Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS29-01 Room:304 Time:May 24 09:00-09:15

Grain size segregation in a fault gouge model

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In Chelungpu fault gouge, the presence of reverse grain size segregation (RGSS), which is marked by the concentration of large grains in the upper part of the gouge layer, is observed [Bouiller et al., 2009]. Gravity kinetic sieving, which is considered as a mechanism of RGSS, needs gravity and substantial voids. If RGSS occurs by this mechanism in a fault, it means there are substantial voids in a fault gouge when faults slip. Of course, gouge layer has few voids because general effective normal stress is in a magnitude of 100 MPa. However, if thermal pressurization (which is a mechanism to increase pore pressure by frictional heating on a fault) occurs, effective normal stress reduces and voids increase in a fault gouge. Then, RGSS in a fault gouge is considered as a convincing proof of thermal pressurization.

However, we have to be careful that this idea is based on an assumption that RGSS occurs by gravity kinetic sieving. Recently, [Fan and Hill, 2011] found that segregation in pipe flow occurs by mechanism which is not kinetic sieving. If this mechanism works in a fault gouge, RGSS in a fault gouge is not a proof of thermal pressurization.

In this paper, I check whether RGSS occurs even if there is no pore fluid and there are few voids by 2-dimensional DEM simulation. For simplicity, fault gouge is composed of 2 kinds of grain which are different in size.

Granular material simulation in a condition that only rocks slip shows that RGSS occurs if the gouge porosity is large and it seems to occur by gravity kinetic sieving. While, RGSS seems to relate with non-linear velocity profile, too (RGSS occurs when velocity profile is non-linear). Then, simulation with artificial non-linear velocity profile is done in order to check which is essentially important for RGSS. As a result, RGSS occurs even if the gouge porosity is low. It is mentioned that RGSS occurs even if the porosity is 0.146 and this value is extremely low. According to this, occurrence of RGSS doesn't mean porosity is high. Regardless of porosity, RGSS occurs with non-linear velocity profile. Next, simulation is done in which the mass and size of 2 kinds of grain are changed independently. RGSS occurs when 2 kinds of grain are the same mass and different in size. On the other hand, RGSS doesn't occur when they are different in mass and the same size. Then, I found that RGSS is induced by the difference not in mass but in grain size. As a result, essential cause of RGSS in a low-porosity gouge is (1) non-linear velocity profile (2) grain size (not mass).

However, why and how non-linear velocity profile is produced in a fault gouge is unknown. Understanding of mechanism how to build non-linear velocity profile in a granular layer is a future work.

Keywords: segregation, gouge, thermal pressurization, non-linear, grain

SSS29-02 Room:304 Time:May 24 09:15-09:30

Water thin film: The effect on the frictional coefficient of minerals and the stability

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Introduction: Fluid/mineral interfaces have an effect on fault slips in the Earth's crust. Deformation of rocks in the Earth's crust is often localized within fault zones, and the slip behavior strongly depends on the frictional strength of these fault zones. Phyllosilicates (e.g., clay minerals and mica) are ubiquitous in natural fault zones and these layered-structure minerals can decrease the frictional strength of the fault zones. One of the reasons to explain the low frictional strength is the lubrication due to adsorbed and interlayer water molecules on these phyllosilicate minerals [1]. To know the lubrication properties and the stability of water on mineral surfaces is important to develop the fundamental physics of fault mechanics. Here we investigated the structure, dynamics and stability of water on the muscovite surfaces using classical molecular dynamics (MD) simulations, density functional theory (DFT) calculations, and x-ray crystal truncation rods (CTR) scattering measurements.

Methods: (1) Classical MD simulations: The interatomic potential models for muscovite, water, and ions were originally developed. These models succeeded to be applied to water/mineral interfaces [2]. (2) DFT calculations: The calculations were performed by the code Quantum-Espresso to know the stability of water confined between muscovite surfaces. (3) Surface x-ray scattering measurements: The measurements were carried out at Photon Factory, KEK, Japan (BL-4C) by using monochromatic x-rays of 11.0 keV.

Structure of aqueous NaCl/Muscovite interface [3]: The sub-A-scale atomic distribution of muscovite surface in aqueous NaCl solution was measured as a function of the distance normal to the interface. The four distinguished peaks were observed at z = 1.4, 2.8, 5.3, and 9 A in the NaCl solution. The electron-density oscillation decayed and disappeared at z ? 12 A. The oscillation of the electron density can be explained by the adsorbed hydrated Na^{+} ions as the inner sphere complexes (IS).

Implications for the mechanism of lubrication: The radius of the first hydration shell of Na^{+} ions adsorbed on the muscovite surface was extended over 4 A from the outermost oxygen layer of the mica surface. In the previous shear measurements of NaCl solution confined between muscovite surfaces [4], the increased viscosity and high lubricity were observed at a surface separation of 6 A, which corresponds to the distance of contact of the first hydration shell of Na^{+} ions adsorbed on opposite muscovite surfaces. To realize water lubrication, the water molecules must be confined between the muscovite surfaces during the shear. In this context, the hydrated Na^{+} ions adsorbed on the muscovite surface as IS could retain the water molecules around them due to the attractive coulomb forces and be a candidate for an effective lubricant between muscovite surfaces.

The stability of hydration shell: The stability of water around Na^{+} ions at high temperature and pressure conditions was discussed by the combined methods of DFT calculations, the thermodynamics, and the shear measurements. The compressive differential stress larger than 1.7 GPa was necessary to squeeze out the water film.

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Keywords: NaCl, adsorbed water, clay minerals, mica, lubrication, San Andreas fault

SSS29-03 Room:304 Time:May 24 09:30-09:45

Dynamic fault branching with thermal pressurization

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We numerically investigate the effect of thermal pressurization (TP) on fault branch behavior during dynamic rupture propagation; a situation is likely to occur during large earthquakes at subduction interfaces.

We consider a 2-D mode II rupture that propagates along a planar main fault and encounters an intersection with a pre-existing branching fault. The fault system is in an infinite, homogenous, and elastic medium, and it is subjected to uniform external stresses. The friction coefficients and Dc are assumed to be uniform and the same on the two faults. The numerical algorism is based on the 2-D boundary integral equation method (BIEM) using the integration kernels proposed by Tada and Madariaga (2001, IJNME). A rupture is initiated in a small patch on the main fault, and then proceeds spontaneously, governed by a slip-weakening law with the Coulomb failure criteria. On a fault with TP, we allow effective normal stress to vary with pore pressure change owing to frictional heating using the formulation of Bizzarri and Cocco (2006, JGR).

We reveal that TP can alter the rupture propagation paths in the cases where a dip angle of the main fault is shallow. The rupture propagation paths depend on the branching angle when TP is not in effect on either of the faults, as described by Kame et al. (2003, JGR). On the other hand, the ruptures propagate along the main fault in the cases with TP on the main fault, and ruptures propagate along the branch when TP is in effect on both faults. These features are observed, regardless of the branching angle. Thus, the dynamic rupture processes are strongly controlled by TP, compared with the branching angle.

Finally, we consider the case when free surface exists above the branch fault system. It should be noted that full space and half space computations are the same until the reflected waves from free surface arrive at the branch fault system. Therefore, the above discussion is valid for half space case as far as we focus on the branching. However, once the reflected waves from the free surface arrive at the branch fault, they promote the rupture propagation along the branch fault. In this case, the rupture can propagate along both faults by the existence of the free surface in addition to TP on the main fault.

Keywords: fault branching, spontaneous ruptures, thermal pressurization

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SSS29-04 Room:304 Time:May 24 09:45-10:00

Dynamic Ssimulation of Bbranch Ffault Fformation Cconsidering Mmix Mmode Rrupture: Comparison with Natural Examples

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We investigate the formation process of wing-crack like sequentially occurring branch faults. Such branch faults are found in field examples of exhumed fault rocks [e.g., Di Toro et al., 2005, Nature] and laboratory examples formed during dynamic rupture propagation [e.g., Griffith et al., 2009, Geology]. Recent theoretical studies suggested that the angles and lengths of branch faults reflect dynamic rupture processes of main faults, which the branches are grown from, and the rupture velocities [Rice et al., 2005, BSSA] and the length [Ando and Yamashita, 2007, JGR] of the main faults can be estimated by using these geometrical parameters. In fact, Di Toro et al. (2005) used the theory and the model of Rice et al. (2005) to infer the condition for exhumed branches filed by pseudotachylyte. However, these physical models lack some ingredients such as actual dislocations due to branching [Rice et al., 2005] or the mix mode rupture [Ando and Yamashita, 2007]. In this study we extend the numerical simulation method developed by Ando and Yamashita (2007) using the boundary integral equation method (BIEM) in order to deal with the mode I rupture as well as the previously implemented mode II. We perform the spontaneous rupture simulation to track the self-chosen fault growth path under various conditions of model parameters including the rupture velocity, the frictional coefficients and the stress angle. The results are compared with the field example of the extension cracks branched from the 1-mm-thick ultracataclasite, which are found in the Late Cretaceous Shimanto accretionary complex in eastern Kyushu, southwest Japan. The extension cracks having the length of a few mm exhibit a peak in the distribution of the branch angles around 60 degrees from the ultractaclasite, which is much higher than the numerical prediction only considering the mode II with the Coulomb criterion, 30 degrees.

Keywords: branch fault, wing crack, fault zone, dynamic rupture, accretionary complex, simulation

Japan Geoscience Union Meeting 2013
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SSS29-05 Room:304 Time:May 24 10:00-10:15

Physical property transition and calculation of damage parameter of a fossilized subduction zone megasplay fault

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Subduction zone megasplay faults are known to cause great earthquakes and tsunamis and have been the subject of numerous geological and geophysical studies, but their initiation and evolution remains poorly constrained. Therefore, the Nobeoka Thrust in the Shimanto belt in Kyushu, a fossilized megasplay fault in ancient accretionary prism is studied to understand the mechanism of the megasplay fault. In this study, we investigate the physical property and deformation pattern of the Nobeoka Thrust from core description and logging data from the Nobeoka Thrust Drilling Project (2011).

The fracture zone (damage zone) observed in the hanging wall, fault core, and footwall of the Nobeoka Thrust have two types; cohesive/mineral vein filled fracture zones and brecciated fracture zones. The former causes high peak in resistivity and P and S-wave velocity while the latter causes rise in caliper and porosity, and drop in resistivity and P and S-wave velocity. These two types of fracture zones coexist and the brecciated zones are generally in the center of the main fracture zone, whereas the cohesive structures are distributed above and below the brecciated zones.

Here We assume that at the highest peaks in resistivity, strain is accumulating towards the main fracture zones, causing strain hardening, but eventually collapses to become strain weakening, at which point critical stress state is attained. Why does resistivity rise with strain accumulation (strain hardening), even though porosity does not show significant decrease and start to decrease after its maximum peak? Strain accumulation appears to cause strengthening, and rocks become more cohesive, and eventually, reach its yield point.

On the other hand, cross correlation with neutron porosity and resistivity at intervals of porosity increase in the fracture zones first shows sharp drop in resistivity in the lower porosity, but later once porosity reaches a certain value, decrease in resistivity becomes gradual, and porosity increase becomes more significant. Here, this porosity boundary is named <percolation threshold>.

We further set a hypothesis that the geometry and density of the cracks transit with strain accumulation. During strain hardening (resistivity increase), cracks are randomly distributed, and as number distribution increase, cracks will start to coalescence. Propagation of the cracks will occur after coalescence, and not until then would porosity start to increase. Once the geometry and distribution (distance ?between the crack) reach their critical values, and once they attain the <percolation threshold>, increase in porosity is observed. Here, We assume that this threshold corresponds with the transition in geometry (aspect ratio), size, and distribution of the cracks.

Motivated by these observations and hypotheses, I analyze what factors including the geometric attributes and distribution of cracks relate with the critical failure condition at the fracture zones in the hanging wall, footwall and main fault core of the Nobeoka Thrust. In this study, from lithology/structure data from core description and logging data, I extract number distribution as crack density, estimate crack geometry (aspect ratio of the crack: width(along depth)/diameter) from resistivity and porosity data, and parameterize these components to apply to percolation theory and damage mechanics (micromechanics) model of interactive wing cracks, which derives concepts from Griffith's crack theory that considers the effect of initially present microcracks, and critical stress formulated by inverse square root of crack length. To geometrically and physically investigate the development of fault mechanisms and evolution of the Nobeoka Thrust, I examine the dynamic transition with stress at the <resistivity peak> above the main fracture zone, <center> of the main fracture zone, and the <percolation threshold>.

Keywords: Accretionary prism, Megasplay fault, Geophysical logging, Physical property

Japan Geoscience Union Meeting 2013
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SSS29-06 Room:304 Time:May 24 10:15-10:30

Smooth stress drop under very heterogeneous background stress

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There is a long lasting discussion why stress drop of an earthquake is uniform independent of its focal depth. This feature affects the friction law of earthquake rupture whether the absolute stress is important for the friction during an earthquake. Here, we propose a model that explains the seismological observation based on our recent experiments.

We conducted a series of large-scale biaxial rock friction experiments using the shaking table at NIED. Slip surface dimension is 1.5m in length and 0.5m in width. During the experiments, many stick slip events were observed by an array of strain gauges glued close to the slip surface at the side of the rock sample. Among them, we could capture many confined stick slip events whose rupture did not reach the edge of the sample. These events could be considered very similar situation as those of natural earthquakes. Mizoguchi et al. (2012) reported that the rupture length of these events seemed proportional to the amount of stress drop, suggesting a scaling relation between size and stress drop in the laboratory.

Here, we found that such confined events occurred under very heterogeneous stress environments. Such stress heterogeneity might come from the complicate geometry of sliding surface. However, during the confined event, the stress drops rather smoothly independent of the absolute stress level (since we know the initial stress state, we can measure the absolute stress). This feature suggests that the rupture propagation (or constitutive relation) is rather independent on the fluctuation of total stress field. In contrast, the amount of slip is considered rather continuous due to smooth stress drop distribution in space, which is quite reasonable in the theory of continuum medium. We think that this slip controlled feature could be a main reason for the constant stress drop observation in seismology.

SSS29-07 Room:304 Time:May 24 10:30-10:45

Microstructures and formation process of slickenside

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”Slickenside” is a well-studied microstructure created on fault surface. It represents a shiny and smooth fault plane. However, its generation process and influence on faulting behavior have not studied in detail so far. Therefore, we aimed to study the microstructures of natural slickenside and conducted frictional experiments. We used ATEM and AFM for observing the microstructures, and a rotary shear apparatus for conducting frictional experiments.

Natural slickenside sample is collected from Glarus thrust, east of Swiss Alps. Glarus thrust is developed within 1 m layer of Lochseiten limestone (LK) calc-mylonite, which has an extremely sharp contact fault plane with a very shiny slickenside layer. The parallel striations can be seen on the slickenside. Frictional experiments were performed on cylinders of Carrara marble at slip rate of 0.1 m/s with normal stress of 1.0 - 3.0 MPa, and displacement of $<$ 5 m.

The observation of natural slickenside led the following results: 1) Slickenside is an extremely thin layer with several tens nm in thickness. 2) This thin layer consists of very fine particles with oblate shape (long axis: several tens nm, aspect ratio: ˜0.1). The results of the friction experiment are as follows: 3) Slickenside is created at the presently applied slip rate of 0.1 m/s. The microstructure of the slickenside is same as natural one. 4) The slickenside is widely developed at higher normal stress and/or with longer displacement. 5) At higher normal stress condition, the slickenside is created even at short slip displacement. 6) The generation of slickenside doesn’t decrease the frictional coefficient drastically. 7) The slickenside is created only on the grinded tiny grains of calcite, which is produced on the slip surface in the initial stage of experiment. This observation suggests that the studied slickensides (both natural and experimentally generated) are tribofilms.

Keywords: slickenside, faulting, microstructure, Glarus thrust, friction experiment

SSS29-08 Room:304 Time:May 24 11:00-11:15

A diagnostic technique of the origin of dark fault rocks using ESR spectrum analysis

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In fault zones, we often observe dark fault rocks indurated and magnetized by frictional heating. Although the magnetic source of dark fault rocks may be magnetite (Fe_3O_4) or maghemite (gamma-Fe_2O_3), it is difficult to distinguish between magnetite and maghemite because both have a similar crystal structure and can be transformed into each other by oxidation or reduction (Fukuchi, 2012). When the magnetic source is magnetite, it means that the fault rock was formed in a reductive environment, whereas the existence of maghemite indicates that it was formed in an oxidative environment. Therefore, it is important to determine the magnetic source for understanding the oxidation-reduction reaction occurring in the fault zone in earthquakes. On the other hand, siderite ($FeCO_3$), which is often detected from fault zones, can produce magnetite or maghemite via wustite (FeO) by thermal decomposition, so that siderite may be concerned in the magnetic source of dark fault rocks. The thermal decomposition products from siderite remarkably vary their phases with the abundance of oxygen and temperature (Darken & Gurry, 1946). Therefore, detailed heating experiments controlling the degree of vacuum are required to investigate the thermal decomposition products. In this study, I carried out heating experiments of natural siderite under various conditions of temperature and pressure and identified component minerals of the thermal decomposition products from natural siderite by XRD (X-ray diffraction) analysis. In addition, I revealed that the lineshapes of ESR signals detected from the thermal decomposition products vary with temperature and pressure using ESR spectrum analysis. Moreover, I attempted to diagnose the origin of dark fault rocks in the Nojima fault zone or other fault zones on the basis of the type of ESR lineshape.

The XRD and ESR measurements show that there are three types of magnetite as a thermal decomposition product of siderite, that is, disproportionation-originated, oxidation-originated and melting-originated magnetites and that the ESR lineshape obtained from magnetite depends on the origin of magnetite. As a result of ESR spectrum analysis, the disproportionation-originated magnetite with low crystallinity has a g-value of 2.1-2.3 and a half-linewidth/peak-to-peak linewidth ratio (Delta ratio) of 1.45-1.62, implying the intermediate lineshape between the Gaussian line (1.177) and the Lorentzian one (1.732), while the oxidation-originated magnetite has a g-value of 2.2-2.4 and a Delta ratio of 1.10-1.30 close to the Gaussian line. The melting-originated magnetite has a similar g-value of 2.2-2.3 but a much lower Delta ratio of about 0.9 than the Gaussian line. On the other hand, dark fault rocks in the Nojima fault zone show a g-value of 2.13-2.24 and a Delta ratio of 1.423-1.487, consistent with the values obtained from the disproportionation-originated magnetite with low crystallinity. This means that the Nojima dark fault rocks have not been melted and oxidized and besides have been instantaneously produced at temperatures of 350 degree C or more under a reductive environment.

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Keywords: electron spin resonance, ESR spectrum, frictional heat, siderite, wustite, magnetite

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS29-09 Room:304 Time:May 24 11:15-11:30

A new fault-thermometer based on vitrinite maturation by frictional heat

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To detect frictional heating effects along faults provides key insight into the dynamics of earthquakes and faulting [e.g., Brodsky et al., 2010]. Evidence of substantial frictional heating along a fault is also a reliable indicator determining whether a fault has slipped at high velocity in the past, which is crucial for assessing earthquake and tsunami hazard. The vitrinite reflectance (R_o) measurement has been considered a possible thermometer of fault zones, especially in accretionary wedges where vitrinite fragments are common [e.g., Sakaguchi et al., 2011]. Under normal burial conditions, vitrinite reflectance (R_o) increases by irreversible maturation reaction as temperature is elevated and thus sensitively records the maximum temperature to which the vitrinite is subjected. However, the commonly used kinetic models of vitrinite maturation [e.g., Sweeney and Burnham, 1990] may not yield accurate estimates of the peak temperature in a fault zone resulting from fast frictional heating rates [Kitamura et al., 2012; Fulton and Harris, 2012]. Thus, we performed high-velocity friction experiments aimed at revealing coal maturation by frictional heat generated at slip velocities representative of natural earthquakes up to 1.3 m/s. Our previous results [Kitamura et al., 2012] show that coal can mature in typical earthquake rise time (e.g., ~10 seconds), and herein we indicates R_o increases exponentially with peak temperature exponentially.

Using the correlation between R_o and temperature rises we estimate the dynamic friction during coseismic faulting in two natural fault zones : one is a fault in the Shimanto accretionary prism and another is a megasplay fault in the Nankai trough. The fault zone in the Shimanto accretionary prism has a very narrow shear localized zone with ~8 mm thickness. An average R_o of vitrinite grains in host rocks is ~1.2% which corresponds to a maximum burial temperature of about 180^oC using the geothermometer by Sweeney and Burnham (1990). In contrast, R_o values in the localized zone ranges between 1.7 to 5.6%. The high R_o corresponds to ~630^oC using our new thermometer. We estimate the dynamic shear stress of 0.79 MPa (that corresponds to 0.01 in friction coefficient) from the observed heat anomaly, assuming the fault movement of displacement at maximum burial depth of ~6 km (~76 MPa effective normal stress). We also apply this way to the heat anomaly detected by vitrinite reflectance in the shallow portions of the megasplay fault [Sakaguchi et al., 2011]. R_o anomaly across the fault zone is about 0.6% that corresponds to temperature rise of 170^oC using our fault thermometer. This temperature anomaly can be explained by dynamic shear stress of 0.53 MPa (dynamic friction of ~0.18), assuming fault displacement of 15 m at the current depth conditions. These results are consistent with the estimate of dynamic friction from temperature measurement across the fault zone after the 1999 Chi-Chi, Taiwan earthquake [e.g., Kano et al., 2006] and with the result of high-velocity friction experiments [e.g., Di Toro et al., 2011]. The fault-thermometer based on coal maturation can be a possible tool to estimate of fault parameters from natural fault zones.

Keywords: fault, frictional heating, vitrinite reflectance, carbonaceous matter, Earthquake

SSS29-10 Room:304 Time:May 24 11:30-11:45

Frictional properties of comminuted dolerite gouges at low to high slip velocities

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We investigated how frictional properties of ground dolerite gouges change according to grinding time. We have ground crushed and sieved grains of dolerite using an automated flint mill for 10 minutes, and 6, 12, 24, 36, 48 and 60 hours. 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 amount of amorphous phase.

We have conducted friction experiments on the dolerite gouges ground for 10 minutes, 24 hours and 60 hours using a high-temperature biaxial apparatus at temperatures of room temperature and 120 degrees Celsius, a normal stress of 20 MPa, and slip velocities changed stepwise between 2 micrometer/s and 20 micrometer/s. Irrespective of temperature and grinding time, friction coefficients are ˜0.7 and decrease with increasing slip velocity or vice versa, i.e., velocity weakening. At room temperature, slip-dependent frictional behavior shows a correlation with grinding time; gouges ground for 10 minutes, 24 hours and 60 hours exhibit slip-softening, steady-state slip and slip-hardening, respectively. In contrast at 120 degrees Celsius, gouges exhibit steady-state slip irrespective of grinding time.

We also have conducted friction experiments on the dolerite gouges ground for 10 minutes, 12 hours and 60 hours using a low- to high-velocity rotary shear apparatus at room temperature, a normal stress of 2 MPa, and constant slip velocities ranging from 2 micrometer/s to 1.3 meter/s. Friction coefficients of gouges ground for a specific time do not change much according to slip velocities slower than 4centimeter/s, whereas they dramatically decrease with increasing slip velocity at velocities faster than 4 centimeter/s, down to ˜0.2 at 1.3 meter/s. At a specific slip velocity slower than 4 centimeter/s, the gouges ground for 12 and 60 hours show friction coefficients (0.56-0.69) larger than that of the gouge ground for 10 minutes (0.55-0.6), while at a specific slip velocity faster than 4 centimeter/s, the former gouges show friction coefficients (0.14-0.47) smaller than that of the latter gouge (0.21-0.54). In addition, as in the biaxial friction experiments, gouges ground for 10 minutes, 12 hours and 60 hours exhibit slip-softening, steady-state slip and slip-hardening, respectively.

The above frictional properties of dolerite gouges depending on grinding time can be explained by the amount of moisture adsorbed in amorphous phase. Submicron-size amorphous particles have a tendency to accrete around clast grains by moisture adsorbing and electrical forces. The gouge ground for a longer time contains a larger amount of amorphous phase so that a larger amount of moisture is adsorbed, which would then result in a higher friction due to moisture-adsorbing strengthening (Mizoguchi et al., 2006, GRL) if the slip surface temperature is lower than 100 degrees Celsius. If the slip surface temperature becomes higher than 100 degrees Celsius, however, moisture adsorbed in amorphous particles would be lost to result in a lower friction, which should be more pronounced in the gouge ground for a longer time. It is likely that the slip surface temperature became higher than 100 degrees Celsius at slip velocities faster than 4 centimeter/s. The difference in slip-dependent frictional behavior according to comminution time suggests that moisture adsorbing in amorphous phase occurs even during the friction experiments.

Keywords: Dolerite gouges, Amorphous phase, Frictional properties at low to high slip velocites

SSS29-11 Room:304 Time:May 24 11:45-12:00

Foreshocks and migrations of early aftershocks for the 2007 Noto Hanto, Japan, earthquake

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It is crucial importance and challenging of extracting slip behavior on a fault from any earthquake catalogue. The JMA catalogue has been well constructed using continuous waveforms observed by a nationwide permanent seismic network. However, temporal changes in the completeness magnitude threshold of the JMA catalogue are sometimes problematic. Especially, small magnitude earthquakes tended to be masked by overlapping arrivals of waves from different earthquakes and incoherent noises. In order to investigate the high-resolution spatio-temporal variations of foreshocks and early aftershocks of the 2007 Noto Hanto earthquake, we applied a matched-filter technique to detect missing events with the use of continuous three-component velocity seismograms recorded by a dense network of continuous and highly-sensitive seismic stations. We identified three foreshocks within about 12 minutes prior to the initiation of the mainshock rupture. These foreshocks were relocated in the vicinity of the initiation point of the mainshock rupture, where a low-velocity and high-conductive body are imaged by previous studies [Kato et al., 2008; Kato et al., 2011; Yoshimura et al., 2008]. We found out that the newly detected aftershocks migrated in along-strike with logarithmic time since the mainshock origin. The early aftershock migration is significant toward the southwest direction. The post-seismic deformation suggests that afterslip occurred along the source fault plane [Hashimoto et al., 2008]. Thus, the aftershock migration with logarithmic time scale is likely explained by propagating afterslip.

SSS29-12 Room:304 Time:May 24 12:00-12:15

Diversity in the initial phase of dynamic earthquake rupture in multiscale asperity model

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Seismological observations [e.g., Abercrombie and Rice, 2005] suggest that a larger earthquake has larger fracture energy G_c. One way to realize such scaling is to assume a hierarchical patchy distribution of G_c on a fault; there are patches of different sizes with different G_c so that a larger patch has larger G_c. Ide and Aochi [2005] conducted dynamic rupture simulations with such a distribution of weakening distance D_c in a linear slip-weakening law, initiating ruptures on the smallest patch which sometimes cascades into a larger scale. They suggested that the initial phase of a large earthquake is indistinguishable from that of a small earthquake. Noda et al., [submitted to JGR; 2012 SSJ annual meeting] conducted 3D simulations of sequence of earthquakes in a similar multiscale asperity model with a rate-and-state friction (RSF). Multiscale asperities were represented by a distribution of the state evolution distance in the aging version of RSF evolution law.

A circular rate-weakening patch, Patch L (radius R^L) has been modeled which has a smaller patch, Patch S (radius R^S), in it by the rim. Those patches have their nucleation radii, $R^L{}_c$ and $R^S{}_c$ for Patch L and Patch S respectively, which are determined by the RSF parameters. Here we shall call the ratio of the radii R^L/R^S the scale gap, and the ratio of the patch size to the nucleation size $R^L/R^L{}_c$ = $R^S/R^S{}_c$ the brittleness of the system. Up to $R^L{}_c$ or $R^S{}_c$, compact quasistatic nucleation basically follows $1/t_f$ acceleration where t_f is time to the earthquake, with amplitudes depending on the characteristic slip of state evolution of the patch. If the scale gap dominates, ruptures nucleated in Patch S cannot cascade up into a large earthquake spanning Patch L, and large earthquakes are necessarily preceded by large nucleation inside Patch L but out of Patch S. If the brittleness dominates, the ruptures nucleated in Patch S necessarily cascade up and span Patch L, and large quasistatic nucleation never occurs. If the brittleness and the scale gap are comparable, large earthquakes are initiated in a variety of ways in a single simulation In short, a large nucleation always results in a large earthquake, while a small nucleation occasionally causes a large earthquake through cascade-up. These connections between the size of quasi-static nucleation and the eventual earthquake size were fully reported previously by us.

In the present talk, we focus on so-called 'initial phase', that is, the growth of moment release rate right after it has exceeded a threshold level set to define the onset of dynamic earthquake rupture. In most of our simulations, 'initial phase' correlates with the size of preceding quasi-static nucleation, not caring the eventual earthquake size. Initial phase is strong and short when the preceding quasistatic nucleation is small, while it is gentle and lasting long when preceded by large quasi-static nucleation, as argued previously [e.g., Shizazaki and Matsu'ura, 1998]. However, we also found cases where dynamic rupture of a large earthquake preceded by a large quasistatic nucleation began with a sharp quick initial phase. This happens when the large nucleation interacts with Patch S. The sharp initial phase in this case should be regarded as a frictional noise passive to the ongoing acceleration of large nucleation. This is conceptually distinct from the Patch S event that cascades up, though telling the difference without seeing the spatio-temporal evolution of slip may be difficult.

Keywords: Earthquake cycle, Multiscale asperity, Rate-state friction

SSS29-13 Room:304 Time:May 24 14:15-14:30

Slow events and giant earthquakes in friction experiments of polymer gels

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When a soft polymer gel is slid against a counterpart, unlike the cases for rock specimen, slip events of various sizes from microscopic to the sample size are often observed, and their statistics follow the Gutenberg-Richter scaling. Furthermore, complex slip dynamics accompanying fast and slow slip can be generated by controlling the rheology of the gel samples [1].

In this presentation, we report on our experimental studies on sliding friction between a plexiglass block and a silicone gel with different degrees of viscoelasticity. The system shows slow slip events in viscous gels and fast events for less viscous gels, and the size-duration relation follows M0 to T ˆ(1/2) for viscous gels. We will also report more detailed analysis by applying the PIV (Particle Image Velocimetry) method to visualize the elementary rupture processes as well as development of the stress field towards a giant slip event.

Reference:

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Keywords: earthquake, analog experiment, slow slip, PIV, rheology

SSS29-14 Room:304 Time:May 24 14:30-14:45

Reduction of frictional stability illuminated by rapid afterslip following the 2011 Tohoku-oki earthquake

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Spatial and temporal variations of seismic and aseismic slip on plate boundary faults have been interpreted to result from spatially heterogeneous distribution of frictionally unstable, rate-weakening, regions and frictionally stable, rate-strengthening, regions. Spatial distribution of frictional stability is usually assumed to remain stationary with time and this assumption has been supported by a number of observations. However, experimental and modeling studies show that frictional stability is not a stationary feature but is variable depending on slip rate and that this nonstationary behavior is an important factor in controlling extent of earthquake ruptures and evolution of slip rate. Here we invert Global Positioning System (GPS) data following the 2011 moment magnitude (MW) 9.0 Tohoku-oki earthquake to derive spatial and temporal evolution of afterslip and postseismic shear stress changes on the plate interface. We find that rapid afterslip for the first 15 days and subsequent slower slip cannot be reproduced by slip on a rate-strengthening patch with stationary frictional stability but can be reconciled with reduced frictional stability at high slip rate during the early period and progressive increase in frictional stability with decrease in slip rate. The slip rate dependence of frictional stability is qualitatively similar to laboratory measurements for serpentinite. The reduced frictional stability at high slip rate could potentially control rupture extent of early interplate aftershocks by promoting significant rupture propagation into the rapid afterslip area.

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS29-15 Room:304 Time:May 24 14:45-15:00

Revisit of the 2010 Darfield, New Zealand, Earthquake

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The Japanese Advanced Land Observation Satellite (ALOS) observed many earthquakes and volcanic eruptions and gave us invaluable information during 2006 to 2011. We detected deformations associated with these events using PALSAR onboard ALOS.

On September 3, 2010, a Mw 7.0 earthquake hit south Island of New Zealand. The epicenter is located in the Canterbury plain west of Christchurch. Fortunately, there were no report of serious damages. Though no active faults were had not been identified in the GNS's map before the occurrence of this event, clear surface trending in the E-W direction ruptures appeared.

Urgent observations of PALSAR were conducted and LOS changes exceeding 1m was detected. We recognized complicated pattern of fringes along the surface rupture, implying complex configuration of the source fault. Low coherence is recognized consistent with the distribution of surface rupture. The zone of low coherence has a large bend in its middle. Aftershock distribution is also complex there. We assume 7 segments of fault along the low coherence zone, fit observed fringes and estimated about 5 m slip at maximum.

In order to examine preseismic deformations, we apply time series analysis with StaMPS to the PALSAR images acquired during 2007 to right before the event. The result shows LOS increase in the zone of low coherence in the interferogram encompassing the main shock. Especially, a shape of zone of LOS increase is similar to that of low coherence. However there are LOS increase in other areas, we reserve the conclusion that LOS increase is related to the source fault. There are some reports of correlation between LOS changes in the alluvial plains and base structure, there remains a possibility that faults which formed base structure might be responsible for the earthquake.

Keywords: InSAR, PALSAR, InSAR time series analysis, Darfield earthquake, New Zealand, inland earthquake

SSS29-16 Room:304 Time:May 24 15:00-15:15

Fractal characteristic of fracture in glass or rock mineral by 3D X-ray CT measurement

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Because fracture geometry in solid rock affects greatly the seismic activity in that area (e.g. Oncel *et al.*, 2001; Dieterich and Richards-Dinger, 2010), it is necessary to grasp complexity of fracture distribution. They have been studied using fractal theory (e.g. Ohno and Kojima, 1992; Sukumono *et al.*, 1997). However these measurements have not considered three-dimensions heterogeneity of the fractures patterns. Actual fractures extend in space, moreover, many geological features including the growth pattern of earthquake rupture zones are statistically self-affine (Turcotte, 1989; Nagahama, 1994). So we should analyze the fracture geometry spreading in the space and measure them considering the anisotropy of fracture geometry.

In this study, we examined the fractal characteristics of fracture geometry of experimentally fractured mineral samples for anisotropy measurement using 3D micro X-ray Computed Tomography (CT) techniques. The samples are initially homogeneous borosilicate glass and single crystals of quartz. Samples were shaped into cylinders of 12.7 mm length and 6.0 mm diameter for glass, and 7.5 mm length and 3.0 mm diameter for single crystals of quartz. We performed fracture experiments under atmospheric pressure (uniaxial compression) and at a confining pressure (P_c) of 300 MPa with nominal axial strain rate of 5.0x10^{-4}/s using a Griggs apparatus at room temperature. In an experiment using the glass sample at P_c = 300MPa, brittle fracture occurred at differential stress of about 3.2 GPa, and bottom half of the glass sample was broken into fine fragments. In an experiment using the quartz sample, at P_c = 300MPa brittle fracture occurred at differential stress of about 7.0 GPa and top half of the sample was broken. Moreover, at uniaxial compression brittle fracture occurred at differential stress of about 2.5 GPa and bottom half of the sample was broken significantly. The obtained samples were scanned by micro X-ray CT at 3~10 x10^{-6} m spatial resolution using a 111~121 kV and 61~111 x10^{-6} A X-ray source. ImageJ was used for image processing. Then we measured the fractal dimensions of fracture on the space distributions using Box-Counting method (D_{BC}) and particle size distribution (D_{PSD}) for each slice of micro X-ray CT images sliced both perpendicular and parallel to the direction of maximum compressive stress (sigma 1 direction).

The fracture space distributions of the glass sample broken at P_c = 300MPa is fractal. D_{BC} of slices parallel to the sigma 1 direction were concentrated from 1.4 to 1.6 regardless of slices direction and location. Otherwise D_{BC} of slices perpendicular to the sigma 1 direction increase from 1.1 to 1.7 toward the highly fractured bottom side. D_{PSD} of slices perpendicular to the sigma 1 direction of the quartz sample broken at uniaxial compression similarly increase from 0.8 to 3.1 toward the highly fractured bottom side. Because the the fractal dimension of fracture surface roughness is proportional to the energy per unit mass required for fracturing (Nagahama and Yoshii, 1994), our result implies the possibility of heterogeneity in fracturing energy distribution even in highly homogeneous samples. We also compared D_{BC} with D_{PSD} in the glass sample by SEM images at the range from 1 to 100 x 10^{-6} m, where both showed the fractal nature. The relation between D_{BC} and D_{PSD} is 2 D_{BC} = D_{PSD}, that is not consistent with the theoretical formula 2 D_{BC} = D_{PSD} +1 which presumed isotropic fracture (Nagahama, 1992). Therefore, the present result shows that fracture distributions are possibly anisotropic indicating the necessity to consider the anisotropy of fractal characteristic in case of comparison with the fractal dimensions of different analyzing directions.

Keywords: fractal, 3D X-ray CT images, anisotropy, fracture geometry

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS29-17 Room:304 Time:May 24 15:15-15:30

Spatial variations in fault zone structures along strike-slip faults: an example from active faults in southwest Japan

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Active faults and related fault-zone structures that form at shallow depths within the upper crust are closely related to the long-term seismic faulting history of seismogenic faults (e.g., Lin, 1999, 2008; Sibson, 2003; Lin et al., 2010). Accordingly, the analysis of deformation structures along active fault zones provides important information in reconstructing the long-term seismic faulting behavior of active faults and in understanding the tectonic environment and history of such faults.

This study presents a case study on the structures of strike-slip fault zones of the Arima-Takatsuki Tectonic Line (ATTL) and Rokko-Awaji Fault Zone (RAFZ), which consist of multiple right-lateral strike-slip active faults in southwest Japan. The formation mechanisms of damage zone and their tectonic implications are discussed.

Field investigations reveal spatial variations in fault zone structures along strike-slip active faults of the Arima?Takatsuki Tectonic Line (ATTL) and the Rokko?Awaji Fault Zone (RAFZ) of southwest Japan, which together form a left-stepping geometric pattern. The fault zones are composed of damage zones dominated by fractured host rocks, non-foliated and foliated cataclasites, and a fault core zone that consists of cataclastic rocks including fault gouge and fault breccia. The fault damage zones of the ATTL are characterized by subsidiary faults and fractures that are asymmetrically developed on each side of the main fault. The width of the damage zone varies along faults developed within granitic rocks of the ATTL and RAFZ, from ˜50 to ˜1000 m. In contrast, the width of the damage zone within rhyolitic tuff on the northwestern side of the ATTL varies from ˜30 to ˜100 m. The fault core zone is generally concentrated in a narrow zone of ˜0.5 to ˜5 m in width, consisting mainly of pulverized cataclastic rocks that lack the primary cohesion of the host rocks, including a narrow zone of fault gouge (<0.5 m) and fault-breccia zones either side of the fault. The present results indicate that spatial variations in the width of the damage zone and the asymmetric distribution of damage zones across the studied strike-slip faults are caused by local concentrations in compressive stress within an overstep area between left-stepping strike-slip faults of the ATTL and RAFZ. The findings demonstrate that fault zone structures and the spatial distribution of damage zone are strongly affected by the geometric patterns of strike-slip faults.

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Keywords: Arima-Takatsuki Tectonic Line, strike-slip active fault, fault damage zone, cataclastic rock, fault gouge, fault breccia

SSS29-18 Room:304 Time:May 24 15:30-15:45

Petrological characteristics of cataclasitic peridotite xenolith from NE Japan

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A deformed peridotite xenolith from Ichinomegata crater, the Northeast Japan arc, one of the most famous mantle peridotite xenolith localities (e.g., Kuno, 1967; Takahashi, 1978), is studied in detail. Deformed peridotite xenoliths with mylonitic textures have been documented from several localities (e.g., Basu, 1977; Yang et al., 2010), and possibly have been derived from ductile shear zones in the upper mantle (e.g., Xu et al., 1993). The Ichinomegata peridotite discussed here has a peculiar cataclastic texture totally different from those mylonitic peridotite xenoliths.

The peridotite is a mixture of coarse grains (up to 1.3 mm across) and fine grains (more than 1 um across) of olivine, orthopyroxene, clinopyroxene, chromian spinel, and amphibole. All grains possibly formed by fragmentation of mantle minerals, including the pyroxene-spinel symplectite, which is a reaction product between olivine and plagioclase (Takahashi, 1986). Coarse mineral grains are angular and rarely kinked, but never elongated. It has the same mineral assemblage as ordinary lherzolite xenoliths from Ichinomegata, and is totally free of serpentine and other low-temperature alteration minerals. Grain sizes of the peridotite satisfy the power law distribution, which indicates fragmentation (e.g. Turcotte, 1986).

Coarse minerals are equivalent in mineral chemistry to ordinary lherzolites reported from Ichinomegata (Abe et al., 1992). The Fo of olivine is around 90, and chromian spinel shows a low Cr#, around 0.2. Clinopyroxenes show LREE-depleted chondrite-normalized patterns. The textural and chemical characterristics suggest that an ordinary mantle lherzolite protolith was in-situ fractured in the upper mantle to form this cataclasite. This peridotite provides us with the evidence for brittle fracture in the upper mantle where plastic deformation is dominant.

Some of fine-grained minerals have different chemical characteristics from ordinary xenoliths. The fine-grained olivine show relatively high Fo (91-93) and CaO content (0.1-0.3 wt%) at the rim, the core showing the same composition as the coarse one. The CaO content of pyroxenes is higher in orthopyroxene but lower in clinopyroxene than in coarse grained equivalents, indicating some higher temperatures indicate that of equilibration. These features indicate that the fine grains were formed simultaneously with or subsequently to fracturing. The zoned fine olivine is probably a residue after melting generated by frictional heating, and fine pyroxenes are precipitates from the frictional melt.

Keywords: peridotite, cataclasite, xenolith, mantle

Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SSS29-19 Room:304 Time:May 24 15:45-16:00

Geodetic observation and modeling of viscoelastic relaxation

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Mantle rheology has been inferred from geodtic observation data of post-seismic deformation. In this presentation, how to construct post-seismic viscoelastic relaxation models to be compared with geodetic data have been illustrated with some examples. Practical problems in computations in previous models due to non-linear rheology, compressibility, sphericity of the Earth and self-gravitation are explained. Separation from afterslip also precludes us from inferring mantle rheology. As an example of solving these problems, a method based on a self-gravitating spherical Earth model is presented, which incorporates GRACE satellite gravity observation data. This method is applied to the 2004 Sumatra earthquake, and it is shown that both afterslip and viscoelastic are included in the gravity data. By applying such a method to the 2011 Tohoku earthquake, mantle rheology beneath the Tohoku region can be determined.

Keywords: viscoelastic relaxation, post-seismic deformation, crustal deformation, satellite gravity, earthquake cycle