Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-01 Room:104 Time:May 23 08:30-08:45

Constructing a dynamic framework of earthquake rupture process in terms of inelastic effect

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We focus here on inelastic effects on dynamic earthquake rupture process. The inelastic processes such as damage and plasticity have been widely known to be important for the rupture process and investigated by a number of researchers. For example, energy loss due to damage evolution is suggested to be a mechanism for reducing rupture velocity; damage consists of sets of microcracks created inelastically in a medium. However, the systematic understanding of the inelastic effect in the rupture process has not been done.

We first clarify the importance of the inelastic effect in the view of the pore creation; the interaction among the inelastic pore creation, heat and fluid pressure is assumed. The thin zone inside which the heat generation and inelastic porosity change occur is assumed. The temporal change rate of the inelastic porosity is assumed to be proportional to the slip velocity based on previous laboratory experiments. We derive the two nondimensional parameters Su and Su' which completely control dynamic fault slip behavior assuming a 1-D fault model. The parameter Su denotes the ratio of the effect of inelastic pore creation to that of heat generation on fluid pressure change. This parameter governs stress-slip constitutive law. If Su is greater than the critical value Sc(~1), the slip-strengthening behavior appears; on the other hand, if Su is less than Sc, the slip-weakening behavior is expected. The parameter Su' is associated with fluid flow and proportional to the permeability, so that larger Su' induces more fluid flow. We succeeded in explaining many aspects of dynamic earthquake slip behavior with those two parameters. For example, the regular earthquakes and slow earthquakes are understood in terms of those parameters as follows. Regular earthquakes are characterized by Su>~1 and small Su' in terms of almost constant high-speed slip with relatively short duration. The balance between the strong slip-strengthening due to fluid pressure reduction (Su much larger than Sc) and the slip-weakening due to fluid inflow (large Su') is found to be critically important to simulate slow earthquakes. Our framework can also simulate slow earthquakes coupled with many tremors.

To extend our formulation, it should be noted that off-fault inelastic effect has not been treated in our framework; as mentioned above, we have considered only the thin zone where inelastic effect appears. The off-fault effect is known to be important for the process in terms of, for example, the energy balance law. A viewpoint of damage is introduced here to extend our framework and to describe the off-fault effect. We also note that damage should be treated by second rank tensor variables since damage effect should describe directions, magnitudes and density of microcracks. The energy balance law is derived analytically with the framework based on Murakami and Kamiya (1997). Assuming a 2-D fault model, the inelastic energy loss is found to be proportional to a square of time based on the derived analytical expression. Combining results about damage theory and the damage tensor with heat and fluid effects will be a future work.

Keywords: inelastic effect, heat, fluid, damage

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SSS029-02 Room:104 Time:May 23 08:45-09:00

Real-time monitoring of flow rate through simulated fault rock after friction test

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Fluid pressure cycle as a result of fault-valve behavior, which gives rise to large variations in fault strength, can play a very important role for earthquake recurrence process (Sibson, 1992). Transport properties within fault zone can vary through both coseismic and interseismic periods, and this evolution of transport property is a key to understand the fluid pressure cycle. Here we tried to estimate the evolution of permeability over the coseismic and the beginning of the interseismic periods based on laboratory experiments.

We prepared a set of hollow cylinders of quartz-rich Indian sandstone (outer diameter = 25 mm, inner diameter = 9.5 mm, porosity = 12 ~ 14 %, permeability = 10^{-15} ~ 10^{-16} m^2) for laboratory experiments. To produce a shear deformation in a fault surface, we rotated a part of the cylinders, and the other cylinder was fixed and loaded at a constant normal stress. We increased a pore pressure at an inner cavity of hollow cylinder to force fluid flow from the inner wall to the outer wall. Nitrogen gas was used as a pore fluid, and gas permeability was measured by monitoring the volumetric gas flow rate continuously. We performed friction experiments at 2MPa of normal stress and 3m of slip displacement. Constant rotation speed was applied during sliding, and the rotation speed was changed from 0.00022 to 0.22 m/s to observe the influence of the slip velocity on the permeability evolution.

At the sliding velocity from 0.00022 to 0.022 m/s, gas flow rate was suddenly decreased, and gradually reached a stable rate with sliding. The flow rate was decreased with an increase in sliding velocity. After sliding was stopped, the flow rate was gradually increased, and then reached a stable value. The recovery rate was increased with increasing sliding speed, though it did not recovered the initial value before sliding. At a high velocity of 0.22 m/s, a recovery rate was much larger than that in slow-velocity tests, and flow rate was exceeded the initial value. In some high velocity experiments, flow rate was increased rapidly soon after sliding. We also measured lengths of specimen during experiments, and these results indicate that, in slow slip experiments, a length of a specimen was increased by thermal expansion and gouge formation, and it was gradually decreased after slip stopped, which might be caused by the cooling of a specimen. On the other hand, in high-velocity experiment, a sudden shortening was observed due to thermal cracking and leaking of gouge.

Our experimental results suggest that a fluctuation of flow rate in the fault zone by the shear deformation is mainly induced by two processes. One is a change in the pore fluid viscosity by the temperature change caused by the frictional heating. The other is a permeability evolution of specimen which is caused by gouge formation and crack enhancement that are related to the mechanical deformation. The former process can strongly influence on the change in flow rate in the slow slip shear deformation, and the latter one can be dominative in the high velocity shear deformation.

Keywords: permeability, permeability evolution, fault zone, fault-valve model, Fluid pressure

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SSS029-03 Room:104 Time:May 23 09:00-09:15

Fault lubrication by graphitic fault gouge; implications for fault creep along the Atotsugawa fault system

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Graphite often contained within the fault gouge associated with its geological background (e.g., Zulauf et al., 1990, Manatschal, 1999, Craw, 2002), has a significantly low friction coefficient. Graphite-bearing natural fault gouges are often composed of finely crushed quartzo-feldspathic fragments and highly crystallized graphite with minor accessory clay minerals. Although the graphite content varies depending on faults, most of the blackish fault gouge contains about 3-10 wt% of graphite (particles size of $<$ 10 um) in bulk fault gouge. Oohashi et al. (2011) revealed that graphite shows very low friction coefficient ($u < 0.2$) over a wide range of slip rates of 50 um/s to 1.3 m/s. Consequently, the presence of graphite, even if its proportion is small, possibly reduce the fault strength efficiently.

Effect of weak mineral for strength of natural fault zone is examined to conduct bimineralic gouge experiment. Thus, we conducted frictional experiments with graphite-quartz mixture gouges to determine how amount of graphite is needed to reduce the frictional strength, and textural contribution for weakening. Experimental results clearly indicated that the friction coefficient of the mixture gouge decreases with graphite content according to the power-law relations irrespective of slip-rate; it starts to reduce at the graphite fraction of 5 vol% and reached to the almost same level of pure graphite gouge at the fraction of $>$ 28 vol%. The weakening of mixture gouges $<$ 10 vol% of graphite is associated with slip localization and partial connection of graphite matrix along the surface. On the other hand, $>$ 28 vol% of mixture shows diffused graphite-matrix flow within the slip localized zone due to the development of through-going connection of graphite parallels to the Y and P surfaces. These non-linear, power-law dependency of friction on content which is differ from almost linear trend of clay minerals (e.g., Tembe et al., 2010, Moore and Lockner, 2011) demonstrates that the potential importance of graphite for weakening agent on mature faults even small amounts.

Comparison on graphite content and textural features with our experimental results and natural graphite-bearing faults revealed that the weakening by graphite can be possible in natural fault zones as a consequence of greater displacement. Although shallow faults often contains some extent of clay minerals, effectiveness of graphite for fault weakening surely exceeds that of clay minerals because the weakening effect of 10 % content of graphite is equivalent to that of 30-60 % of montmorillonite and more than 65 % of illite and kaolinite. This weakening may be more effective at depths where smectite could not exist anymore. The weakness of graphite even at low slip-rates may promotes creeping fault motion or afterslip and one of the candidates for long-term fault weakening.

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Keywords: graphite, fault gouge, friction experiment, fault weakening, Atotsugawa fault

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SSS029-04 Room:104 Time:May 23 09:15-09:30

Statistical properties of the characteristic length in friction constitutive law and a evolution law for flash heating

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Despite the long history since 1979 (Dieterich) and 1983 (Ruina), the physical meaning of rate-state dependent friction (RSF) law is not very clear to this date. Heslot et al. (1994) were astute to find out that the time-dependent increase of the true contact area and the thermally activated sliding play essential roles to RSF law. Dieterich and Kilgore (1998) and Nakatani (2001) experimentally confirmed some consequences derived from a theory of Heslot et al.

However, some important problems are still left open. For example, evolution laws (the aging law, the slip law, or others) have not been derived from the rheological properties of true contact area. Thus, the important parameters, which are typically denoted as ”a”, ”b”, and ”L”, are just phenomenological constants, although at least it is well known that the constant ”a” is proportional to temperature. Under this circumstance, the application of the RSF law to natural faults involves the blind extrapolation from laboratory to geoscale, which requires brute courage. Along the line of thought, the derivation of the RSF law from the ”first principle” is essential to the theoretical basis of the application of the RSF law to natural fault (at least aseismic slip rate).

Here we reformulate the RSF law together with evolution laws (the aging and the slip laws) using only the microscopic rheological properties of true contact area. Taking the statistical properties into account, we show that the critical slip distance in the evolution law is a weighted power mean of a linear dimension of true contact patches.

We also take the frictional heat into account to derive an evolution law for flash heating, which is different from that of Beeler et al. Comparison with experiments by Han et al. (2006) reveals that our theory works well.

Keywords: rate- and state-dependent friction, critical slip distance, flash heating

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Transient behavior and stability analyses of a constitutive law accounting for brittle-ductile transition

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Formulating the fault constitutive law under brittle-ductile transition (BDT) which describes not only the steady state flow stress but also the transient behaviors is of great importance in understanding the deep extent of the seismogenic active faults. In this work, we extended an empirical constitutive law suggested by Shimamoto [2004, JPGU] and Shimamoto and Noda [2010, AGU fall meeting] for the steady state flow stress to the transient behavior, and conducted linear and non-linear stability analyses of a spring-slider system with one degree of freedom, similarly to Gu et al., [1984]. Most of physical parameters appearing in the constitutive law and the spring constant are estimated from the laboratory experiments by Kawamto and Shimamoto [1997] and Noda and Shimamoto [2010] for NaCl shear zone except ones related to the transient behavior in the brittle regime. Note that NaCl is so unstable that it is difficult to conduct stable friction experiments without stick-slips in its brittle regime.

In BDT, the steady state flow stress smoothly changes from a ductile flow law to a brittle friction law, and is always smaller than the predictions from both of the laws [Shimamoto, 1986]. For the empirical fitting, Shimamoto [2004, JPGU] suggested a connection:

$t = t_{dss} \tanh(t_{bss}/t_{dss})$

where t is the flow stress, t_{bss} and t_{dss} are ductile and brittle steady state flow stress, respectively. We extended it to:

$t = t_d \tanh(t_b/t_d)$

where t_b and t_d are flow stress formulated in a rate- and state-dependent framework [Ruina, 1983 for brittle friction law, Noda and Shimamoto, 2010 for ductile flow law].

The transient behavior on an abrupt change in the load point velocity is characterized by a peak-decay behavior in the brittle regime and a monotonic decay in the ductile regime. In BDT, a peak-decay is followed by another decay in an opposite direction, often observed in laboratory experiments [Reinen et al., 1994 for chrysotile, Blanpied et al., 1998 for granite, Noda and Shimamoto, 2010 for NaCl]. Such a behavior could be explained by Dieterich-Ruina law with 2 state variables with positive and negative b-values.

Stability of the steady state solution depends on the slip rate, temperature, and the normal stress if the constitutive parameters are fixed; at low slip rate, high temperature, and high normal stress, t_d increases and t_b decreases and thus the ductile flow law becomes dominant which shows rate-strengthening behavior. By comparing the computed stability/instability boundary and experimental data by Kawamoto and Shimamoto [1997], we can estimate the state evolution distance for the brittle constitutive law as 5 microns, based on a reasonable assumption for the a-value.

Noda and Shimamoto [2010] observed permanently sustained oscillation at multiple slip rates with fixed temperature and normal stress near BDT. The finite parameter regime for the sustained oscillation has been understood as a supercritical Hopf bifurcation and generation of a stable limit cycle around a destabilized equilibrium point [Gu et al., 1984]. We have conducted a fully nonlinear analyses using MATCONT [Govaerts et al., 2006], which is a free package for MATLAB. Unfortunately, we found that the system undergoes a subcritical Hopf bifurcation; an unstable limit cycle is absorbed at the Hopf bifurcation. Further study is needed to resolve this problem. The continuation between the brittle and ductile regime is not unique so that there may be a more plausible function following the same empirical approach. The brittle friction law may have 2 or more state variables which probably make the Hopf bifurcation super critical. Also, constructing the model of the physical processes operating in BDT and formulating a physics-based constitutive law deserves future study.

Keywords: fault constitutive law, brittle-ductile transition

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SSS029-06 Room:104 Time:May 23 09:45-10:00

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 processes 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. The results show that before the occurrence of a large event, the deviation of the differential stress becomes small in a surrounding area of the large event. 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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SSS029-07 Room:104 Time:May 23 10:00-10:15

Semi-controlled earthquake-generation experiments in South African gold mines (2010)

Hiroshi Ogasawara[1*], R Durrheim[2], M Nakatani[3], Y Yabe[4], A Milev[5], A Cichowicz[6], H Kawakata[1], O Murakami[1], M Naoi[3], H Moriya[4], T Satoh[7], Research Group[8]

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We report on the research activity in FY2010 for a 5-year project to monitor in-situ fault instability and strong motion in South African gold mines. The project has two main aims: (1) To learn more about earthquake preparation and generation mechanisms by deploying dense arrays of high-sensitivity sensors within rock volumes where mining is likely to induce significant seismic activity. (2) To upgrade the South African national surface seismic network in the mining districts. This knowledge will contribute to efforts to upgrade schemes of seismic hazard assessment and to limit and mitigate the seismic risks in deep mines.

As of February 2011, 45 boreholes totalling 1.9 km in length had been drilled at project sites at Ezulwini, Moab-Khotsong and Driefontein gold mines. Several dozen more holes are still to be drilled. Acoustic emission sensors, strain- and tiltmeters, and controlled seismic sources are being installed to monitor the deformation of the rock mass, the accumulation of damage during the preparation phase, and changes in dynamic stress as the rupture front propagates. These data will be integrated with measurements of stope closure, stope strong motion, seismic data recorded by the mine-wide network, and stress modelling. Preliminary results will be reported at IUGG meeting.

The project is endorsed by the Japan Science and Technology Agency (JST), Japan International Cooperation Agency (JICA) and the South African government. The contributions of Seismogen CC, OHMS Ltd, Anglogold Ashanti Rock Engineering Applied Research, Gold Fields Seismic Department and the Institute of Mine Seismology are gratefully acknowledged.

Keywords: South African gold mines, Closed distance from hypocenters, Earthquake & AE, Strain & Tilt, Dynamic rupture process, Transmitted electric wave

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Viscoelastic Model of 2004 Sumatra-Andaman Earthquake observed from near (AGNeSS) and far field GPS measurements

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The 2004 Sumatra-Andaman (SA) earthquake occurred due to the subduction of the Indo-Australian plate beneath the Eurasian plate along the Sunda trench. Coseismic deformation of the 2004 SA earthquake was detected by Global Positioning System (GPS) over a wide area in the Southeast Asia. [i.e. Vigny et al., 2005: Subarya et al., 2006; Hashimoto et al., 2006]. In addition, postseismic deformation has been detected by GPS in the Andaman Islands [i.e. Paul et al., 2007; Gahalaut et al., 2008] and Thailand [Satirapod et al., 2008].

We have been operating a GPS network in northern Sumatra called AGNeSS (Aceh GPS Network for Sumatran Fault System) from 2005 and also detected significant postseismic signal. AGNeSS is a densification of the area for about 150 km by 150 km wide which located in the northern region of Sumatran fault. AGNeSS constituted of campaign and continues GPS sites. Totally, 20 campaign sites were obtained during our field observation. Meanwhile, our continuous GPS site, USKL, has been operated since March 2005.

Thus we try to model postseismic deformation combining all those available data. By assuming a coseismic fault model the 2004 SA and the 2005 Nias earthquakes [Einarsson et al., 2010], we predict postseismic viscoelastic relaxation and compare the model calculation with observation. We use PSGRN/PSCMP program developed by Wang et al. [2006]. We assume three-layered structure, a Burgers viscoelastic layer is intervened between the elastic suface layer and the Maxwell viscoelastic substratum. Here, we did not use Maxwell rheology since it can not match with GPS observation [Paul et al., 2007].

We assume that viscosity for Maxwell element is 10ˆ19 Pa s. Our result shows that the viscosity for Kelvin element is 2x10ˆ18 Pa s. Our rheology model is similar to those obtained by Hoechner et al. [2010] and Pollitz et al. [2008]. However, our current viscoelastic model here can not match the vertical deformation data in northern Sumatra. On the other hand, the model reproduces both the horizontal and the vertical GPS data in the Andaman Islands well [Hoechner et al., 2010].One possible reason is that other physical process such as an afterslip has may have significant contribution to the postseismic deformation. Our current estimate of the elastic layer thickness is 55 km. However, the best fit model for elastic depth in Andaman Islands is 40 km [Hoechner et al., 2010]. This result indicates that there is structure heterogeneity between north Sumatra and Andaman Islands.

Keywords: 2004 Sumatra-Andaman earthquake, GPS, viscoelastic deformation

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Petrographical Characteristics of Mylonitic Pseudotachylyte in Peridotitic Fault Zones

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Major earthquakes nucleate approaching the brittle-ductile transition zone (BDT) of rocks. Geological study of natural seismogenic faults is important for understanding earthquake-related processes.

Pseudotachylyte(PsT) is a fault rock produced during earthquakes, formed via frictional melting of the fault. Presence of glasses or dendritic microlites is the microstructural evidence for PsT identification. However, under high ambient temperature conditions typical of BDT, such textures are susceptible to recrystallization. Hence, there can be a bias that much seismic record of BDT has been overlooked. Also, there are several reports of PsTs intimately associated with ultramylonites, which implies some ultramylonites may have formed via frictional melting. Using a working category ”mylonitic pseudotachylyte (M-PsT)” for such ultramylonite-like fault rocks which imply a seismic melting origin, we are studying PsTs and mylonites cropping out in the Balmuccia peridotite body in northwestern Italy. In this presentation, ”mylonite” means ordinary mylonite formed only by solid state deformation.

There are networks of PsT and M-PsT and cataclasite faults and shear zones of mylonite in the study area. Cataclasites associated with M-PsT usually show partial recrystallization. The observable displacement of single jerk PsT faults ranges through 10cm ˜ several tens of centimeter. There is a tendency such that the more melt-origin texture is obliterated by recrystallization, the less the fault has injection veins. However, there are some faults that contain both PsT and M-PsT textures gradually changing from one to the other.

M-PsT consists of porphyroclasts and ultrafine matrix. M-PsT faults often sharply cut coarse crystals of the wall, or have gradual boundaries with wall mylonite. The grain size of the matrix is submicron ˜ a few microns, and constituent minerals are olivine, spinel, orthopyroxene, clinopyroxene, hornblende, dolomite, small amount of sulfide, and/or plagioclase. The grain boundaries of matrix minerals often form triple junctions. The formation depth of M-PsT is estimated from the mineral paragenesis to be about 20-40km. Matrix olivines have lattice preferred orientation (LPO). The M-PsT matrix has a collective optical anisotropy observed under polarization microscope, whose optical axes are consistent with the olivine LPO. Some porphyroclasts show texture of recrystallized cataclasite. The mineral clasts are olivines and spinels, and relatively rare pyroxenes.

M-PsTs are distinguishable from cataclasite or mylonite. Compared to cataclasite matrix, M-PsT matrix looks uniform in the grain size and is high in modal per cent. Cataclasite is clast?rich and the grain size ranges widely. Mylonite matrix has typically larger grain size (˜a few tens of microns) and is typically colorless, whereas M-PsT matrix is pale brownish under optical microscope (probably due to minute sulfide particles in the matrix.)

Mylonitic PsT sometimes contain characteristic ”spinel coronas” where deformation and recrystallization is not intense. The texture is such that aluminous spinel clast is surrounded by a corona that consists of fine-grained chromian spinel and interstitial Al-, Ca-rich phases. This corona is thicker far from the wall of the vein. Similar texture occurs in natural glass-bearing PsT in the same massif and in PsT produced by high velocity rotational shear experiment of the Balmuccia peridotite.

Another textural feature is that crack-like orthopyroxene or olivine exists inside coarse olivine or clinopyroxene, respectively. This texture is found only inside or vicinity of the M-PsT vein. The crack-like morphology and the spatial intimacy of the texture to fault implies that the texture is characteristic of seismic deformation.

These observational features of ultramylonite-like fault rock will be interpreted in relation to seismic processes. These kinds of studies can contribute to our understanding of deep seismicity.

Keywords: pseudotachylyte, ultramylonite, brittle-ductile transition, peridotite, microtexture, mylonitic pseudotachylyte

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Seismic slip recorded in fluidized ultracataclastic veins: an example from the Shimotsuburai Fault, central Japan

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It is well known that large earthquakes occur repeatedly along pre-existing mature active faults and that the history of seismic slip may be recorded by the meso- and microstructures in fault rocks that form at all depths from the near-surface to deep levels within fault zones in the crust. It is possible, therefore, to gain an insight into the deformation process of seismic slip recorded in seismogenic fault zones by studying the macro- and microstructures, fabrics, physical properties, and chemical compositions of fault rocks exposed at the surface. In this study, we report typical fluidized ultracataclastic veins formed repeatedly along the active Shimotsuburai Fault of the Itoigawa?Shizuoka Tectonic Line (ISTL) active fault system.

Field investigations and meso-microstructural analyses reveal that multi-stage veinlet ultralcataclastic rocks, composed of aphanitic pseudotachylyte (Pt) and unconsolidated fault gouge and alluvial deposits, are widely developed within a fault shear zone (<5 m wide) as simple veins, breccias, and complex networks, along the Shimotsuburai Fault. Early veins are generally fractured and overprinted by younger veins, indicating that vein-forming events occurred repeatedly within the same fault zone. Microstructurally, both the Pt and fault gouge veins are characterized by a superfine- to fine-grained matrix and angular?subangular fragments ranging in size from sub-micron scale to several centimeters. Powder X-ray diffraction patterns show that the fault veins and injection veins of fault gouge and Pt are characterized by crystalline materials composed mainly of quartz and feldspar, similar to the host granitic cataclasites.

Based on the meso- and microstructural features of ultracataclastic veins and the results of powder X-ray diffraction analyses, we conclude that i) the Pt veins were generated mainly by crushing rather than melting, ii) multi-stage veinlet fault gouge and Pt formed repeatedly within the fault-fracture zone via the rapid fluidization and injection of superfine- to fine-grained materials derived from the host granitic rocks during seismic faulting events, and iii) veins of alluvial deposit formed by liquefaction associated with strong ground motion during large-magnitude earthquakes that occurred along the ISTL. The present results show that the fluidized ultracataclastic veins and alluvial deposit veins record paleoseismic faulting events that occurred within a seismogenic fault zone; consequently, these features are a type of earthquake fossil, as is melt-origin pseudotachylyte.

Reference:

Lin, A. (2011). Seismic slip recorded in the fluidized ultractaclastic veins formed along the coseismic shear zone during the 2008 Mw7.9 Wenchuan earthquake, Geology, in press.

Keywords: ultracataclastic veins, pseudotachylyte, earthquake fossil, fluidization, fault gouge, fault rocks

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Internal structure and high-velocity friction studies on the Longmenshan fault that caused the 2008 Wenchuan earthquake

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A challenge in fault and earthquake studies is whether a recent well-instrumented earthquake can be reproduced or not based on measured frictional properties of fault zones that caused the earthquake. In collaboration with Institute of Geology, China Earthquake Administration, the author has studied internal structures of Beichuan fault zone at a large outcrop in Hongkou, Sichuan Province. This fault is the major fault in the Longmenshan fault system that ruptured for more than 250 km during Wenchuan earthquake, and the vertical offset at near Hongkou outcrop is 4 to 5 m. Fault zone consists of clayey fault gouge of about 1 m in width and of fault breccia zones of 30-40 m in width on the hanging-wall side. Slip zone during Wenchuan earthquake was 10-20 mm, but overlapping striations indicate that localization of slip to an even narrower zone of a few to several millimetres occur during seismic fault motion. Graphite was found close to the coseismic fault and it might have formed during seismic fault motion. Fault gouge contains illite and chlorite, but not smectite. Black gouge found in fault core in WFSD-1 (Wenchuan Earthquake Fault Scientific Drilling Project) was not found on the Hongkou outcrop.

High-velocity friction experiments were conducted on fault gouge from this outcrop to understand the dynamic weakening processes of the fault during Wenchuan earthquake. Experiments were done on gouge of about 1 mm in thickness between a pair of solid cylindrical specimens of Belfast gabbro of about 25 mm in diameter under dry conditions, using a rotary-shear high-velocity frictional testing machine at Kochi Core Center of JAMSTEC and a rotary-shear low-to-high-velocity friction apparatus at Hiroshima University. Frictional coefficient decreases from around 0.6-0.8 at slow slip rates to 0.1 to 0.2 at high slip rates. An exponential slip-weakening was confirmed and empirical relationships for the slip-weakening distance and for steady-state frictional coefficient were determined as functions of normal stress and slip rate. A very small temperature anomaly detected WFSD-1 hole at a likely coseismic fault at a depth of 590 m suggests that frictional coefficient during the Wenchuan earthquake was far smaller than 0.1 (Mori et al, 2010). Present experiments reproduced duplex-like structures and shear bands as observed in fault zones in Hongkou outcrop. But any mineralogical changes was not recognized in the samples and present experiments could not reproduce fault rocks similar to the black gouge recognized in WFSD-1 hole. Experiments at normal stresses of at least 10 MPa, corresponding to the depth of the coseismic fault in the drill hole, are needed in the future to reproduce intrafault processes at depths. This requires a new specimen assembly that can prevent gouge leakage at high normal stresses.

Fault motion during an earthquake does not occur at a constant slip rate; it undergoes initial acceleration to the maximum slip rate, and then it decelerates and stops during an earthquake. The servo-motor of the low to high-velocity apparatus was controlled electronically to produce linear accelerating/decelerating slip history and a slip history characterized by regularized Yoffe function (rapid initial acceleration followed by nearly exponential deceleration). Better control of servo-motor has made it possible to conduct friction experiments with complex slip histories. Frictional behaviors of Longmenshan fault gouge are characterized by peak friction, nearly linear slip-weakening and final strength recovery. Slower deceleration causes more pronounced strength recovery which can act as brake to fault motion to promote pulse-like rupture propagation during an earthquake. A modified empirical law of Sone and Shimamoto (2009) describes observed behaviors for variable slip histories reasonably well, using parameters determined in constant slip-rate tests.

Keywords: Wenchuan Earhquake, Lognmenshan Fault, High-velocity friction experiment

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-12 Room:104 Time:May 23 11:30-11:45

Effect of acceleration on frictional properties of faults

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Recent high-velocity friction experiments shows that frictional resistance of faults increases rapidly at the onset of sliding over distance of more than several centimeters, that is followed by prolonged slip-weakening. The initial frictional barrier may affect how earthquake ruptures propagate into the shallow crustal depth, but it received little attention up to now. Thus we have conducted constant acceleration experiments on simulated gouge using a rotary-shear friction apparatus. We especially focus on the effect of acceleration of fault on the initial frictional barrier.

In the experiments, we slid a simulated fault at a constant slip rate of 0.1 mm/s and then suddenly increase slip rate to 1.3 m/s with different acceleration of from 0.13 to 13 m/sˆ2. In all runs, friction coefficient is 0.6˜0.7 at slip rate of 0.1 m/s and then increases by 2˜10% over distance of several centimeters as a fault starts to accelerate. Amplitude of the initial frictional barrier and hardening distance seem to depend on acceleration. When a simulated fault overcomes the initial barrier, friction coefficient gradually decreases with slip toward the steady-state value of 0.1˜0.2. In order to evaluate whether the initial barrier can affect rupture propagation, we estimate a ratio of the frictional work consumed on fault during the initial hardening stage to the frictional work during the slip weakening. The ratio is about ˜0.01 at acceleration of 0.13 m/sˆ2, but tends to increase with acceleration to ˜0.1 at 13 m/sˆ2. The result suggests that as the rupture speed increases, the effect of initial frictional barrier at the onset of rapid faulting could not be negligible and must be incorporated into the analysis of earthquake rupture propagation.

Keywords: fault, friction, earthquake, acceleration, slip hardening

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-13 Room:104 Time:May 23 11:45-12:00

Acoustic properties across the high velocity sheared zone

Eiichi Fukuyama[1*], Futoshi Yamashita[1], Kazuo Mizoguchi[2]

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We investigated the transmitted waves emitted from a piezo-electronic device during the high velocity slip experiments. We modified the high velocity shear apparatus installed at NIED to make it possible to measure the transmitted waves across the sliding interfaces. In this experiment, we used a pair of solid cylindrical sample of monzodiorite from Zimbabwe whose length and diameter are 43mm and 40mm, respectively. Input signal was a single sine pulse with 20Vpp and 0.5MHz. Since the resonance frequency of piezo device is 2MHz for parallel motion and 0.5MHz for perpendicular motion, the received signal is expected to be dominant in shear wave motions.

Before the experiment, we measured the transmitted waves under various normal stress conditions without rotating the samples. As expected, amplitude increases linearly with increasing the normal stress (from 1MPa to 8MPa), indicating the increase of contact area in the interface.

Then, we conducted a friction experiment with continuously monitoring the acoustic amplitudes. The experiment was done under constant slip velocity of 0.08m/s under constant normal stress of 3MPa. Under this condition, no visible melting occurred. A single 0.5MHz sine pulse was shot at an interval of 1KHz. To monitor the averaged variation of the amplitude, 10000 traces were stacked to get a single observed trace, therefore the stacked traces were obtained every 10s. Since total amount of slip was 110m in about 20 seconds, we obtained 125 stacked traces during the sliding. We measured the maximum amplitude of each trace between 30-50 micro seconds after shoot time, which mainly includes S-wave arrival time. The variation of maximum amplitudes seem to be related to the friction coefficient. When the friction decreases, maximum amplitude increases.

We could get some information on the high slip friction from the above amplitude variation of transmitted waves.

Keywords: high-velocity friction experiment, amplitude of transmitted wave, friction, fault

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-14 Room:104 Time:May 23 12:00-12:15

Induced seismicity along a fault due to fluid circulation: conception and application

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It is believed that the some seismicity is driven by the fluid circulation within fault zone and different rheology models have been proposed principally based on the Darcy's law, fluid flow in porous medium. Although it is very difficult to quantify such feature in natural seismicity (some aftershocks of large earthquakes, or seismicity in subduction), the direct application is the induced seismicity at the geothermal sites where micro-fracturing (seismicity) is necessary to allow fluid circulation between two wells and thus the assessment of such seismicity becomes also important. In this study, we construct a conceptual model for the simulators, taking into account of elastic and plastic porosity change (e.g. Segall and Rice, 1995) and fault width evolution (e.g. Yamashita, 1999), supposing first that the seismicity (fluid flow) expands dominantly along a plane. In fact, for an injection of about a few 10 l/s, pore pressure increases immediately (about 1 min) up to more than 10 MPa. This is much faster than the fluid circulation in general. This requires that the fracturing co-seismic process should play a dominant role for bringing the fluid circulation.

Keywords: induced seismicity, fluid, porosity, Darcy's law, fault rheology

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-15 Room:104 Time:May 23 12:15-12:30

Fluid-rock interaction in a fault during coseismic slip

Go Honda[1*], Tsuyoshi Ishikawa[2], Wataru Tanikawa[2], Tetsuro Hirono[1]

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The generation of a high-temperature hydrous fluid by frictional heating is generally regarded as possible products of coseismic slip. They are critical in controlling effective stress and fault mechanics. For example, in a process termed thermal pressurization, pore fluid pressure produced by frictional heating can reduce the effective normal stress acting on the fault surface. This may lead to a marked reduction in fault strength during slip. This process should be reflected in the chemical composition of slip zone rocks. Recently, records of fluid-rock interaction in a fault during coseismic slip are recognaized in Taiwan Chelungpu, Shimanto Kure, Boso Emi by trace elements and isotope analysis (Ishikawa et al., 2008; Hamada et al., 2011). Concentrations of fluid-mobile trace elements (Sr, Cs, Rb, and Li), and Sr isotope ratios are very sensitive to fluid-rock interaction at high temperature, making them strong indicators of frictional heat in the slip zone. Li, Rb, Cs compositions of these slip zone are lower and Sr higher compared with those of host rock. These changes of trace elements also showed that the temperature of the slip surface have reached more than 350 ^{o}C.

In Shimanto Kure OST, which was an ancient megasplay fault that took place at 2.5-5.5 km depth, we discovered not only records of fluid-rock interaction but also those of melting. These findings suggest the thermally-enhanced pressure might not have reached a sufficient level to cause thermal pressurization, and the temperature continued to increase to cause melting. Comparison with a shallow slip zone at 1-2 km depth (Boso Emi), where only thermal pressurization occurred, indicated that the transition from melt lubrication at depth to thermal pressurization at shallower depths along a megasplay fault may occur during rupture propagation.

We are also just now conducting high-velocity frictional experiments on fault gauge under wet condition to inspect generation of high temperature fluid and influence on slip behavior. The core sample from the Taiwan Chelungpu Fault Drilling Project (TCDP) was used in experiments as a fault gauge sample, which is composed predominantly of siltstone. We analyzed trace element and Sr isotope ratio on samples before and after experiments to estimate whether fluid-rock interaction occurred in fault gauge during shearing. The change of trace element compositions and Sr isotope ratio was not recognized in case of low confining pressure and low slip velocity. The maximum temperature of slip surface in that case was 250 ^{o}C. This indicates that generation of fluid-rock interaction requires more high temperature because fluid mobile elements (Cs, Rb, and Li) in sediments are significantly mobilized in fluids above 300 ^{o}C, and Sr in sediments increases around 300 ^{o}C (You et al., 1996).

We will present these the latest experimental results and natural fault recording fluid-rock interaction at this meeting.

Keywords: coseismic slip, fluid-rock interaction, trace elements, high velocity frictional experiments

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS029-16 Room:104 Time:May 23 12:30-12:45

Effects of shear-induced dehydration of serpentine on the mechanical behavior

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The frictional properties of serpentinite are of particular interest in the study of earthquake generation processes along subducting plates and transform faults. Previous studies showed that the rheology of serpentinite is quite complicated, but that complicated rheology is not yet fully understood. We were not able to pinpoint the role of serpentinite in fault behavior and/or earthquake occurrence. Currently it becomes imperative to investigate the rheology of serpentine-bearing fault comprehensively. Serpentine accompanied by high pore water pressure at wedge mantle has a possibility to affect occurrences of slow earthquakes and/or non-volcanic tremors [e.g., Obara, 2002] at a place where a subducting plate contacts a serpentinized mantle wedge. Here we will report results of experiments the transient behaviors of the serpentine gouge to stepwise change in slip velocity under high temperature condition. We conducted the shear-sliding tests on the serpentine gouge (almost pure antigorite) using a gas-medium, high-pressure, and high-temperature triaxial testing machine. Sliding deformation was applied on the thin zone of the gouge (c.a. 0.8 mm) between two alumina blocks with oblique surfaces at 30? to the cylindrical axis, under various temperature conditions. The experiments were carried out using a constant confining pressure (100 MPa), a constant pore-water pressure (30 MPa), and a range of temperatures (from room temperature to 600 deg.C). The transient responses of mechanical characteristics following stepwise changes in the slip velocity were documented at each temperature. Slip rates varied between 0.0115 micron/sec (~36 cm/yr) and 11.5 micron/sec (~1.0 m/day).

Both the strength and the shear behavior showed the drastic change at around 450 ~ 500 deg.C. The average strength at 1.4 mm of the displacement showed a sharp rise of c.a. 0.15 of the friction coefficient between 400 deg.C and 450 deg.C, which friction increasing was quite large. The transient behavior to the stepwise change in the velocity also indicated change in the type of the behavior drastically, from the creep-type behavior at 400 deg.C to the frictional (or stick-slip) behavior at the temperature higher than 450 ~ 500 deg.C.

Although only a limited volume of the serpentine was involved in the dehydration reaction, X-ray diffraction analyses and scanning electron microscopy observations showed that forsterite had nucleated in the experimental products at the temperatures higher than 450 ~ 500 deg.C that were associated with frictional behavior. Sub-micron-sized, streaky forsterite masses in shear-localized zones may be evidence of shear-induced dehydration that caused strengthening and embrittlement of the gouge (refer to Takahashi and Shimizu, 2011, in S-IT39 at this year JpGU Meeting for details of the microscopic observations).

Our observation revealed that the serpentine at the shear-localized zone were reacted preferentially, implying a possibility of shear-induced dehydration reaction at the fault having the hydrous minerals. Moreover, this localized reaction can control the deformation style of the fault even though the dehydration was limited. At the outset of the dehydration, both the strength and shear behavior are already controlled by physical properties of the reaction products. Owing to the drained condition, the mechanism of embrittlement was not due to the pore pressure increasing. Thus it also suggests that the fault with hydrous minerals becomes brittle once the dehydration reaction starts even if the P-T condition and/or poroelastic condition do not allow the pore pressure increasing.

Japan Geoscience Union Meeting 2011
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SSS029-P01 Room:Convention Hall Time:May 23 14:00-16:30

Finite element modeling of stick-slips on a solid surface with many asperities

Mamoru Hyodo[1]*, Hide Sakaguchi[1], Takane Hori[1]

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Friction is the tangential force resisting the relative motion of solid surfaces or material elements sliding against each other. Since all real surfaces have topography (or roughness) in the microscopic view, they touch at a few points or asperities, when they are brought together. Hence, macroscopic friction is regarded to be the sum of interacting forces at such microscopic asperities. For an contacting asperity, we consider the additional deformation at the area surrounding the asperity. In such a case, depending on the deformation amount, the real area of contact at the asperity will largely increase or decrease. Such a change in contact state at the asperity affects not only the interacting force at the asperity but also the macroscopic friction. Furthermore, it is expected that friction between solid surfaces has a possible dependence on materials, since the deformation of the solid material is strongly depend on their properties (rigidity, viscosity, etc.). The effects of the deformation and property of materials on friction, however, have not been explicitly included in many existing friction laws.

Therefore, in this study, we examine these effects on macroscopic friction through a finite element modeling of stick-slips on a solid surface with many asperities. As a tentative result, the calculation with 50 asperities repeats stick-slips with various sizes, though the maximum number of asperities which break in an event is much smaller than 50. Hence, the macroscopic friction is almost constant, and steady slip motion of two blocks is generated.

In the presentation, we will show the detail of our finite element modeling and calculation results with various material property or asperity distributions.

Japan Geoscience Union Meeting 2011
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SSS029-P02 Room:Convention Hall Time:May 23 14:00-16:30

Quartz amorphization due to friction and wear : Raman spectroscopic analysis

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Solid state amorphization of minerals is known to occur in hardness indentations, during ball milling, in diamond anvil experiments, and in shock experiments. A production of SiO2 amorphous material is also reported in experimentally created fault gouges [1]. High speed friction experiments of quartz rocks imply extraordinary weakening at seismic rates [2]. Because weakening requires the combined effects of large displacement and high velocity, formation of a thin silica gel layer which comprises of very fine particles of amorphous silica was thought to cause weakening. Therefore, physical process of amorphization is important to better understand weakening of quartz bearing rocks at seismic rates. In this study, we conducted a pin-on-disc experiment to investigate details of amorphization of quartz [3]. Discs were made of single crystals of synthetic and Brazilian quartz. The normal load and sliding velocity were ranged from 0.01 N to 1 N and from 0.01 m/s to 0.25 m/s, respectively. The friction experiments were conducted using quartz and diamond pins (curvature radii of 0.5 ~ 1.5 mm) to large displacement (~80 m) under controlled atmosphere. Raman microspectroscopy (excitation wavelength 532.1 nm) provides lattice vibrational modes, and was used to investigate the degree of amorphization of samples. Raman spectra of frictional tracks on the disc show clear bands at wavenumbers of 126, 204, 356, 394, and 464 cm-1, their bands are restored E(LO+TO), A1, A1, E(TO), A1 vibration modes respectively. However, the bands at 464 and 204 cm-1 gradually broaden to reveal shoulders on the higher-wavenumber side of these peaks. Especially, a new distinguished peak appears at 480cm-1. In an experiment conducted at low stress (125 MPa) to large displacement (~ 80 m), Raman spectra show complete lack of lattice vibrations mentioned above, indicating that quartz lost intermediate range structure of SiO2 during friction experiments. In the presentation, we will present the degrees of the amorphization as a function of normal stress, displacement and sliding velocity.

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Keywords: friction experiment, amorphization, raman spectroscopic analysis, weakening

Japan Geoscience Union Meeting 2011
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SSS029-P03 Room:Convention Hall Time:May 23 14:00-16:30

Raman spectroscopic characterization of fault gouge rapidly healed after dynamic weakening

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How rapidly fault strength recovers after an earthquake is an important question for understanding the earthquake generation mechanism in seismic cycles. Recent friction experiments at coseismic velocities revealed that the fault can completely regain its strength to pre-slip level within few days (Mizoguchi et al. 2009, BSSA). However the factor causing such rapid fault healing after dynamic weakening is still not understood. We expected that the reformation of a certain type of chemical bond is responsible for fault healing. Thus, we performed high-velocity friction experiments on quartz gouge at a slip velocity of 1.3 m/s, normal stress of 1.0 MPa and displacement of >10 m. At this condition, the simulated fault weakened markedly with displacement to friction coefficient of ~0.2. In order to identify the chemical bonds that play a key role in fault healing after dynamic weakening, the slip surface of gouge zone was analyzed immediately after the experiments using a laser Raman microscope. We found a characteristic peak at ~1600 cm-1 in a Raman spectrum detected only from the dynamically weakened gouge at high velocities. This peak corresponds to bending vibrations of a H2O molecule. The peak appeared just after the experiment and its intensity decreased with time. After two days, the peak totally disappeared. Interestingly the time scale of existence of the peak is almost same as that of gouge healing. We propose a hypothesis that the excitation of bending vibrations of a H2O molecule by shear and/or frictional heat during rapid sliding and the degradation of the vibrations after the termination of the sliding results in the dynamic fault weakening and the rapid fault healing, respectively.

Keywords: fault, healing, H2O

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SSS029-P04 Room:Convention Hall Time:May 23 14:00-16:30

Contact state of simulated fault via electrical resistance

Futoshi Yamashita[1*], Eiichi Fukuyama[1], Kazuo Mizoguchi[2], Takashi Yanagidani[3]

[1]NIED, [2]CRIEPI, [3]None

Earthquake is a frictional sliding of fault. If we can monitor the frictional strength of fault with maintaining the contact state between rocks, therefore, we will obtain valuable information which can help us to understand the frictional property of rocks and the fault sliding mechanisms during earthquake. From the point of view, we focused on electrical property of fault plane. In the previous experiment, we successfully observed decrease in the electrical resistance of simulated fault caused by increase in the normal stress and formation of molten layer. In this meeting, we will show the estimated contact state of simulated fault via the electrical resistance during rotary-shear frictional tests. We adopted an electrometer (Keithley 6514) to measure extreme high resistance of dry rocks. This instrument enables us to measure resistance up to 210 G ohm by impressing high voltage of 250 V. At first, we conducted simple press test. We used two cylindrical gabbros from India as rock samples with the diameter of 25 mm and the length of 30 mm. The rock samples were installed into the rotary-shear frictional testing apparatus (Shimamoto and Tsutsumi, 1994; Mizoguchi and Fukuyama, 2010). The normal stress was changed between 0 and 8 MPa by 0.5 MPa in each step after maintaining the state for 300 s. The electrical resistance of fault should be more than 210 G ohm with the normal stress of 0 MPa, because the electrometer could not work at the stress. The resistance decreased from 90 G ohm at 0.5 MPa to 30 G ohm at 8 MPa accompanying with the increase in normal stress. This can be interpreted that increase in the normal stress enlarged real contact area of the fault, which causes decrease in the resistance. Next, we monitored the resistance of fault during low-velocity frictional test. We used the same rock samples of the press test. The normal stress of 3 MPa and the equivalent slip velocity of 5.3 x 10^{-3} m/s were maintained during the test. Frictional strength, which is defined as the ratio of shear stress to normal stress here, suddenly increased up to 0.8, weakened to 0.2, and fluctuated between 0.2 and 0.6. The electrical resistance drastically decreased from 130 to 8 G ohm after starting the frictional test, and fluctuated between 10 and 30 G ohm after the first decrease. Comparison between changes in the frictional strength and the resistance revealed that the increase in frictional strength synchronized with the decrease in resistance, and vice versa. This observation can be explained by the idea that the increase in real contact area of fault causes the increase in frictional strength as well as the decrease in resistance. Next, we conducted high-velocity rotary-shear frictional test with frictional melting. We maintained the normal stress of 3 MPa and the equivalent slip velocity of 1.3 m/s. The amount of slip distance was attained to 52 m. During one second after starting frictional sliding, the fault showed the first weakening, and after that, the fault showed the second strengthening and weakening associated with the frictional melting introduced by Hirose and Shimamoto (2005). The electrical resistance decreased from 70 G ohm to 3 G ohm just after the start of sliding and continued to decrease up to 1 G ohm. Detailed investigation of the early stage of sliding revealed that rate of the decrease in resistance became greater with transition from the first slip weakening to the second strengthening. This would correspond to the stage that local melting at some asperities stated to connect each other. After that, the frictional strength attained to the second peak, which looks to synchronize with temporal stop of the decrease in resistance. This can be interpreted that the melt patches grew to molten layer in the fault. We also observed step-like decreases in the resistance, which should be associated with growth of the molten layer. We will quantitatively discuss the frictional mechanisms of fault by detail analysis.

Keywords: Electrical resistance, Fault, Friction, Frictional melting, High-velocity rotary-shear frictional test

Japan Geoscience Union Meeting 2011
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SSS029-P05 Room:Convention Hall Time:May 23 14:00-16:30

Influence by teflon contamination on the fault slip behavior during high-speed friction experiments

Nozomu Hirai[1], Go Honda[1*], Wataru Tanikawa[2], Tetsuro Hirono[1]

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There are many natural fault zones including clayey fault gauge. It is important to understand coseismic slip behavior of fault gauge because it has a great influence on frictional strength.

When we conduct high velocity frictional experiments on fault gauge, we generally use a Teflon sleeve which covers the fault to confine the gauge in the fault during shearing. As a preliminary experiment, we conducted high velocity frictional experiments on illite powder samples, using a rotary shear, high speed frictional testing apparatus. We considered the illite powder to be fault gauge. The gauge sample was put between a pair of gabbro cylinders. When we conducted thermogravimetry and differential scanning calorimetry on gauge samples after experiment, the contamination of more than 10wt% Teflon into gauge samples during sharing was recognized. This weight of Teflon contamination increased with increasing normal stress and displacement. Because frictional coefficient of Teflon is low compared with a rock, Teflon contamination into gauge sample is considered to have influence on frictional strength. In order to investigate this influence, we conducted experiments using 0wt%, 10wt%, 20wt%, 30wt%, 40wt%, 50wt% Teflon contaminated beforehand into gauge samples. We evaluated the slip behavior by Teflon contamination from this experiment result.

Keywords: slip behavior, high-velocity friction experiments, teflon, differential scanning calorimetry, thermogravimetry

Japan Geoscience Union Meeting 2011
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SSS029-P06 Room:Convention Hall Time:May 23 14:00-16:30

Microfracture analysis of damage zone along active faults

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Brittle faulting along faults in the crust often results in the fault zone structure characterized by a fault core surrounded by a damage zone. The fault core is narrow localized shear deformation zone consisting of fault gouge, fault breccia and cataclasite. Previous studies showed a clear relationship that the width of the damage zone becomes thick with the net displacement occurred along faults (e.g., Mitchell & Faulkner, 2009). The damage zone width is important for understanding the degree of maturity of a previously unknown fault and its associated seismic hazard. In the damage zone, fractures develop at various scales, from ˜ ?m to ˜ m, and their density typically increases with proximity to the fault core. We examined the spatial distribution of the microfracture density around a newly-found active fault in Takiyama area, east of Tottori plain (Sasaki et al., this 2011 JGU meeting).

The studied fault zone consists of the 1 m thick fault core of the purple-colored clayey fault gouge and the fault breccia with cataclastic foliation, and the surrounding damage zone developed in Cretaceous Kyushozan granite. The boundary plane between the fault gouge and the fault breccia has a strike of N79W and a dip of 87N, corresponding to a fault plane. We collected ten orientated samples 19.4 m to 329 m from the fault core. The samples were coated with epoxy and then thin sections were cut perpendicular to the fault plane and parallel to a horizontal plane because the slip direction is unknown. More than 10 quartz grains per sample were analyzed for the microfracture density measurements. Quartz is suitable to estimate the damage that the rock sample has sustained because quartz without cleavage acts as an isotropic medium for fracturing. We counted the number of microfractures that intersected a line which was drawn from the edge of each quartz grain, through the center point, to the other edge of the grain. The linear microfracture density for each sample is calculated to be the total number of microfractures intersecting the lines divided by the total counting line length. The microfractures we counted are divided into (1) healed fracture (fluid inclusion planes), (2) sealed fracture filled with clay minerals and (3) open fracture. The linear density of open fractures increases as the fault core is approached. The other fractures do not show a clear relationship between the microfracture density and the perpendicular distance from the fault core. In this presentation we will discuss whether such a spatial distribution of microfractures is structural characteristics of damage zone along active faults.

Keywords: active fault, Damage zone, microfracture

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SSS029-P07 Room:Convention Hall Time:May 23 14:00-16:30

Structural analysis of shear zone developed in Sakaitoge Fault

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Active fault zones and their related cataclastic fault rocks formed by seismic faulting at shallow depths within the upper crust are closely related to the long-term seismicity and tectonic history of faults. Studying on deformation structures of active fault zones, therefore, provides important information for accessing the long-term seismic faulting behaviors and understanding the tectonic environment and history of active faults. In this paper, we present a case study on the fault shear zone structures developed along the Sakaitoge-Kamiya Fault, central Japan by field investigation and meso- and microstructural analyses of fault rocks.

The Sakaitoge Fault, the northern segment of the NW-SE trending Sakaitoge-Kamiya Fault zone, extends for about 30 km in the southern Hida Mountains of central Japan. Previous studies show that the total displacement is about 4.5 km, having a left-lateral strike-slip movement sense and that the youngest seismic event occurred in the past 1400 yr (Kano et al., 2001).

Field investigations and meso- and microsructural analyses reveal that the shear-zone of the Sakaitoge Fault is mainly composed of non-foliated cataclasite and foliated cataclasite, fault gouge and fault breccia. The foliations and Riedel shear structures indicate a uniform left-lateral strike-slip sense. The foliations developed in both the cataclasite and the fault gouge shows that the Sakaitoge Fault had been moved in the same shear sense since the formation of cataclasitic rocks.

Keywords: Sakaitoge fault, shear zone, foliation

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Earthquake fossil: ultralcataclastic veins occurred along the Arima-Takatsuki Tectonic Line

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In this study, we present a case study of veinlet ultracataclastic rocks from the Arima-Takatsuki Tectonic Line (ATTL), southwest Japan. Field investigations and meso-microstructural analyses reveal that numerous veinlet ultralcataclastic rocks, composed of aphanitic pseudotachylyte (Pt) and unconsolidated fault gouge and alluvial deposits, are widely developed within a wide fault zone of ˜200 m as simple veins, breccias, and complex networks along the ATTL. These veinlet fault rocks generally show dark, green, gray, brownish-red in color. Microstructurally, all these veins are mainly characterized by a superfine- to fine-grained matrix and angular?subangular fragments ranging in size from sub-micron scale to several millimeters. Powder X-ray diffraction patterns show that all veins are characterized by crystalline materials composed mainly of quartz and feldspar, similar to the host granitic rocks.

Based on the meso- and microstructural features of ultracataclastic veins and the results of powder X-ray diffraction analyses, we conclude that i) all veinlet ultracaclastic rocks were generated mainly by crushing, ii) the veinlet and network veins formed repeatedly within the fault-fracture zone via the rapid fluidization and injection of superfine- to fine-grained materials during seismic faulting events; iii) the pseudotachylyte veins formed by crushing but not melting. The present results show that the fluidized ultracataclastic veins record paleoseismic faulting events that occurred within a seismogenic fault zone; consequently, these features are a type of earthquake fossil, as is melt-origin pseudotachylyte.

Reference: Lin, A. (2011). Seismic slip recorded in the fluidized ultractaclastic veins formed along the coseismic shear zone during the 2008 Mw7.9 Wenchuan earthquake, Geology, in press.

Keywords: pseudotachylyte, veinlet fault rock, Arima-Takatsuki Tectonic Line

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High-velocity weakening of the black fine-grained fault rock from the Ghost Rocks Formation, Kodiak Island, Alaska

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In Kodiak Island, Alaska, an accretionary complex that has been interpreted as an analogue of paleo-decollement zones exposes (Fisher and Byrne, 1987). Recently, dark gray to black, locally vitreous, ultra-fine grained fault rock (black fault rock, BFR) was reported from the fault zones in the Kodiak accretionary comlex (Ghost Rocks Formation), as a possible rare example of rocks that preserved a record of seismogenic faulting along subduction zones (Rowe et al., 2005). The fault rock is characterized with the following features; In the BFRs, pseudotachylyte occurs as a possible evidence for the operation of frictional melting (Meneghini et al., 2009), and on the other hand, the BFRs contain ductile deformation fabrics, which suggests association of cataclastic flow (liquefaction) process at high slip rates (Brodsky et al., 2009).

In this study, frictional properties of cataclastic melange rock exposed adjacent to the BFRs was investigated using a rotaty-shear frictional testing machine at Kyoto University. The samples for the experiments were collected from cataclastic argillaceous melange rock, which is likely the source of the BFRs. The collected samples were manually disaggregated and sieved in order to eliminate clasts larger than about 0.17 mm. Frictional experiments on the assembled samples were performed at a constant slip velocity of 300 mm/s over a range of normal stresses from 0.4 MPa to 1.0 MPa at dry condition.

At the lowest normal stress of 0.4 MPa, the experimental fault exhibited slip weakening behavior. Upon initiation of slip, shear stress decreased exponentially from initial peak value to residual almost steady-state value after about 20 m displacements. Thickness of the sample monotonically decreased during the run, suggesting a gradual compaction of the sample with the slip. On the contrary, for the tests at higher normal stresses from 0.6 to 1.0 MPa, frictional behavior of the argillaceous rock sample comprises of three stages; weakening stage from initial peak value, which is followed by a rapid friction increasing stage toward the second peak value, and a further gradual friction decreasing stage following the second peak friction. Interestingly to note, the sample started to dilate (expand) following the initial compaction stage. The beginning of the dilation roughly correlates with the onset of the increasing period of shear stress towards the second peak value. Our experimental results suggest that frictional heating plays an important role for the stress increasing behavior of the sample following the initial slip-weakening at normal stresses $>$ 0.4 MPa.

Keywords: rock friction, pelitic rock, Kodiak Island

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Internal and permeability structures of faults developed in the Shimanto accretionary prism in Kochi prefecture

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Hydrological properties of major faults within accretionary prisms have attracted much attention recently in regard with its role on the earthquake generation processes within a shallow part of subduction zones. However internal and permeability structures of low-angle fault zones in accretionary prism have not been fully understood yet. We thus described the occurrence of large-displacement fault zones in the Cretaceous Shimanto belt in SE Kochi prefecture, and determined their permeability structures by laboratory fluid-flow tests. Among many faults in the research area, large-displacement faults were determined from temperature gap across the fault using a Vitrinite reflectance technique.

We focused on two fault zones with inferred displacement of >2 km; one is developed in a sequence boundary between basalt and pelitic breccias, and the other is in a melange zone. These fault zones are composed of cataclasite and clay-rich gouge zones. As total thickness of the fault zones is less than a few meters, fault slip is localized into thin gouge zones with average thickness of ~3 cm. The ratio of fault thickness to displacement of the fault zone is ~10^-5, that is far low as compared with worldwide displacement-thickness scaling relationship (10^-3 to 10^-1; e.g., Shipton et al. 2006). Fluid-flow experiments at effective pressures up to 100 MPa showed that permeability of the hanging wall was relatively low (10^-18-10^-20 m^2 at effective pressures of >50 MPa), while it is higher by 1-3 orders of magnitude in the footwall and fault zones. The permeability structures imply that high pore fluid pressure could be sustained within the fault zone, which may promote the thrust movement. Furthermore, the relatively thin fault zones with respect to displacement may be due to low strength of such low-angle faults that are energetically easy to propagate in a shallow part of subduction zone without forming a wide damage zone.

Keywords: fault, accretional complex, permeability

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Fluid-rock interaction in the fault gauge of the Median Tectonic Line

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Frictional heating during coseismic slip induces transient fluid-rock interaction and fluid transfer. In order to understand these physicochemical process and mechanism, we performed geochemical analyses of major- and minor-element concentrations and Sr isotope. The fault gouge samples used were collected from the Anko outcrop, Nagano prefecture, of the Middle Tectonic Line. Using the fluid-mobile trace element spectrum, which is sensitive to fluid-rock interaction at high temperatures, we estimated that the black gouge experienced frictional heating of approximately 150 degree Celsius. This temperature signal probably indicates that frictional heating have occurred in the gouge together with high amount of coseismic fluid transfer.

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Spontaneous dynamic rupture propagation with thermal pressurization: Phase transitions of pore fluid

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We investigate whether or not an increase in pressure and temperature of pore fluid due to thermal pressurization (TP) can cause phase transition of pore water, on the basis of 3-D numerical simulations for spontaneous dynamic ruptures. Mizoguchi et al. (2007) conducted friction experiments and observed a decrease in friction owing to the phase transition of water from liquid to vapor. Although effect of TP has been investigated using numerical simulations (e.g., Urata et al., 2008), the phase transition of pore water controlling TP has never been considered. In this study, we discuss possibility of the phase transition and its effects on dynamic ruptures. Our numerical algorithm is based on the finite-difference method by Kase and Kuge (2001). Pore pressure and temperature are calculated by the formulations of Bizzarri and Cocco (2006), and simply compared to a water phase diagram. Any processes of the phase transitions are not included in our simulations. We put a vertical strike-slip square fault with the length of 6 km. The fault is subjected to external normal and shear stresses. We examine cases when the external stresses are either uniform or depth-dependent. Under the uniform stresses, initial values of stresses, pore pressure, and temperature are uniform and independent of depth, whereas the values increase with depth under the depth-dependent stresses. The values of the uniform stresses correspond to those at a depth of 3 km in the depth-dependent stresses.

Judging from the temperature and pressure of pore water, liquid pore water is likely to change to supercritical water in most part of the fault under the uniform stresses, whether TP works or not. On the other hand, under the depth-dependent stresses, liquid pore water is likely to change to supercritical water in deeper portions than about 2 km. In both cases, TP promotes the transition. The phase transition from liquid to vapor is not likely to occur. According to PROPATH[1)], the transition from liquid phase to supercritical one can cause changes in viscosity, compressibility, and thermal expansion of water, which can affect TP. The changes due to the transition would have two opposite effects on TP; suppressing a rise of pore pressure from temperature increase, and decreasing hydraulic diffusivity. We include the changes due to the transition in numerical simulations of dynamic ruptures and investigate whether or not the phase transition of pore water causes TP to be more effective.

[1)] PROPATH Group, PROPATH : A Program Package for Thermophysical Properties, version 13.1, 2008.

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Numerical models of slow slip events in Shikoku based on observed distribution of tremor and plate configuration

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Recent studies revealed that slow slip events (SSEs), low-frequency tremors, and very low frequency earthquakes occur in several subduction zones. In the subduction zone of the Nankai trough from Shikoku to Kyushu, shallow very low frequency earthquakes are found along trench axis, and episodic low-frequency tremor and short-term SSEs (ETSs) are found at the deeper extent of the locked region of megathrust earthquakes. In addition, long-term SSEs repeatedly occur in the Bungo channel, and locate at the shallower extent of the ETS region. We successfully reproduced recurrence of short- and long-term SSEs in the flat plate model (Matsuzawa et al., 2010, JGR). Recently, we also reproduced recurrence and segments of short-term SSEs in the Kii-Tokai region, incorporating the actual distribution of tremor and the shape of the subducting Philippine Sea plate. In this study, we aim to reproduce the recurrence of short- and long-term SSEs in the Shikoku region, incorporating the actual distribution of tremor and the shape of the plate.

The ETSs occur at the transitional zone of friction from brittle behavior of megathrust earthquakes to ductile deformation of stably subducting plate. To model such transitional frictional property, we adopted a rate- and state-dependent friction law with cut-off velocities based on the experiment of halite (Shimamoto, 1987), as in Shibazaki and Shimamoto (2007). In the ETS and long-term SSE region, high Vp/Vs is reported (Shelly et al., 2006; Matsubara et al., 2009), which implies high pore pressure. Therefore, we assumed low effective normal stress in those regions. We modeled the shape of the subducting Philippine Sea plate based on Shiomi et al. (2008) and Baba et al. (2006). In our numerical simulation, the plate interface is modeled by ~65,000 triangular meshes within a semi-infinite elastic medium. In our model, we defined ETS regions with transitional frictional property, based on the actual distribution of tremor (Obara et al., 2010). Outside of the ETS regions below the locked region, velocity-strengthening friction is assumed. A long-term SSE region is introduced in the Bungo channel as a low effective normal stress region, as modeled in Matsuzawa et al. (2010). Assuming the above frictional parameters and the shape of the subducting plate, we calculated the temporal evolution of slip on the plate interface.

In our numerical result, recurrences of short- and long-term SSEs are reproduced. The typical scale of activities is larger in western Shikoku than that in eastern Shikoku, as observed in tremor. Our numerical simulation also reproduced the observed characteristics that the major tremor activity usually starts from the deeper part of ETS region (Obara et al., 2011). However, there exist differences between observation and our simulated results. For example, transient slow events are found between the ETS region and the locked region of megathrust earthquakes in central Shikoku, though no transient event has reported at that region. Comparison of such differences may lead us to a more realistic numerical model, and may be a key to further understanding of subduction processes.

Keywords: slow slip event, numerical simulation, Shikoku, seismic cycle

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Slow and rapid slip in sliding friction between polymer gel and plexiglass

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When a soft and sticky gel is slid against a hard substrate, spatio-temporal stick-slip motions and the power-law statistics (GR law) are often observed. In this presentation, we report our experimental studies on sliding friction between silicone gel and plexiglass with various degrees of viscoelasticity in silicone gel.

The system shows slow slip events in viscous gels and rapid events

for less viscous gels, and the size-duration relation follows M0 to T ^(1/2) for viscous gels. We will also report more detailed analysis by modeling and vislization of the contact area.

Keywords: slow slip, laboratory experiment, polymer gel, scaling law

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Formation of graphite during high-velocity friction experiment under H_2 atmosphere

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Graphite-bearing brittle faults are often found within the non-carbonaceous host rocks such as granite or marble (e.g., Nojima fault; Arai et al., 2002). Precipitation of graphite from C-O-H fluid system is widely accepted under the high P/T conditions of lower crust. However, it is considered to difficult to awake graphite precipitation under the upper crustal conditions, and formation process along the shallow fault zone is still not understood. Meanwhile, in last several years, experimental studies clearly suggested that mineralogical transformation took place in a few tens of seconds during coseismic fault slip (e.g. Han et al., Oohashi et al., 2011). Thus, we conducted high-velocity friction experiment under the C-O-H atmospheric conditions to determine if graphite forms from non-carbonaceous host rocks during rapid sliding.

Experiments were conducted using rotary-shear, low- to high-velocity friction apparatus under H_2 gas atmosphere, and Carrara marble (99% calcite and very small amount of silicate) is used for the host rock. Rock to rock experiments (bare surfaces) were conducted at normal stress of 2.0 MPa and slip rate of 1.3 m/s under the H_2 purged atmosphere. After the friction experiment, we can observe patches of blackish material on the slip surface, whereas the slip surface deformed under the air/Ar atmosphere maintains original white color. According to laser Raman spectroscopic analysis, two broad peaks correspond to the fundamental peaks of the graphite (or carbonaceous material) at a wavenumber of 1350^{-1} and 1590 cm^{-1} were detected from the patches of blackish material.

The Carrara marble used for the experiment is very pure and composed of 99% calcite, thus, it is unlikely that graphite appeared from carbonaceous material originally presents in the rock. Additionally, no visible color change was observed prior and after the HV friction experiment under the air and Ar atmospheres. Hence, the appearance of solid carbon is attributable to the atmospheric difference during the experiments. Possible explanation is formation of graphite via gas phase reaction of following chemical reaction: $2H_2+CO_2->C+2H_2O$. Salotti et al. (1971) conducted reaction experiment of calcite at the temperature of 500 degrees celcius, gas pressure of 13.8 MPa and duration of 6 hours under C-O-H atmosphere, and demonstrated formation of well-crystallized graphite on the surface of calcite. Although two of these conditions were not met in our high-velocity experiments with gas pressure of 0.1 MPa and duration of less than hundreds of seconds, temperature must have exceeded 500 degrees celcius since calcite decomposed into CaO and CO_2 (decomposition temperature of calcite: $>$720 degrees celcius). The reaction is temperature dependent so this is why the reaction accomplished at these experimental conditions. This result suggests that if rapid faulting occurs within the calcareous rocks (e.g., marble, limestone and rock rich in carbonate vein) under the reducing environment (H_2 or CH_2 atmosphere), graphite forms in response to frictional heating.

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Keywords: Nojima fault, Graphite, Carbonate minerals, High-velocity friction, Mechano-chemical reaction

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Relationship between dehydroxylation reaction of clay minerals and their inner structure and frictional property

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Transient frictional heating during earthquake slip induces dehydroxylation of phyllosilicate minerals. As this reaction is endothermic and releases H2O, it may affect dynamic fault weakening and the energetics of earthquakes. To elucidate this question, we measured thermal property, chemical kinetic parameters, and frictional property of dehydrated clay minerals (montmorillonite, illite, and kaolinite), and observed the inner structure under scanning electron microscope. We then discuss the relationship among the reaction, structure (fabrics), and frictional property, and also argue their implications on dynamic fault weakening and energetics during an earthquake.

Keywords: clay mineral, dehydroxylation