-half of the gouge ranging from 90 to 300 degrees Celcius 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 allow 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

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SSS29-10 Room:A05 Time:May 24 16:15-16:30

Thin share localization in matured mylonitic rock

TAKAHASHI, Miki[1*] ; VAN DEN ENDE, Martijn[2] ; NIEMEIJER, Andre[2] ; SPIERS, Chris[2]

[1]IVGE, GSJ, AIST, [2]HPT 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 pseudtakylite 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 (coseismic). 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 $3*10^{-5}$ 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 stranirate. At lower strainrate ($<1*10^{-3}$ sec^{-1}), the deformation feature was characterized by velocity-strenghtening and mylonitic texture. On the other hand, at higher strainrate ($>1*10^{-3}$ 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 μm 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 pseudtacylite.

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 pseudtakylite zones developed in the mylonite. The mechanical behavior of the mylonite at the earthquake would not obey the RSF law.

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

KITAMURA, Manami[1*] ; SONE, Hiroki[2] ; KITAJIMA, Hiroko[3] ; HIROSE, Takehiro[4]

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

SSS29-12 Room:A05 Time:May 24 16:45-17:00

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

TAKADA, Youichiro[1*]

[1]Disaster 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

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

INAZU, Daisuke[1*] ; ITO, Yoshihiro[2] ; SAFFER, Demian[3] ; HINO, Ryota[4]

[1]The University of Tokyo, [2]Kyoto University, [3]The Pennsylvania State University, [4]Tohoku 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*10^16J. Since the heat content was loaded with several hours, the estimated heat flux is to be 2*10^12J/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

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Large-scale earthquake cycle simulations with Hierarchical Matrices Method

OHTANI, Makiko[1*] ; HIRAHARA, Kazuro[1]

[1]Sci., 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

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

MATSUZAWA, Takanori[1*] ; SHIBAZAKI, Bunichiro[2]

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