SSS29-01 Room:105 Time:May 21 13:45-14:00

Fluid-induced swarm activity as revealed by precisely determined hypocenters and focal mechanisms of earthquakes

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A swarm earthquake sequence is often assumed to be triggered by fluid flow within a brittle fault damage zone, which is supposed to be highly permeable. However, there is little seismological evidence of the relationship between the fluid flow within fault damage zone and the occurrence of swarm earthquakes. Here, we proposed that the 2009 swarm activity at Hakone volcano provide a good example of such fluid-induced activity.

We relocated 1,156 events that occurred in Hakone caldera during the period from August 4 through August 13, 2009 with the double-difference (DD) method (Waldhauser and Ellsworth, 2000). For the relocation of the hypocenters, we used the differential arrival time obtained by both manual picking and wave form cross-correlation analysis. We determined focal mechanisms from the absolute P- and SH-wave amplitudes by adding the P-wave polarities.

We demonstrate that the swarm earthquakes are concentrated on four thin plane-like zones whose thickness is approximately 100 m. One of the nodal planes of the focal mechanisms agrees with the planar hypocenter distribution. The thickness of the plane-like zones is considered to be statically significant, considering the location error of the hypocenters. The value of thickness is consistent with that of fault damage zone for a fault with 1 km length [e.g., Vemilye and Scholz, 1998].

The swarm earthquakes in the initial stage of the activity exhibited a feature of hypocenter migration that can be represented by a diffusion equation. Based on the spatio-temporal distribution of the earthquakes, the hydraulic diffusivity (D) is estimated to be approximately 0.5 to 1.0 m2/s. The values of D are comparable to those estimated in other studies based on the reservoir-induced seismicity, the water injection-induced seismicity, and the spatio-temporal distribution of swarm activities. The observations imply that swarm earthquakes were triggered by diffusion of highly pressured fluid within the fault damage zone.

Keywords: swarm earthquake, fluid, fault damage zone, hypocenter distribution, focal mechanism

SSS29-02 Room:105 Time:May 21 14:00-14:15

Fault geometry affecting spatial distribution and evolution of fracture zones

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There are many major, mature faults in Japan which have been in the plate boundary zone for more than 200 Ma. Such mature faults mostly have heterogeneous structures as a result of interactions between multiple faults. In this presentation, heterogeneity of the spatial distribution and characteristics of fracture zones in mature faults is discussed based on detailed and broadscale geological mapping, including the case study in the area around the Atotsugawa Fault, a long-lived active fault in central Japan (Niwa et al., 2008, J. Geol. Soc. Jpn.; Niwa et al., 2011, Eng. Geol.).

Specifically in fault tips and steps, models of pervasive development of fracture zones are proposed (Sibson, 1986, PAGEOPH). First, the occurrence of a compressional step was recognized by means of aerial photograph interpretation and regional distribution of fracture zones. Detailed geological observation suggests that shear planes with NNE-SSW and NW-SE strikes, high-angle oblique to the trend of the Atotsugawa Fault, are characteristically developed in the step. The shear planes with NNE-SSW and NW-SE strikes can be a part of the composite planar fabric such as R_2 surfaces (Davis et al., 1999, JSG) or deformation band (Okubo and Schultz, 2006, Geol. Soc. Amer. Bull.), which are dominantly developed within compressional steps. Fracture zones in the step are characterized by high densities of fractures and intense brecciation of fragments and minerals, but displacements and rotations of fragments are poorly developed. These characteristics are consistent with the previously proposed conceptional models of fracture zone development in steps (e.g. Sibson, 1986, PAGEOPH).

In addition, more broadscale geological mapping was carried out in the western part of the Atotsugawa Fault to elucidate the spatial distribution of the fracture zones. Within 500 m of the fault trace, the number of exposed fracture zones increases sharply and most fracture zones greater than 2 m width are concentrated. The number and width of the exposed fracture zones display almost the same pattern between a compressional step and a long strand, in contrast with several concepts that fracture zones are pervasively developed around a compressional step. Based on rock features and deformation fabrics at meso- and microscopic scales, once fracture zones had formed, epigenetic deformation was concentrated in the older fracture zones.

Fracture zones less than 2 m width are sparsely but widely distributed in the study area. Most of them are formed by fracturing and weathering accompanied by displacement along joints, schistosities or lithological boundaries, and lack continuity at geological map scale. From a viewpoint of the microscopic observation, they display brittle fracturing characterized by the development of network-patterned cracks and simple fragmentation without ductile shearing, indicating deformation near the surface, under low confining pressure. Various origins of them are proposed: e.g., subsidiary displacement accompanied activities on the surrounding major faults; dilatation due to the decrease in the confining pressure near the land surface; or the displacement of the weak planar structures caused by non-tectonic movement such as gravitational sliding, etc. Based on the comparison with epicenter distribution in the study area, some of them possibly indicate an evidence of ancient shallow earthquakes at a point distant from the fault trace.

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EFFECT OF PORE PRESSURE ON THE FRICTIONAL BEHAVIORS OF SERPENTINITE

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Slow earthquakes (e.g., slow slip events, very low frequency earthquakes and non-volcanic tremors) have been detected in subduction zones where relatively young and hot slabs are subducting, such as southwest (SW) Japan. Low velocity anomaly and high Poisson's ratio have been detected in these regions, suggesting a possible role of serpentinite and high pore fluid pressure triggering these events [1,2]. However, the physical mechanisms of slow earthquakes are not fully understood, although the slow earthquakes are characterized by a different scaling law to the regular earthquakes [3].

In this study, we focus on the effect of pore fluid pressure on the frictional behaviors of serpentinite, and discuss a possible role of high pore pressure on the asperity model and enhancement of slow earthquakes at the subducting plate interface.

In order to test frictional behaviors of serpentinite at high fluid pressure, we used a gas confining medium triaxial deformation apparatus at our institute. In this system, serpentinite samples are grinded cylindrical shape with precut at an angle of 30 degrees. One piece of the samples is drilled through to the slip surface for fluid conduit. Stating material is highly dense and isotropic antigorite serpentinite from Nishisonogi metamorphic belts, Nagasaki, Japan. In the experiments, argon gas and distilled water are used as a pore fluid for dry and wet experiments, respectively. Deformation experiments are conducted at a constant rate (0.001 mm/s) at a constant Pc of 150 MPa and room temperature.

At initial stage, shear stress increases lineally with displacement and reaches a steady value after the yield points. We then stepped pore fluid pressure (Pp) to test frictional response on the serpentinite sliding surface. Initial value of Pp ranged from 50 to 145 MPa, and the magnitude of step changes of Pp ranged from 7.8 to 71.0 MPa. Step changes in Pp were accomplished within $<$0.3 s. Shear stress has been sifted simultaneously with Pp steps and reached a new steady state condition. The stress weakening was observed after increasing Pp (decreasing effective pressure), and the stress strengthening was seen after decreasing Pp. The shear stress shows lineally correlation to the effective stress, suggesting that Coulomb's law is applicable for the sliding test due to pore fluid injection and ejection.

The steady-state shear stresses at wide range of Pp were converted to frictional coefficient f. Under dry conditions (Ar gas was used as a pore fluid), friction coefficient is estimated to be ˜0.66, which is similar value of Byerlee's law. However, under wet conditions (distilled water as a pore fluid), the friction coefficient is slightly smaller, f ˜ 0.51, compared to the dry experiments. The difference in frictional coefficient can be caused by charged water on the crystal surface, which might reduce frictional resistance on the sliding surface under wet environments. Molecular dynamics simulation has shown that sheet-structure minerals, such as mica, tend to adsorb more water on grain surface [4].

Our experimental results indicate that migration of aqueous fluids in subduction zone setting can cause mechanical weakening on the subducting plate interface. Consequently, asperity on the plate boundary might be controlled by heterogeneous distribution of fluids and its significant role of frictional strength on the serpentinized sliding surface.

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Keywords: Serpentinite, Pore pressure, Friction coefficient, Deformation experiment, Slow earthquakes

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SSS29-04 Room:105 Time:May 21 14:30-14:45

Suppression of slip and rupture velocity increased by thermal pressurization: Effect of Dilatancy

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We investigate effect of dilatancy on dynamic ruptures with thermal pressurization (TP), taking into account a power law relationship between permeability and porosity, based on 3-D numerical simulations of spontaneous rupture propagation obeying a slip-weakening Coulomb failure criterion.

Effects of dilatancy on rupture propagation with TP were often investigated in 2-D numerical simulations, or with attention only to behaviors at a single point on a fault plane. Moreover, in the previous simulations, it has never been considered that permeability can change with porosity. Because the hydraulic diffusivity, which controls TP, is proportional to permeability, the changes in permeability along with porosity would affect TP and dynamic ruptures.

To consider changes in porosity and permeability in dynamic ruptures with TP, we solve the thermal and hydraulic diffusion equations with a porosity term by the finite-difference method. Our numerical algorithm for dynamic ruptures is based on the method by Kase and Kuge (2001). Pore pressure from the diffusion equations is included in effective normal stress, while slip velocity and shear stress give the heat source in the diffusion equations. In our model, the frictional heating and the processes of dilatancy occur within the shear zone. We consider both reversible and irreversible changes in the porosity (Segall and Rice, 2006), assuming that the irreversible change is proportional to the slip velocity. Permeability changes with the porosity, according to the power law by David et al. (1994). We put a square fault with the length of 4 km in the infinite medium. The fault is subjected to uniform external stresses.

We reveal that the slip amount decreases with increasing dilatancy coefficient or exponent of the power low, and the rupture velocity is predominantly suppressed by the coefficient. This is observed whether applied stresses are high or low. The deficit of the final slip concerned with the coefficient could be smaller as the fault size is larger.

SSS29-05 Room:105 Time:May 21 14:45-15:00

Monitoring of slip weakening process using transmitted acoustic waves

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To investigate the physical process of slip weakening at subseismic slip rate, Fukuyama et al. (2011, JpGU; 2011, AGU) measured the transmitted acoustic waves during high slip velocity experiments. They concluded that at steady state after the slip exceeds the slip weakening distance, fluctuation of friction, which is typical for the gabbro rock sample at room humidity and room temperature, is controlled by the characteristic size of voids inside the gouge layer. In the experiment, two different proportional coefficients can be found between the friction and transmission coefficient. At beginning before the slip reached the slip weakening distance, the slope was steep, while at the steady state stage, slope became gentle. This difference might be caused by the different process between the weakening and steady state stages. Here, we theoretically investigate this difference. In the scattering theory, Q^{-1} value increases as a function of void size as well as a function of thickness of the gouge layer. In the steady state stage, we assumed that the thickness of the layer does not change. Here, we examine if the steep slope at slip weakening stage can be attributed to the growth of layer thickness or not. We conclude that the steep slope can be explained by the layer growth process. This technique enables us to investigate the generation process of the gouge layer, which might be an origin of the slip weakening process of slip at subseismic slip rate.

Keywords: slip weakening, transmitted waves, high slip rate friction, gouge layer

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SSS29-06 Room:105 Time:May 21 15:00-15:15

Frictional behavior and BET surface-area changes of SAFOD SDZ gouge at intermediate to high-velocity regimes

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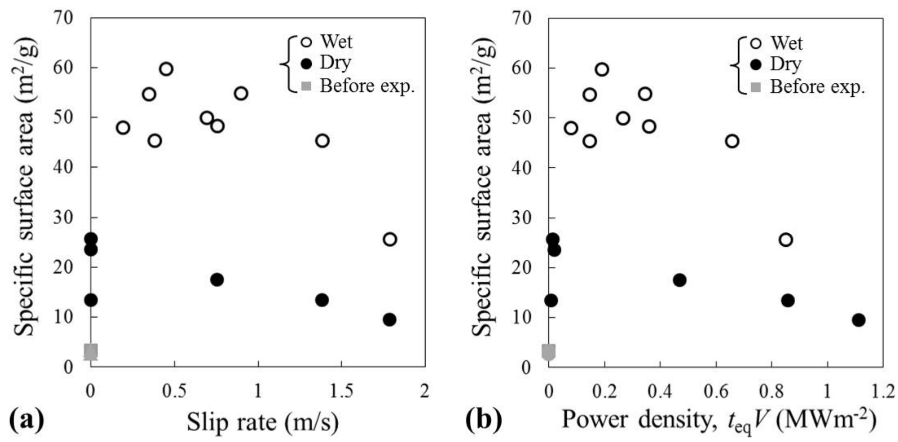
San Andreas Fault Observatory at Depth (SAFOD) Drilling site is located at near the southern end of the creeping section of the San Andreas fault and SAFOD drill cores may provide a clue for the cause of diverse fault motion. We were provided with precious core sample (Phase III core; Hole G-Run 2-Section 8) from southwest deformation zone (SDZ) where creep is confirmed by the borehole casing deformation. Sample for this study was limited to about 6 grams and 6 runs were done at intermediate to high slip rates (10^{-5} to 1.3 m/s) and a normal stress of about 1 MPa and under both dry (room humidity) and wet (with 25 wt% of H_2O added, drained tests) conditions, using a rotary-shear low to high-velocity friction apparatus at Hiroshima University at. One gram of gouge was placed between host rock of Belfast gabbro of 25 mm in diameter with Teflon sleeve outside to contain gouge. Slip rates was decreased first and was increased in step-wise manners to obtain steady-state friction for two runs at intermediate slip rates. Friction coefficient increases from about 0.2 to 0.37 as the slip rate increases from 0.8 x 10^{-5} to 9.7 x 10^{-3} m/s, connecting reported data at the low and high slip rates. Data shows pronounced velocity strengthening at intermediate slip rates which should act as brake for a rupture to grow and this may be a reason for having creep behavior. On the other hand, the steady-state friction markedly decreases at high velocity. Four experiments were conducted at subseismic to seismic slip rate both at dry and wet conditions demonstrating marked slip weakening of gouge at high slip rate. The results agree with reported results for central deformation zone (CDZ). The property of high-velocity weakening may allow earthquake rupture to propagate into the creeping section, as in the case of 1857 and 2004 ruptures, once the intermediate strength barrier is overcome.

BET surface area of gouge (A_{BET}) was measured before and after deformation to determine the energy used for grain crushing. The initial specific surface area (2.6-3.4 m^2/g) increases to 14-24 m^2/g for gouge deformed dry at intermediate slip rates and to 45-60 m^2/g for most gouge deformed at subseismic to seismic slip rates (Fig. 1). The results indicate that about 2 % and less han 1 % of the frictional work is absorbed in grain crushing for dry and wet gouges, respectively, if the fracture surface energy of muscovite (0.38 J/m^2) is used as the surface energy of phyllosilicate-rich SAFOD gouge. Thus grain crushing cannot be an important energy sink during seismic fault motion. The surface area tends to be lower for gouge deformed at high slip rates for both dry and wet gouges. This results and SEM observations of gouge strongly suggests that welding of grains takes place at high slip rate due to frictional heating and counteracts the surface-area increase due to grain crushing. Thus intrafault processes are more complex than in a simple scenario of ”grain crushing and surface-area increase” assumed in recent studies. Surface area is greater for wet gouge than for dry gouge suggesting that pore water separating gouge particles suppresses grain welding. Surface-area measurements are useful to monitor the grain-scale processes during fault motion.

Keywords: BET surface area, Intermediate to high-velocity friction, SAFOD, Energetics of seismic fault motion



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SSS29-07 Room:105 Time:May 21 15:30-15:45

Strain anomalies induced by 2011 Tohoku earthquake observed by means of a dense GPS network in NE Japan

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We evaluated an anomalous crustal strain in the Tohoku region, northeastern Japan associated with a step-like stress change induced by the Tohoku earthquake (Mw 9.0) that occurred off the northeastern Japanese coast in 2011. The source area of the event was extremely large. Hence, the gradient of the observed eastward coseismic displacements at GPS stations had a relatively uniform EW extension in northeastern Japan, suggesting that the induced stress change in this area was uniform. Accordingly, anomalies in the coseismic crustal strain change should reflect the inhomogeneity of rheological crustal characteristics. The deformation anomaly was depicted by subtracting the crustal deformation, which was calculated with a coseismic source model, consisting of two rectangle faults estimated by the observed crustal deformation. The difference in the EW extension anomaly in the forearc and backarc regions possibly indicates a dissimilarity of stiffness, depending on the crustal structure of the Tohoku region. The EW extension in the Ou-backbone range, a strain concentration zone in the interseismic period, was smaller than the predicted extension. This evidence suggests the hypothesis that the viscosity of the lower crust beneath this region is low.

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SSS29-08 Room:105 Time:May 21 15:45-16:00

Stress state and deformation mechanism in the Nankai Trough subduction system

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In subduction zones, the updip transition from aseismic to seismic slip behavior with increasing depth is coincident with porosity loss associated with consolidation, lithification, and diagenesis. Porosity decreases from ~80% within incoming sediments to less than 10% in subducted/accreted rocks at burial depths of a few to ~15km, as observed in the ancient accretionary prism outcrops. Stress states are one of the most important factors governing porosity loss, deformation modes, and fault strength, because in subduction systems where tectonic stress is large, sediments are subjected to complicated stress conditions in time and space. In the Nankai Trough, the input sediments on the subducting Philippine plate and shallower sediments in the modern accretionary prism have been recovered during the Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) expeditions. In this study, we aim to understand the evolution of physical properties (porosity, permeability, and P-wave velocity) and sediment deformation in subduction systems by conducting deformation experiments on both the input sediments and the prism sediments from the Nankai Trough. We conducted ~30 uniaxial and triaxial (both triaxial compression and triaxial extension) deformation experiments on sediments recovered from different depths at different drill sites. Cylindrical samples were deformed by controlling confining pressure, axial stress, and pore pressure, and all pressures, axial displacement, and pore volume change were monitored. Permeability, and ultrasonic velocity were also measured during consolidation and deformation.

We deformed samples of Lower Shikoku Basin (LSB) silty-claystone (initial porosity of 44%) from Site C0011 are loaded under a range of different stress paths including isotropic loading, triaxial compression, and triaxial extension by controlling axial stress (up to 70 MPa), confining pressure (up to 70 MPa), and pore pressure (0.5-28 MPa). We find that the evolution of physical properties (porosity, permeability, and P-wave velocity) is dependent on both effective mean stress and differential stress. Differential stress enhances reduction in porosity and permeability and results in an increase in P-wave velocity. The relationship between defined by our experimental data is fit well by a Cam-Clay model, which describes elasto-plastic behavior of sediments. We also find that the input sediments at the reference sites (Site C0011 and Site C0012) are normally consolidated or slightly overconsolidated, whereas the prism sediments are highly overconsolidated. In particular, mudstones of similar age (Miocene) show a progressive increase in the degree of consolidation with a distance from the deformation front. This suggests tectonic stress (i.e., larger horizontal and differential stress within the accretionary prism) enhance further consolidation and porosity loss, and thus induce brittle faulting deformation rather than cataclasitc flow deformation.

We also apply our observed experimental relationship between P-wave velocity and stress state to estimate in situ stress state and pore pressure within a well-defined low-velocity zone (LVZ) identified in the outer accretionary wedge [Park et al., 2010]. This LVZ is located at ~3 km depth, immediately above the decollement and extends from 15-35 km from the trench. Our lab data constrain the in situ vertical effective stress to be 7-14 MPa, effective maximum horizontal stress of 28-35 MPa, and excess pore pressure of 23-16 MPa. This corresponds to a value of the pore pressure ratio lambda$*$ = 0.53-0.77. This technique to estimate the in-situ stress from the empirical relationship between P-wave velocity and stress states can be further tested in the future drilling to the deeper accretionary complex and the plate boundary faults.

Keywords: subduction zone, IODP, NanTroSEIZE, deformation

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SSS29-09 Room:105 Time:May 21 16:00-16:15

Earthquake sequense simulations accounting for brittle-plastic transition

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In understanding sequences of earthquakes from the point of view of mechanics and structural geology on the fault rocks, brittle-plastic transition of rocks is of great importance as evidenced by field observations of repeated overprinting of pseudotachylyte (frictional melting) and mylonitic (ductile) deformations [e.g., Lin et al., 2005]. Near the down-dip limit of the earthquake ruptures which produce such fault rocks, mylonitic deformation which takes place dominantly during interseismic periods probably affects the stress accumulation process in the shallower brittle zone where earthquakes nucleate. Earthquake generation process is often discussed in terms of the rate-dependency of the frictional resistance of a fault [e.g., Tse and Rice, 1986]. On the other hand, the brittle-plastic transitions are typically expressed as a strength profile across the crust [e.g., Goetz and Evans, 1979]. Given the rate-strengthening characteristics of ductile plastic deformation, these two pictures are closely related to each other [e.g., Sholtz, 1988]. Quantitative discussion by actually solving or simulating sequences of earthquakes on a fault accounting for brittle-plastic transition is required to connect mechanics and structural geology on the fault-rocks.

Recent development of an empirical constitutive equation of a shear zone accounting for brittle-plastic transition (friction-to-flow law) [Shimamoto, 2004, JpGU meeting, Noda and Shimamoto, 2012] enables us simulating sequences of earthquakes consistently with the Brace-Goetz strength profile. The fault model [e.g., Kawamoto and Shimamoto, 1997] which is conceptually constructed based on experimental studies is realized in numerical simulations in which both long-term tectonic loading and coseismic inertial effects are fully accounted for [e.g., Lapusta et al., 2000]. By referring the investigation of the texture of experimental specimens [e.g., Hiraga and Shimamoto, 1987], we can discuss expected fault rock structures after simulations of earthquake sequences. We will also discuss the similarities and differences between the earthquake sequences produced by the logarithmic rate- and state-dependent friction law and the rate- and state-dependent friction-to-flow law.

Keywords: Sequence of earthquakes, Brittle-plastic transition

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SSS29-10 Room:105 Time:May 21 16:15-16:30

A shock-compression experiment of peridotites: toward a better understanding of focal mechanics of deep earthquakes

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Generation of earthquakes that infers fault motions in deep earth remains unsolved problems of solid earth sciences. Frictional melting is well expected at fault planes at high confining pressure and the formation of melt layers will result in a rapid release of cumulated stress leading to a large earthquake (e.g., Kanamori et al, 1998). The occurrence of ultramafic pseudotachylyte in exhumed mantle-derived peridotite mass testifies such mechanism does occur in the upper mantle (Ueda et al, 2008). Conventional friction melt experiment using a rotary high-speed shear testing apparatus cannot be directly applied to the deep earthquakes because of the technical limitation to the confining pressure, which is typically below tens of mega Pascal. We have started a new experimental project using a powder propellant gun at the Shock Wave and Condensed Matter Research Center of Kumamoto University. With this machine it is possible to apply the uniaxial shock stress to samples up to 10~20 GPa by impacting flyer plate with a speed of 1 to 2 km/s. We have performed several shots using natural peridotites and olivine single crystals and observe that multiple shear planes being generated in the samples after such intense compression although any clear textural evidence that indicates frictional melting has not yet been detected. Reviewing the instrumentation and the experimental strategies, we will report some preliminary results of the microstructural observation of shock compressed samples, including an olivine single crystal.

Keywords: shock melting, deep earthquake, frictional melting, peridotite, earthquake source mechamics

SSS29-11 Room:105 Time:May 22 09:00-09:15

Drilling the Alpine Fault: Preliminary project report

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The Alpine Fault, which is dextral-reverse delineates at the Australia-Pacific plate boundary on the west side of the south island, New Zealand. It causes large earthquakes at every 200-400 years (most recently 1717, with expected Mw <7.9). Quaternary fault motions have been determined from landscape features and the deformed rocks around the fault have been investigated in numerous exposures (e.g., Norris and Cooper, 2007, AGU). Recently, microstructures and deformation mechanisms of deformed rocks around the fault have been discussed based on the fabric analyses of quartz (Toy et al., 2008, JSG). It has been proposed that anomalous seismic wave speeds apparent in large-scale seismic transects result from fluid presence within the fault rocks (Stern et al., 2001, Geology). Exhumation occurs rapidly (6-9 mm/yr) from depths of as much as 20-30 km (Little et al., 2005, GJI), yielding young samples.

The drilling project of the Alpine Fault (Deep Fault Drilling Project; DFDP) mainly focus on (1) evolution of a orogenic system, (2) transition between brittle and plastic deformation mechanisms, and (3) seismogenesis and the habitat of earthquakes. The following themes have been identified on which to focus; (a) stresses, fluid pressures, permeabilities, and temperatures adjacent to the Alpine fault, (b) strain localization within the fault core and surrounding damage zone, and the deformation mechanisms related to these, (c) the seismic velocity structure at centimeter to kilometer scales, (d) the deformation mechanisms of minerals (developments of crystallographic preferred orientation; CPO) and reactions (e.g, chloritic alteration), (e) interactions between metamorphic fluids and fault rocks, (f) the thickness of the active slip zone and accompanying damage zone, (g) possibility of episodic slow slip or low-frequency tremor, and (h) developments of pseudotachylyte and element motilities. The Japanese team are involved in (c), (d), and (h) in detail.

The Alpine Fault drilling project has been in planning since 2008, and the drilling started in January 2011. The first phase (DFDP-1), which targeted to drill to 150 m, finished in February 2011, and the samples have already been provided to scientists. Work has now begin on DFDP-2, during which it is planed to drill to 1500 m through the Alpine Fault. DFDP-2 has financial support from the as International Continental Scientific Drilling Program (ICDP). In this presentation, we outline this drilling project.

Keywords: ICPD, J-DESC, contributions of Japanese team

SSS29-12 Room:105 Time:May 22 09:15-09:30

Internal structures and high-velocity frictional properties of Longmenshan fault zone: the current status of researches

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Disastrous Wenchuan earthquake (12 May 2009, Mw 7.9) was accompanied by surface ruptures of about 280 km in EW extension mostly along existing Longmenshan fault system (e.g., Lin et al., 2009, Tectonophysics). Wenchuan Earthquake Fault Scientific Drilling (WFSD) has started about two years ago under the leadership of Z. Xu and this was the third rapid drilling into seismogenic fault immediately after a large earthquake, following the drilling into the Nojima and Chelungpu faults. Compared with the latter two, a big advantage of studying the Longmenshan fault system is that deep exhumed fault zones such as low-temperature mylonites are exposed on surface (e.g., Xu et al., 2008, Episodes). One has a chance to construct a fault model for shallow to deep portions of the fault by combining studies of coseismic surface ruptures, shallow drill cores and exhumed fault rocks that formed at depths. WFSD drilling is still underway although initial results from series researches were reported at AGU fall meeting in 2010. Unfortunately, however, WFSD drill cores are not released for physical property measurements as yet. Thus Institute of Geology, CEA drilled five shallow holes into the Beichuan-Yingxiu fault and studied fault zones at several surface outcrops. We report here internal structures of fault zones as studied at Hongkou, Pingxi and Xiaojiaqiao outcrops and from Shenxigou shallow drill core. All gouge from those fault zones exhibit dramatic slip weakening at high velocities and we compare experimental results for fault gouges from those locations to delineate heterogeneity in frictional properties of faults. Fault gouge exhibits considerable variation even from the same fault outcrop. WFSD data will be included if cores are available in the near future.

Keywords: Longmenshan fault, Wenchuan earthquake, Fault rheology, High-velocity friction, Fault rock, Earthquake mechanism

SSS29-13 Room:105 Time:May 22 09:30-09:45

Amorphization of clay minerals by thermal and mechanochemical processes, and its implications for seismic faulting

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Amorphous nanoparticles on the slip surface have been paid much attention since they give significant influences on the frictional properties. They are considered to be formed by combined processes including mechanical, chemical and thermal ones. It is well known that clay minerals are easily transformed into amorphous materials mechanochemically by grinding. We performed experimental studies on amorphization of kaolinite and saponite, common clay minerals under a surface environment.

Heat treatment: Crystalline kaolinite was completely decomposed and transformed into amorphous phase after 1 hour heating at 600 degrees Celsius and also after 1 minute heating at 1000 degrees Celsius. Saponite was completely decomposed and transformed into enstatite after 5000 minutes at 680 degrees Celsius and after 60 minutes at 800 degrees Celsius. The activation energy of amorphization of kaolinite was estimated to be 98kJ/mol.

Mechanochemical process: Dry grinding experiments of crystalline kaolinite and synthetic saponite using a planetary ball mill were conducted. Amorphization is completed after 3 hours milling (400 rpm) for kaolinite and 9 hours for saponite. Aggregates of nanoparticles were observed with FE-SEM. The injection energy during the experiment is estimated to be 9550 kJ/kg for kaolinite and 28700 kJ/kg for saponite.

The maximum temperature on a fault surface could be as high as 1000 degrees Celsius by frictional heating. The fracture energy in large earthquakes is estimated to be 1000 to 10000 kJ/kg. Thus kaolinite can be transformed into amorphous phase in faulting. Saponite is less easily amorphized than kaolinite. This is concordant with the observation at Taiwan Chelungpu fault core (Hirono et al., 2008).

Keywords: clay minerals, amorphous, mechanochemical, frictional heating, faulting

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SSS29-14 Room:105 Time:May 22 09:45-10:00

Mechanochemical effect on chemical reactions during earthquake slip

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Transient frictional heating in a fault zone during earthquake slip induces various chemical reactions. In the case of the Chelungpu fault in Taiwan, which slipped during the 1999 Chi-Chi earthquake, material within the slip zone was reported to be relatively low in inorganic carbon (mainly calcite), smectite, and kaolinite contents, compared with the surrounding rocks. These characteristics have been attributed to friction-induced thermal decomposition of calcite, dehydration of interlayer water and dehydroxylation of smectite, and dehydroxylation of kaolinite, and the released gas and fluids from such reactions have a strong role in dynamic fault weakening, similar to that of thermal pressurization. However, mechanochemical effect by coseismic slip is not fully considered on such process. Here we performed high-velocity friction experiment of clay mineral, and analyzed the samples after the experiments using TG-DSC, XRD, ATR-IR, and particle size analyzer. In this presentation, we show the preliminary result and discuss the mechanochemical effect on the chemical reaction during earthquake slip.

SSS29-P01 Room:Convention Hall Time:May 22 17:00-18:30

Three-dimensional attenuation structure beneath the Tokai region, central Japan

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Long term slow slip (LTSS) and non-volcanic low frequency earthquakes (LFEs) were reported in the central part of the Tokai district, central Japan. Such LTSS and LFE events are considered to take place at transition zone from stick-slip zone to stable sliding zone and to be associated with fluids on the subducting Philippine Sea plate's surface. To clarify the spatial variation of the physical properties in this region, we estimated a three dimensional seismic attenuation structure using joint inversion method.

In this study, we used 3688 spectra of 140 earthquakes which were observed by both temporary stations conducted from April to August in 2008 and permanent stations. Frequency band was divided equally among 24 between 0.78125 and 18.75 Hz and equally among 8 between 18.75 and 31.25 Hz. We gave Q blocks by dividing study area into 7 in the N-S direction between 137E and 138.5E degree, into 6 blocks in E-W direction between 34.5N and 35.7N, and 6 depth layers. We estimated frequency independent Q value of each block.

In the shallow depths from surface to 5km, we found a lower Q zone located along the Median tectonic line which divides the southwestern Japan into two parts; a old geologic belt and a new accretionary belt. In the lower crust of the land plate at the depths of 17 to 25km, a very high Q zone (about 2000) exists just above the region where large slip rate was observed in LTSS between 2001 and 2005. Since very few earthquakes occur in this high Q zone, that portion might consist of harder rocks than surroundings. On the contrary, the region just beneath the large slip zone has lower Q than surrounding area. Comparing our results with the seismic velocity structure derived from travel time tomography, we found the high Q zone approximately coincides with relatively high velocity zone, and lower Q zone corresponds to the relatively low velocity and high Vp/Vs region. As mentioned in previous studies, low Q zone with low velocity and high Vp/Vs is interpreted as the zone which involves high-pressure fluid. Probably the high Q zone above the large slip zone works as a cap rock and prevents the fluid moving toward the shallow part, then the fluid pressure becomes high and it affects the occurrence of slow slip in this region.

Keywords: attenuation structure, Q value, Tokai region, slow slip

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SSS29-P02 Room:Convention Hall Time:May 22 17:00-18:30

Propagation dynamics of episodic tremor and slip governed by fault rheology and heterogeneity

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Slow earthquakes called episodic tremor and slip (ETS) propagate over 100 kilometers at low velocities, ~10 kilometers per day, along several plate interfaces. These low velocities differentiate slow earthquakes from ordinary earthquakes, and thus understanding their propagation processes is fundamental to understand the diversity and universality of earthquake processes. Comprehensive modeling and previously-unreported correlations of migration patterns with energetics of tremor observed in Japan show that rheological fault heterogeneity essentially governs ETS propagations. The fault has persistent small-scale segmentation, where the propagations always energetically started in brittle sections and decelerated in the ductile sections; spontaneous rupture calculations constrain the ductility to that caused by the Newtonian plastic flow or dilatant strengthening, but not by large-scale fluid flows.

Keywords: Slow earthquake, Rheology, Tremor, Model, Rupture dynamics, Simulation

SSS29-P03 Room:Convention Hall Time:May 22 17:00-18:30

Shallow very low frequency earthquakes off Sanriku, Japan

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Activities of shallow very low frequency earthquakes (VLFEs) have been reported around the trench axis of the Nankai subduction zone and the off-Tokachi region (e.g., Obara and Ito, 2005; Asano et al., 2008). In NIED, epicenters of seismic sources including VLFEs are routinely located by an array analysis technique using Hi-net high-sensitivity accelerometers (Asano et al., 2008). Some of the epicenters are located off the Pacific coast of Tohoku, though the number in this region is much smaller than that in the off-Tokachi region. However, these events are not fully examined, as most of these sources have been thought to arise from earthquakes and microseisms. In addition, a slow slip event has been recently reported in the off-Sanriku region (Ito et al., 2010). In this study, we aim to detect VLFEs off Sanriku with a waveform correlation analysis.

The array analysis with Hi-net high-sensitivity accelerometers detected a seismic source off Sanriku at 22h, 10 March, 2011. We estimated a CMT solution of this event using F-net broadband seismometers and Hi-net high-sensitivity accelerometers (Ito and Obara, 2006). The result shows a reverse fault mechanism located at the depth of 18 km with Mw3.5. This event is not clear at the frequency of several Hz, and dominant at 0.05-0.1 Hz, though a typical dominant frequency of regular earthquakes with similar magnitude and close hypocenter is several Hz. Therefore, this event is considered as a VLFE.

Other VLFEs off Sanriku are detected by a waveform correlation analysis adopted in Asano et al. (2010). Averaged cross correlation values are calculated using broadband seismograms at six F-net stations which are bandpass-filtered between 0.02 to 0.1 Hz. The VLFE at 22h, 10 March 2011 are adopted as a template event in this correlation analysis. Epicenters of similar VLFEs are searched within the range of one degree both in the longitudinal and latitudinal direction. If the averaged cross correlation value is over 0.3, we manually check the waveforms and select the events which are not attributed to near- or far-field earthquakes and microseisms.

Applying this technique to the period between 2005 to 14:46, 11 March 2011, we detected two VLFEs on 12 December 2007, one VLFE on 5 July 2009, and another VLFE on 10 March 2011. Activities of VLFEs off Sanriku are much lower than that off Tokachi, where accumulated counts of VLFEs are about six thousand (Asano, 2011). These VLFEs are located at the north of the aftershock area of the M7.3 off-Sanriku earthquake on 9 March 2011. In addition, the activity of regular earthquakes is low in this region. It is not revealed whether the VLFEs occur on the plate interface or within the overriding plate in this region. If we assume that the VLFEs are slip of plate interface, our result implies that frictional property shows stable sliding at this region in a usual state. Shibazaki et al. (2011) numerically reproduced large and great earthquakes which recur at the intervals of one hundred and several hundred years, respectively. In their model, it is assumed that the surrounding region of asperities shows a velocity-strengthening behavior at low and intermediate slip velocity, and strong velocity-weakening at high slip velocity. The detected VLFEs are located at the surrounding region of the asperity of the M 7.3 off-Sanriku earthquake on 9 March 2011, and at the region with large slip of the 2011 off the Pacific coast of Tohoku earthquake. Perhaps, the frictional property assumed in Shibazaki et al. (2011) may be actually important in the seismic cycles of the Tohoku region. A further observation at ocean bottom in this region would reveal the detailed activity of VLFEs.

Keywords: very low frequency earthquake, Off Sanriku

SSS29-P04 Room:Convention Hall Time:May 22 17:00-18:30

3D modeling of the cycle of a great Tohoku-oki earthquake considering thermal pressurization

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During the 2011 Tohoku-oki earthquake, large slips occurred in the region near the trench off Miyagi (e.g. Fujii et al. 2011). Hasegawa et al. (2011) showed that during the earthquake, the background deviatoric stress was completely released. This result suggests that the frictional strength decreased considerably. Recent studies on the fault rheology show that a considerable weakening can occur at a high slip velocity because of thermal pressurization or thermal weakening processes (Tanikawa and Shimamoto, 2009; Di Toro et al., 2011; Tsutsumi et al., 2011). Noda and Lapusta (2010) performed 3D simulations of earthquake sequences with evolving temperature and pore pressure resulting from shear heating, and they found that regions of more efficient thermal pressurization produce relatively large slips, resulting in large events with long interseismic periods. Mitsui et al. (2012) developed a 2D quasi-dynamic earthquake cycle model of the Tohoku-oki earthquake by considering thermal pressurization. The present study develops a 3D quasi-dynamic earthquake cycle model of the Tohoku-oki earthquake by considering thermal pressurization. We use a spectral solver for 1D diffusion problem developed by Noda and Lapusta (2010) to efficiently calculate the temperature and pore pressure evolution on a fault plane. We set several asperities in the regions off Miyagi, off Fukushima, and off Ibaraki, and set long asperities near the trench. We set the frictional properties of velocity weakening in the asperities; however, we set velocity strengthening outside of the asperities. Further, we set a low value for hydraulic diffusivity in the shallower part of the plate interface off Miyagi. The preliminary results show that M7.5 class earthquakes occur at the zone with relatively large hydraulic diffusivity. When rupture occurs around the low hydraulic diffusivity zone, significant thermal pressurization occurs and results in large and fast slips. This rupture propagates to the surrounding region and to the asperities of M7.5 earthquakes, because thermal pressurization occurs as a result of large slip even in the region of large hydraulic diffusivity.

Keywords: the 2011 Tohoku-oki earthquake, 3D earthquake cycle model, thermal pressurization

SSS29-P05 Room:Convention Hall Time:May 22 17:00-18:30

Mechanical processes of preparation for large scale events

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In order to forecast the occurrence of large events in the Earth's crust, we need to understand their preparation process. Although some precursory phenomena have been proposed as preparation process for large events, most of their mechanical background is not clear. To understand the mechanical processes before large scale events, we examine numerical experiments in which multi-scale events spontaneously occur using discrete element method. The results show that before the occurrence of large events, the deviation of the direction of principal stress axes becomes small in a surrounding area of the large events. This represents a kind of homogenization of the stress field before a large event. After the large event, the stress distribution becomes scattered where only small events can occur.

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Numerical simulation of a shape of an off-fault microcrack distribution observed in natural faults

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Rupture propagation on a fault plane forms microcracks outside the slip zone. Formation of microcracks consumes the energy for the rupture propagation. Off-fault microcracks are thus important and has been investigated in both field observations (Vermilye and Scholz, 1998) and numerical calculations (Andrews, 2005; Hok *et al*., 2010). The number density of the microcracks outside the slip zone inferred from numerical experiments sometimes differs from those obtained in the field observations. Field observations show that the number density of the microcracks is almost constant along the fault direction whereas, in the numerical experiments, the width of the region in which microcracks distribute increases linearly with the rupture propagation distance. This result from numerical experiment suggests that number density of microcracks around a fault increases proportionally to the propagation distance.

In this study, we assume a two-dimensional mode III fault and show that the initial stress field affects the microcrack distribution. We use the Coulomb failure criterion both for the rupture propagation on the fault plane and formation of the microcracks. In order to use the Coulomb failure criterion for the off-fault failure, we calculate maximum shear stress and normal stress at each locus. When these stresses satisfy the Coulomb failure criterion, off-fault microcracks form. We vary the initial stress field and cohesion as parameters.

We find that, when the initial shear stress (sigma_yz) which drives the on-fault rupture propagation decreases linearly along the fault, the final stress drop becomes negative and fault-tip growth is arrested. In this situation, the width of the microcrack distribution does not increase as a function of the rupture propagation distance, but becomes almost constant. This result is similar to the distribution observed in natural faults. In contrast, when the initial shear stress decreases linearly perpendicular to the fault plane, the width of the microcrack distribution perpendicular to the fault plane does not decrease.

Another our finding is that larger cohesion makes the width of the microcrack distribution smaller. We obtain similar results when the lithostatic stress is larger. This is because both cohesion and the lithostatic stress increases the critical stress to cause failure.

We infer that the microcrack distribution can become a measure of the initial stress field.

Keywords: microcrack, numerical simulation, stress field, arrest of fault-tip growth

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Dynamic change of flow rate in impermeable fault rock

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Hydrological and hydro-geochemical changes are often observed soon after big earthquakes at active faults and hot springs, and a part of them were caused by a rapid change of permeability structure of a fault zone. Change of fluid transport properties in fault zones plays an important role in dynamic processes during large earthquakes as well as earthquake cycle processes. However, the physical and chemical processes responsible for the evolution of hydrological properties in fault zones during earthquake are not well known.

Therefore a rotary shear testing apparatus at Kochi Core Center was used to understand the physical process for the changes of fluid transport properties in a fault zone by real-time measurement of gas flow rates during and after frictional sliding.

We prepared a pair of hollow cylinder (inner diameter=9 mm, outer diameter= 25 mm, length=20 mm), and to demonstrated the frictional sliding, one cylindrical specimen was fixed and the other rotated under a fixed axial stress. To measure the permeability, radial flow from the inner wall to the outer wall of the specimen was induced by applying a differential pore pressure between the inner and outer walls. Real-time change in permeability is evaluated by monitoring the flow rate during the frictional test. Nitorgen gas was used as a pore fluid. We conducted friction tests at various slip rates (0.076 mm/s to 190 mm/s) and 2 MPa of normal stress with 1.5m of displacement. We used Aji granite in friction tests, and gas permeability of intact host rock that shows 10^{-19} m^2 was lower than that of the simulated fault specimen before sliding (10^{-16} m^2 at 2 MPa of normal stress, and 10^{-18} m^2 at 50 MPa).

Permeability is changed during the sliding in all tests, and when initial permeability is smaller than 10^{-17} m^2, average flow rate during sliding increases, on the contrary, flow rate decreases during sliding when initial permeability is larger than 10^{-17} m^2. Flow rate decreased by 10 % of the flow rate at the end of sliding, reaching a steady state within ten minutes, but for slip velocities greater than 50 mm/s, the flow rate increased after the end of sliding. The reduction in flow rate after sliding is probably caused by the thermal expansion of sliding surface due to frictional heating, and the cooling after sliding decreased the aperture and results in the decrease in permeability of slip surface. Increase in flow rate at high velocity condition is induced by the increase in viscosity of nitrogen gas by frictional heating.

At the same slip velocity, average flow rate during sliding is proportional to coefficient of friction. Slip surfaces of hollow specimen is partly covered with sheet silicate fine-grained gouge layers, and the gouge layers imply low friction and low permeability. Therefore the increase in the ratio of gouge materials among the contact area will induce a reduction in flow rate that associates with lower friction and permeability. A connectivity of sheet-silicate gouge layers will influence on the permeability as well. In the future, we can estimate the friction coefficient from the flow rate or permeability of sliding surface of active fault zone by applying our study.

Keywords: permeability, frictional heating, wear, earthquake, fault, flow rate

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Energy partition for grain crushing in quartz gouge and sintering effect during subseismic to seismic fault motion

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To determine how much of the frictional energy consume in grain crushing is important because this fraction will affect the energy used for frictional heating which in turn can affect the mechanical properties of a fault during seismic fault motion. In addition, it is geologically important to understand the formation and developing process of the mature fault zones.

Thus we have conducted friction experiments on quartz gouge as a simple case at subseismic to seismic slip rates. Quartz was selected because it is a very common mineral in fault zones and its surface energy is measured (about 1 J/m2, Brace and Walsh, 1962). Brunauer-Emmett-Teller (BET) surface area of quartz gouge was measured before and after shearing. Measurement of BET surface area provides more direct data on surface-area change than grain-size measurement does. Our recent results show that grain crushing absorbed only 0.02~0.22 % of frictional work. Thus, grain comminution is unlikely to be an important energy sink at least for mature faults with well-developed slip zone.

Another new finding from our study is that the BET surface area of quartz gouge deformed at high slip rates begins to decrease after a certain displacement. Sawai et al. (2009) also have found that the surface area of Nojima fault gouge decreases, rather than increases, with shearing deformation at seismic slip rates. Our observations of quartz gouge revealed that fine grains formed cohesive aggregates and dendritic clusters. In particular, the dense granular aggregate strongly suggests that sintering of gouge partially occurred. The bulk temperature rise in quartz gouge in our experiments would be on the order of several hundred degrees Centigrade in view of recent experiments under similar conditions and temperature calculations (Mizoguchi et al., 2009; Kitajima et al., 2010; Han et al., 2011). This may not be enough for full sintering to occur, but flash heating probably contribute to partial sintering (see Rice, 2006; Han et al., 2007a, 2007b; Oohashi et al., 2011).

Keywords: High-velocity frictional experiment, Energy budget, Fracture energy, Sintering

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An effect of grain size on high velocity slip behaviors of olivine aggregates

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Olivine is a key mineral that controls the slip behavior of seismic faults in deep oceanic crusts at mid-ocean ridges and subduction zones. However, its frictional property is not well understood, especially at coseismic slip velocity (i.e. >0.1 m/s). In this experimental study we crushed and sieved San Carlos olivine into four grain size ranges (3, 5, 15, 35, and >50 micron). The olivine aggregates of 0.5 g were deformed dry to >10 m displacement at velocity of 0.0013-1.3 m/s and normal stress of 0.5-2.0 MPa using a rotary-shear apparatus, in order to reveal the effect of initial grain size on slip behavior at high velocities. In addition, we examined the microstructures of the simulated fault zone that control the high-velocity slip behaviors using a FE-SEM.

The experiments at high velocity showed a typical slip weakening behavior: friction coefficient is 0.7-0.9 at the initiation of slip and it decays exponentially to a steady-state stage of 0.2-0.3 over a slip weakening distance Dc. Dc decreases from 40.0 to 4.0 m as increase in normal stress from 0.5 to 2.0 MPa, respectively, following a power-law relation. There is no clear grain size dependence of friction level and Dc. In contrast, slip weakening behaviors are invisible at velocities of < 0.13 m/s. Such slip-weakening and velocity-weakening behaviors of olivine aggregates are quite similar with other rocks sheared at high velocities (e.g., Di Toro et al., 2011).

A slip localized zone forms during high-velocity sliding and is composed of fine-grained olivine with less than 1 micron. Interestingly thickness of the localized zone tends to become thinner for initially finer grains: thickness of localized zone is 50,33 and 3 micron, respectively. This implies that a positive feedback process between grain-size reduction and slip localization could operate within a gouge zone during cosesmic sliding leading to the dynamic weakening of faults.

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The influence of lubricating agents for the strength reduction of faults

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The weakness of mature faults, which is presumed by lack of heat flow anomaly and stress orientations around faults, is still open to argument. One of the explanations for these weak faults is that the presence of weak minerals (fault lubricants) such as phyllosilicates along the fault zones. Frictional experiments on bimineralic mixtures with phyllosilicates are conducted to examine its operation for weakening agent (e.g. Logan and Rauenzahn, 1987; Brown et al., 2003; Takahashi et al., 2007; Crawford et al., 2008). However, these previous studies are conducted with limited shear strain (mostly $<$10) in spite of significance of fabric development on weakening has been pointed out (Collettini et al., 2009). We thus performed large strain, friction experiments on graphite- and smectite-quartz bimineralic gouges using rotary-shear, low- to high-velocity friction testing apparatus to understand how frictional behavior changes with fraction and shear strain.

Experiments were done with dry and water-saturated conditions for graphite and smectite mixtures, respectively. Experimental results clearly indicated that the steady-state friction of the mixture gouge decreases exponentially with content of graphite/smectite (see figure); it starts to reduce at fraction of 5 vol% and reached to the almost same level of pure graphite/smectite at the fraction of $>$30 vol%. According to textural observation for the graphite mixtures, weakening of $<$28 vol% mixtures is associated with formation of slip-localized zone and development of graphite-lubricated, throughgoing slip surface with progressive shearing. On the other hand, $>$28 vol% of mixtures show diffused, graphite matrix flow within the slip-localized zone due to the development of graphite connection parallels to the Y- and P-surfaces. The relationship between strength versus graphite fraction evolves from early gentle to later abrupt sigmoidal curve with increasing shear strain (see figure). These trends are quite different from that of previous studies, and highlight the importance of shear strain and accompanied textural development on formation of weak fault.

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Keywords: Fault lubricant, Graphite, Smectite, Fault gouge, Fault weakening, Friction experiment

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SSS29-P11 Room:Convention Hall Time:May 22 17:00-18:30

Effects of confining pressure and mineral property on rupture propagation process revealed by unstable-slip experiments

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Episodic slow slip events, as defined by anomalously low rupture velocity within a range of 5 to 15 km/d (0.06 to 0.17 m/s), have been observed in subduction zones, and occur as shear slip on the plate interface downdip of the seismogenic zone. A considerable body of evidence points to high fluid pressures on the plate interface that may reduce effective normal stress and enable slow slip. Laboratory observations on rocks have shown that nucleation of unstable slip consists of an interval of fault creep that localizes and accelerates to a dynamic rupture, with propagating velocity comparable to shear wave velocity of the material. However, in spite of the importance of low effective normal stress in causing slow slip events, the effect of normal stress on the rupture properties of the fault has been yet explored.

In this study, unstable-slip experiments were conducted in a gas-medium apparatus at room temperature, confining pressures of 60-180 MPa, and a nominal strain rate of 1 x 10-3 s-1. We used powders of lizardite/chrysotile (liz/ctl), antigorite, and olivine as the starting material, producing a ~0.7-mm-thick layer of simulated fault gouge between two gabbroic forcing blocks. To monitor directly the strain field parallel to the fault surface, four strain gauges were mounted onto the lower gabbro cylinder along the fault. The friction coefficient was 0.48-0.58 for liz/ctl and 0.67-0.72 for antigorite, while olivine has a friction coefficient of 0.72-0.73.

The stress-strain curves exhibit an initial linear elastic portion, a strain-hardening range in which stress increases with strain and, finally, a range in which the stress levels off or drops off until one sudden, large unstable-slip occurs. At P_c = 100 and 140 MPa for antigorite and olivine, the shear stress dropped to a residual value at least within 50 us during the unstable-slip event. The rupture propagated bilaterally at speeds ranging from a few hundreds meters to a few kilometers per seconds. At P_c = 100-180 MPa for liz/ctl and P_c = 60 MPa for antigorite and olivine, the local strains show that a rupture started to propagate slowly at speeds in the range of 0.7 to 2.0 m/s. Eventually, a rupture propagates at fast speeds. At P_c = 60 MPa for liz/ctl, the shear stress decreased very slowly towards a residual value within ~1 s. The local strains show that a rupture nucleated just before the onset of stress drops, and then propagated at speeds ranging from 0.07 to 0.25 m/s.

There is no systematic dependence of confining pressure on the observed rupture velocity during the fast stress drops. In contrast, the rupture velocity during the slow stress drops appears to decrease with decreasing confining pressure. We thus conclude that the slow rupture propagation process along the gouge-bearing fault is affected by intrinsic material property and confining pressure. A series of slow earthquakes including slow slip may reflect differences in the size and duration of slow rupture phase, which becomes dominant if the weak material exist on the fault at low effective normal stress. In particular, the rupture property characterized by a slow stress drop with anomalously low rupture velocity observed at P_c = 60 MPa for liz/ctl might be analogous to that of slow slip events in nature.

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Contrasting hydrological and mechanical properties between hemipelagic and turbidite muds from the shallow Nankai Trough

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We found that two mud samples cored from shallow (c.a.1000 mbsf) accretionary sediments at Site C0002 of IODP Exp. 315 are different in origin; one is a hemipelagic mud and the other is a turbidite mud. The hemipelagic mud sample is poorer in quartz and feldspar (34 wt%), richer in clay minerals (41 wt%) and uniformly fine-grained, whereas the turbidite mud sample is richer in quartz and feldspar (51 wt%), poorer in clay minerals (37 wt%) and poorly sorted. The former has a small porosity of 11%, while the latter has a large porosity of 38%.

At room temperature, in-situ confining pressures of 36-38 MPa and water pressures of 28-29 MPa, the hemipelagic mud sample has a smaller permeability of $2.9*10^{-19}$ m^2, while that the turbidite mud sample has a larger permeability of $2.3*10^{-18}$ m^2. Triaxial compression experiments at these conditions and an axial displacement rate of 10 micron/s reveal that the former exhibits a smaller peak strength of 14.5 MPa followed by a slow failure lasting for a minute, whereas that the latter exhibits a larger peak strength of c.a. 20 MPa followed by a rapid failure within seconds. Friction experiments at these conditions and axial displacement rates changed stepwise among 0.1, 1 and 10 micron/s reveal that the hemipelagic mud sample has a much smaller friction (friction coefficient = 0.25) than the turbidite mud sample (friction coefficient = 0.53). Although both samples exhibit rate-strengthening behavior upon velocity stepping, the velocity dependence of the former is much larger than that of the latter. In addition, a certain type of flow likely contributes to the former's frictional strength.

Such contrasting hydrological, mechanical and frictional properties between hemipelagic and turbidite muds have important implications for faulting in the shallow Nankai Trough accretionary prism. Faulting would preferentially occur in the hemipelagic mud, because it is weaker than the turbidite mud. The faulting in the hemipelagic mud would occur slowly, and therefore is a possible source of very low frequency earthquakes recently found in the shallow Nankai Trough accretionary prism. Faults formed in the hemipelagic mud are also much weaker in strength than those in the turbidite mud. In addition, the hemipelagic mud is much less porous and permeable than the turbidite mud so that in the former pore pressure likely builds up during deformation and thermal pressurization is expected to occur during faulting, which results in further weakening and large displacements. Our results may constrain the possible properties of mud to generate tsunami earthquakes in the shallow Nankai Trough accretionary prism.

Keywords: Nankai Trough, hemipelagic mud, turbidite mud, permeability, strength, frictional properties

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Characterization of carbonaceous materials in the Taiwan Chelungpu fault by microRaman spectroscopy

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Coseismic slip during an earthquake induces frictional heating in fault zone. Determination of the temperature recorded in the fault is important for estimating the dynamic shear stress and displacement during the earthquake. Here we performed raman spectroscopic analysis of carbonaceous materials from the Taiwan Chelungpu fault, and discuss the capability as new temperature proxy during the earthquake.

Keywords: carbonaceous materials, Raman spectroscopy

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Detection of frictional heat in seismic faults by vitrinite reflectance :Insights from high-velocity friction experiment

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Quantitative assessment of heat generation along faults during fault movement is of primary importance in understanding the dynamics of earthquakes. Last several years localized heat anomaly in a fault zone due to rapid seismic sliding has been detected by various analyses of fault zone materials, such as ferromagnetic resonance signal (Fukuchi et al., 2005), trace elements and isotopes (e.g., Ishikawa et al., 2008) and mineralogical change of clay (e.g., Hirono et al., 2008) and vitrinite reflectance (e.g., Sakaguchi et al., 2011). Among them, vitrinite reflectance method has been used as a geological thermometer for a long time because of its simple and easy way. However, a conversion equation from vitrinite reflectance (R_o) to temperature (e.g., Baker 1988) can not apply for R_o measured in the fault zone as frictional heating duration is quite short and the parallel chemical reaction (or stabilization of kerogen thermal maturation) must not be reached.

Thus, in order to describe a kinetic model of vitrinite thermal maturation at coseismic conditions, we deformed a simulated gouge (a mixture of 90 wt% quartz and 10 wt% vitrinite) at slip velocities of 0.0013 m/s to 1.3 m/s, normal stress of 1.0 MPa and displacement of 15 m under anoxic, nitrogen atmosphere, while measuring temperature in the gouge zone by thermocouples. At velocity of 1.3 m/s, R_o increases from ~1.0 to ~6.0% as a result that temperature in the gouge zone increases gradually with displacement to ~270?C. In contrast, at velocity of 0.0013 m/s, temperature keeps nearly room temperature, most of Ro does not change except for few grains in the slip localized zone. Such grains with high R_o at low velocity may be due to flash temperature at asperity contacts and/or mechanochemical effects that could mature vitrinite. A dynamic kinetic model of vitrinite maturation at different coseismic slip conditions is needed for precise estimation of temperature anomaly along seismic faults and for development of a fault thermometer.

Keywords: fault, frictional heat, Vitrinite reflectance, carbonaceous material

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Detection of seismic frictional heat using scanning ESR microscopy

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The estimate of seismic frictional heat is important to evaluate the total earthquake energy budget. The frictional heat strongly depends on the width of heat generation, so that we need to determine it to exactly estimate the frictional heat from a fault rock. In addition, we must sequentially detect the index of the frictional heat at a resolution of 1 mm or less. In this study, I will explain how to detect the frictional heat from the ESR signals as indices of frictional heat and how to determine the width of heat generation using scanning ESR (electron spin resonance) microscopy. The fault rocks studied are a crushing-originated pseudotachylyte distributed in the Nojima fault zone, Hyogo Prefecture and a melting-originated pseudotachylyte in the Uchinoura shear zone, Kagoshima Prefecture, and besides indurated black materials in the Taiwan Chelungpu fault deep drill Hole B cores (Ma et al., 2006).

The target signals for the detection of frictional heat are FMR (ferrimagnetic resonance) signals produced from iron-bearing minerals and a paramagnetic organic radical produced from organic materials by thermal decomposition during frictional heating. A distinctive FMR signal is detected from the Nojima pseudotachylyte, whose source rock is the granitic fault gouge. Its magnetic source was considered to be maghemite (gamma-Fe_2O_3) with low crystallinity produced by the thermal dehydration of lepidocrocite (gamma-FeOOH) in the fault gouge on the basis of its g-value and lineshape (Fukuchi et al., 2007). However, detailed analyses of ESR spectra indicate that magnetite (Fe_3O_4) with low crystallinity produced by instantaneously thermal decomposition of siderite ($FeCO_3$) also shows the similar g-value and lineshape. If taking account of the initial temperature (about 200 degree C) at the time of formation of the Nojima pseudotachylyte, lepidocrocite cannot stably exist under such high temperature. Therefore, the magnetic source of the FMR signal may be derived from magnetite with low crystallinity produced by thermal decomposition of siderite. The Uchinoura pseudotachylyte whose source rock is the granitic rock also shows a distinctive FMR signal. Since thermal experiments revealed that magnetite can be produced by thermal decomposition of biotite, the magnetic source of the FMR signal may be derived from the biotite-originated magnetite (Fukuchi, 2012). On the other hand, no prominent FMR signal is detected from the black material in the Taiwan Chelungpu fault zone, so that I use a paramagnetic organic radical (g=2.004), which may be produced by thermal decomposition of organic materials in muddy stone.

The scanning ESR microscope used for the detection of frictional heat has a TE_{111} mode cavity with a pinhole of 1.6-2.6mm in diameter and an internal 100kHz modulation coil that improves the detection sensitivity. At this stage, the resolution of detection is estimated at 0.1 mm. 2-Dimensional ESR analyses indicate that the multiple peaks of FMR signal intensity having resulted from ancient frictional heating events are detected from the Nojima pseudotachylyte and the width of heat generation is estimated at 0.5-1.0 mm. In case of the Uchinoura pseudotachylyte, the contacting part with an intrusion vein shows very high FMR signal intensity, while the inner part of the intrusion vein has almost uniform and low signal intensity. Since FMR signals disappear just at the moment their magnetic source minerals melt, we can judge the origin of pseudotachylyte (melting or crushing) from the FMR signal intensity and distribution inside the pseudotachylyte vein. On the other hand, the black material in the Chelungpu fault zone shows a higher 2-D intensity of organic radical than its source rock.

Keywords: electron spin resonance, ferrimagnetic resonance, ESR microscopy, organic radical, earthquake, frictional heat

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Microstructures of pulverized fault rocks: Examples from San Andreas Fault and Arima-Takatsuki Tectonic Line

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Fault damage zone is gradually formed into the surroundings of the fault layer by the overlap of shear strain and the accumulation of wear (Sholtz, 1987Geology). However, it have been reported recently that 'pulverized fault rocks', characterized by no shear strain and remarkable shatter in situ, are distributed along large strike slip faults such as SAF (Dor et al., 2006EPSL). The development of such damage zones cannot be explained by the conception of wear. In recent study, it is thought that it formed in a moment when an earthquake rupture progresses on a fault plane. Moreover, it argues about the asymmetry of the fault damage zone, because 70% or more of pulverized fault rocks in the SAF are distributed over the northeast side of the fault (Dor et al., 2006EPSL). The factor of mechanism which asymmetrical fault damage zone formed are propagative direction of earthquake rupture (Di Toro et al., 2005Nature), hardness of the rock (Ben-Zion et al., 2005EPSL) and supershear rupture (Doan and Gary, 2009Nature Geo).

Nevertheless, there are the following questions in the lithological characteristic and mechanism of pulverized fault rocks. Because pulverized fault rocks have been studied mainly along the SAF (Dor et al., 2006EPSL), it is not understood whether the microstructure and fracture pattern of pulverized fault rocks change with different tectonic settings and rock compositions. Moreover, pulverized fault rocks reported in the SAF are mainly focused on the quartz particles in the granite (Dor et al., 2009PAGEOPH), so the characteristic of the fracture pattern on other rocks and minerals is not clear. It is also not clear that the difference from the deformation process by the weathering and the other brittle fault rocks such as the fault gauge.

We conducted field surveys on ATTL and SAF, and evaluated microstructures of pulverized rocks by using a scanning electron microscope. Pulverized fault rocks which consist of a granite shows thin black with mica, and white with quartz and feldspar. It easily pulverizes by rubbing between fingers. Under the microscope, the intense fractures were observed only in framework silicates (tectosilicates) such as quartz and feldspar. They are shattered to 10-100 micrometers and show fracture pattern of the web structure. However, the original igneous textures of the host rock is maintained and there are not fine-grained matrices which consist only of finely communicated grains like fault gouges. The fractured grains are in the state which left the outside, and the crack of uneven quality exists in the inside of particles. Some quartz particles were seen that the crack goes through different particles and the crack was radiately developed from the contact point of particles. The fracture planes of quartz are smooth with river patterns. The fragments are angler shape and do not show any effect of wear. On the other hand, the fracture planes of feldspar are rough. Inosilicates such as amphiboles are crushed to 10-100 micrometers and have been fragmented along cleavages. The fracture planes are smooth and fragments have angler shapes. Some of amphiboles fracture to different direction from cleavages. Biotite (phyllosilicate) was found to be hardly shattered but kinked along basal planes. They don't show any asymmetric shear structures like mica fish often observed in fault guoges. SEM analysis of these minerals shown above clarified that clay minerals like kaolinite and smectite, and the alteration minerals like sericite and chlorite have not been observed. From the analysis, pulverized rocks have following characteristics: 1) small amount of strains, 2) no shear deformation with asymmetric structures or grain rotations, 3) volume expansions. The observations indicate that pulverized fault rocks differs from the fault gouges formed by wear and shear deformation.

Keywords: pulverized fault rocks, damage zone, fracture pattern

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Formation process of slickenside developed on the Glarus thrust

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We observe microstructures of slickenside developed on the Glarus thrust to clarify its formation process mainly with optical and electron microscopy. Glarus thrust is one of the biggest faults in the world, whose lateral displacement is about 30-40 km. We collected the fallen Lochseiten limestone at Linthal, Swiss. The sharp slickenside is developed in our sample.

The summary of our microstructural observations is the followings. 1) The slickenside was generated during faulting, which was accompanied with brittle deformation of limestone. The brittle deformation occurred at the area only within ca. 1 cm distance from slickenside. 2) The fine calcite grains with several um in size occupy at the area away from the above. These grains were deformed by dislocation creep. And they make a strong lattice preferred orientation created under dextral shear stress condition. The shear direction is absolutely parallel to striation on the slickenside. These results suggest strongly that the Lochseiten limestone were deformed by both of plastic and brittle manners at the same stress condition. Now, we observe the microstructure of the slickenside surface to clarify its formation mechanism.

Keywords: slickenside, faulting, microstructure, Glarus thrust

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Mylonite shear localized region with finite length, associated with mylonitic pseudotachylyte; an ancient hypocenter?

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A mylonite shear localization structure with a finite length in the direction of shear plane, associated with fault vein of mylonitic pseudotachylyte, occurs in the Balmuccia peridotite massif, Ivrea zone, Italy.

The shear localized regionn cut primary pyroxenite marker dykes and deform them macroscopically. The marker dykes distribute with interval of ˜1m, so the rough distribution of the shear localized region can be recognized by marker dyke deformation. The size of the shear localized region recognized on outcrop surface is, at most, ˜40cm across shear plane and ˜2m along shear plane. The maximum shear strain recognized by deflection of the marker dyke is at least 2. Shear localized region with such size and shear strain is rare. The shear localized region is associated with mylonitic pseudotachylyte fault of ˜1mm thickness on the plane where the shear localization is at maximum. Porphyroclast elongation direction in mylonitic pseudotachylyte fault vein plunges ˜50degrees against outcrop surface. Offset of marker dykes by the fault in total is ˜40cm on outcrop surface. The intense shear localization is observed only on southeastern side of the fault.

The mylonite in shear localized region consists of ultramafic protomylonite with recrystallized grains of ˜20microns diameter and porphyroclasts of ˜2mm diameter. The volume percentage of recrystallized grains increase from ˜15% (peridotite), ˜5% (pyroxenite) up to ˜40% (peridotite, pyroxenite) in shear localized region. The mineral assemblages of recrystallized grains both in peridotite and pyroxenite are olivine, clinopyroxene, orthopyroxene, spinel, and hornblende, whereas hornblende is absent in the coarse grained primary peridotite. Porphyroclasts shows undulatory extinction. Purely monophase dynamic recrystallization is extremely rare, and recrystallized grains in olivine porphyroclast are always associated with small amount of spinel, often with clinopyroxene or orthopyroxene. Some clinopyroxene porphyroclasts shows grain bending and splitting associated with undulatory extinction and apature-filling spinel deformed by intra-crystalline diffusion creep. Geothermemetric estimation of the mylonitization around shear localized region yielded 800˜850degreesC.

The fact that shear localized region mainly observed on one side of the fault indicates fault developed after shear localized region is formed. The lithology of fault walls is peridotite and pyroxenite for both sides, so, if the shear localization had postdated seismicity, shear localized region would have been observed on both sides. The other part of the shear localized region is thought to have moved away from outcrop surface by out-of-surface component of slip displacement. Therefore, the rather flattened shear localized region predates the rupture nucleation.

Because there is shear localization, mylonitization is thought to be strain softening process. Existence of soft material in flat body in deformed media yields stress concentration around tips. However, the mylonitization is associated and hence accommodated with hornblende-forming chemical reaction, and recrystallization temperature estimation yielded quasi-uniform temperature. Hence, the mylonitization is thought to have proceeded only at a constant rate constrained by the ambient temperature. As the shear localized region grows larger and becomes elongated, stress around the shear localized region tip grows because of increase of aspect ratio of the region. However, because the mylonitization proceeds only at a constant rate, the mylonitization cannot fully relax the stress concentration. Such formation of finite length shear localization region associated with thermally rate-limited weakening process will inevitably accumulate stress around its tips until breaking the surrounding stronger media even under a far-field stress lower than fracture strength.

Keywords: shear localization, mylonite, pseudotachylyte, pre-seismic deformation, seismogenic process, brittle-ductile transition zone

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Minor element characteristics of melt-origin and crush-origin pseudotachylytes

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Origin of pseudotachylyte is generally divided into melt-related and crush-related types. Melt-origin type contains melt-ralated textures such as glass, glassy material, spherulites, dendritic microlites, vesicles, amygdules, rounded and embayed clasts, and sulfide blebs. In contrast, crush-origin type shows none of these melt textures. However, the development of these textures is dependent on not only maximum temperature reached but also cooling rate. Therefore, the distinguishing between them is difficult. We here adopt the chemical analysis of both types using ICP-mass, and analyzed the trace element and Sr isotope compositions in order to find the good proxy to distinguish their origins. We investigated melt-origin pseudotachylyte from the Asuke Shear Zone and crush-origin pseudotachylyte from the Iida-Matsukawa fault. In this presentation, we show these preliminary results and discuss their characteristics.

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Noble gas release and frictional degassing from faults during coseismic sliding: under controlled gas environment

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Noble gases very limitedly react with other elements because of their inert nature. Therefore, isotope ratios of noble gases in certain minerals are believed to reflect well those of their ambient reservoirs when the temperatures of the minerals containing them went up to their closure temperatures, or higher.

We have reported the resetting of isotope signatures of noble gases released during rotary-shear high-velocity friction experiment on the Aji granite samples shaped as cylinders and rotated at 1.6 m/s at a constant normal stress of 1.4 MPa. Friction increased with slip and reached maximum value at ˜ 5 seconds (”first fuse”; Hirose et al, 2005) after the beginning of the slip. Completely melted glass formed by frictional heat was found only on the sliding surface. The most part of the post experiment specimen were little or not melted, which is possibly due to very short duration of the experiment.

Under controlled gas environment of gabbroid experiment, limited ”first fusion” occurred at the first temperature maxima (corresponding to the displacement of Magnitude -2 ˜ -3). Then, friction suddenly dropped down, and decreased gradually further in several seconds associated with moderate melting (”second fuse”, corresponding to the displacement of the Magnitude 5 or larger, e.g. Kanamori et al., 2005).

Compared with gabbroid experiments, Ar gas degassed at the ”first fusion” when a granite was used for the starting material for the experiment because the granite used, with an age of 77.2 ˜ 87.1 Ma (Yuhara, 2008), contained abundant radiogenic 40Ar. Ar was clearly emitted after only 5 seconds sliding, and with more amounts than with the gabbroid sliding. Also, the timing of melting depended on the atmospheres of the experiment; whether moist-air, dry-air, He or Ar was used in the experiment. These results suggest that the dissipation of friction-induced heat depends on the mass numbers of the ambient gases. Furthermore, in the case that a sedimentary rock containing much higher potassium is in contact with a fault, emission of 40Ar may be faster and much intense during the fault motion. Thus, the liberation of volatiles believed to be detected in some large earthquakes may be controlled by ambient condition of the fault.

Keywords: noble gas, degassing, frictional heating, granit, gabbro

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Amorphization of dolerite gouges and its effects on their frictinnal properties

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We have ground crashed and sieved grains of dolerite using an automated flint mill for 10 minutes, and 6, 12, 24, 36, 48 and 60 hours. Grinding was interrupted for about 15 minutes at every three hours in order to prevent oxidation caused by frictional heat during grinding. TEM observations reveal the abundant presence of submicron-size rounded amorphous grain in ground gouges. Quantitative XRD analyses indicate that amorphous phase is absent in the gouges ground for 10 minutes, but that its amount increases linearly up to ?40 wt% with grinding time up to 36 hours. Grinding for more than 36 hours, however, does not result in any further increase in the amount of amorphous phase. This is probably due to the grinding power of the mill used. SEM observations of ground gouges reveal the abundant presence of the rounded grain with an angular clast core and amorphous mantle, likely grown by accretion of amorphous material around a clast grain as accretionary lapilli. Similar rounded grains have been found in natural and experimentally produced clay-rich fault gouges, and are called ”clay-clast aggregates”. This ”clay-clast aggregate”-like grain increases in amount with grinding time.

We have then conducted friction experiments on the gouges ground for 10 minutes and 36 hours at a normal stress of 7 MPa and displacement rates changed stepwise between 1 and 10 micrometer/s by using a biaxial shear apparatus. The gouge ground for 10 minutes lacking amorphous phase has a larger friction (˜0.6), and exhibits velocity-weakening behavior, whereas the gouge ground for 36 hours containing ˜40 wt% amorphous phase has a smaller friction (˜0.55), and exhibits a quasi-neutral velocity dependence of friction. Thus amorphization of gouge not only reduces frictional strength, but also affects to velocity dependence of friction.