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

Takehito Suzuki[1*]

[1]EPS, Univ. Tokyo

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

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

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

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

Wataru Tanikawa[1*], Takehiro Hirose[1]

[1]JAMSTEC / Kochi Core Center

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

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

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

Kiyokazu OOHASHI[1*], Takehiro Hirose[2], Toshihiko Shimamoto[3]

[1]Graduate School of Sci, Hiroshima Univ., [2]KCC, JAMSTEC, [3]China Earthquake Administration

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.

[References]
Zulauf, G., Kleinschmidt, G., Oncken, G., 1990, Geological Society, London, Special Publications 54, 97-103.
Manatschal, G., 1999, Journal of Structural Geology 21, 777-793.
Craw, D., 2002, Chemical Geology, 191, 257-275
Oohashi, K., Hirose, T., Shimamoto, T., 2011, Journal of Structural Geology, doi:10.1016/j.jsg.2011.01.007
Tembe, S., Lockner, D. A., Wong, T.-F., 2010, Journal of geophysical Research 115, B03416, doi:10.1029/2009JB006383.
Moore, D.E., Lockner, D.A., 2011, Journal of geophysical Research 116, B01403, doi:10.1029/2010JB007881.

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

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

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

Takahiro Hatano[1*]

[1]ERI, the University of Tokyo

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

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

SSS029-05 Room:104 Time:May 23 09:30-09:45

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

Hiroyuki Noda[1*], Toshihiko Shimamoto[2]

[1]California Institute of Technology, [2]China Earthquake Administration

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

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

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

Mechanical processes of preparation for large scale events

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

[1]JAMSTEC

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.

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

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]

[1]Ritsmeikan U. (SATREPS), [2]Witwatersrand Univ., [3]ERI univ. Tokyo, [4]Tohoku Univ., [5]CSIR, [6]Council for GeoScience, [7]AIST, [8]SeeSA, SATREPS

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

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

SSS029-08 Room:104 Time:May 23 10:15-10:30

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

Gunawan Endra[1*], Takeshi Sagiya[1], Takeo Ito[1], Fumiaki Kimata[1], Takao Tabei[2], Didik Sugiyanto[3], Irwandi[3]

[1]Nagoya University, [2]Kochi University, [3]Syiah Kuala University

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

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

SSS029-09 Room:104 Time:May 23 10:45-11:00

Petrographical Characteristics of Mylonitic Pseudotachylyte in Peridotitic Fault Zones

Tadamasa Ueda[1*], Giulio DI TORO[4], Kazuhito Ozawa[3], Masaaki Obata[1]

[1]Earth&Planetary Science, Kyoto Univ., [2]JSPS research fellow, [3]Earth&Planetary Science, Univ. Tokyo, [4]Geoscience, Univ. Padova

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

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

SSS029-10 Room:104 Time:May 23 11:00-11:15

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

Aiming Lin[1*], Jeong-Hwan Shin[1], Ken-ichi Kano[2]

[1]Graduate School, Shizuoka University, [2]Faculty of Science, Shizuoka University

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

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

SSS029-11 Room:104 Time:May 23 11:15-11:30

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

Tetsuhiro Togo[1*], Toshihiko Shimamoto[2], Shengli Ma[2]

[1]Hiroshima University, [2]China Earthquake Administration

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

Takehiro Hirose[1*], Mukoyoshi Hideki[2], Wataru Tanikawa[1], Hiroyuki Noda[3]

[1]JAMSTC/Kochi, [2]Marine Works Japan, [3]Seismological Laboratory, California Ins

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/s^2. 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/s^2, but tends to increase with acceleration to ~0.1 at 13 m/s^2. 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]

[1]NIED, [2]CRIEPI

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

Hideo Aochi[1*], Blanche Poisson[1], Renaud Toussaint[2], Jean Schmittbuhl[2]

[1]BRGM/RNSC, Orleans, France, [2]IPGS-EOST, Strasbourg, France

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]

[1]Osaka University, [2]Kochi Institute for Core Sample Research

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

Miki Takahashi[1*], Shin-ichi Uehara[1], Kazuo Mizoguchi[2], Koji Masuda[1]

[1]Geological Survey of Japan, AIST, [2]CRIEPI

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.