Numerical simulation of dynamic earthquake triggering based on rate- and state-dependent friction law

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Dieterich (1994) represented time to instability as a function of slip velocity assuming single spring-block system based on rate- and state-dependent friction law (RSF), and denoted that increase of the slip velocity due to static stress change triggers earthquakes. We extend this model to the case of dynamic stress change, noting that increment of logarithm of slip velocity is proportional to difference between static stress change and state variable (frictional strength) change. When fault strength is decreased by dynamic stress change due to seismic waves, earthquake occurrence could be advanced, resulting in delayed dynamic triggering even if no static stress change occurs.
We conducted numerical simulations of earthquake triggering assuming a circular asperity obeying RSF law revised by Nagata et al. (2012). In a situation where earthquakes repeatedly occur, we apply dynamic stress disturbance of sinusoidal variation at a certain time. The dynamic stress change causes increase of slip velocity following the RSF law, and resultant slip weakens the frictional strength. This leads to dynamic earthquake triggering depending on the amplitude of the disturbance. When the stress disturbance is sufficiently large, earthquake occurs during the period of stress oscillating. This might correspond to dynamic triggered earthquakes during passage of seismic waves. When static stress is also increased, smaller dynamic disturbance can trigger earthquakes with a shorter delay. Even if static stress change is negative, a certain amplitude of dynamic stress change can trigger earthquakes.
Figure 1 shows relation between the time to instability and the increase of logarithm of the slip velocity at the center of the asperity. Red, blue, and green circles denote triggering due to static stress change, dynamic stress change, and both stress change, respectively.

Keywords: dynamic earthquake triggering

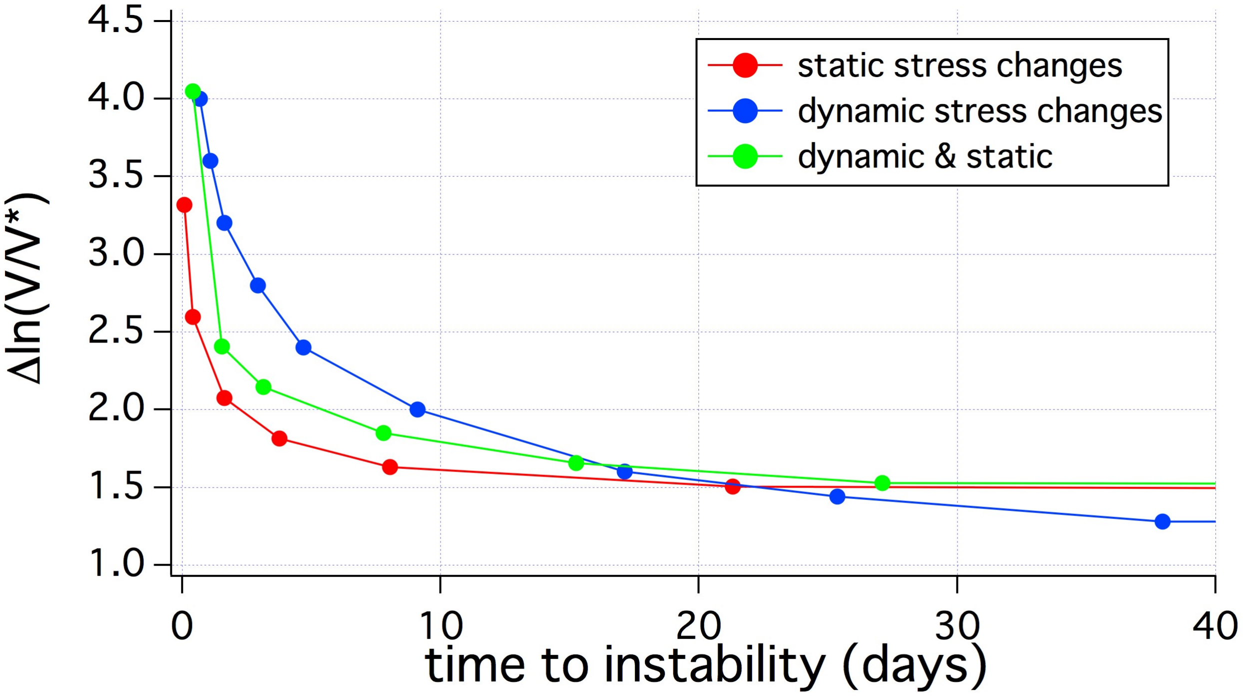
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Δln(V/V*)
0
10
20
30
40
time to instability (days)
static stress changes
dynamic stress changes
dynamic & static

Fig.1

Evaluation of the diffusivity of dissolved ions through grain boundary of quartz and its application to the prediction of frictional healing

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Laboratory and field observations have shown that the frictional strength of a fault under stationary contact increases with time (frictional healing). The origin of frictional healing has been often interpreted as due to the increase in real contact area along fault surfaces. This interpretation was supported by the direct observation of increase of contact area of glass plates with time (Dietrich and Kilgore, 1994). Slide-hold-slide (SHS) friction experiments (e.g., Frye and Marone, 2002; Katayama et al., 2015) have suggested that quartz shows relatively strong frictional healing compared to clay minerals and water plays a critical role for the frictional healing. In addition, temperature has a large effect on the frictional healing. The frictional healing is often characterized by the cutoff time (t_c) beyond which the frictional strength shows a linear recovery with the logarithm of time. SHS tests (Nakatani and Scholtz, 2004; Tenthorey and Cox, 2006) have suggested that t_c decreased from 1.2E+3 to 5.9E+1 sec as temperature increased from 200 to 927˚C. A plausible mechanism of rapid healing at high temperature is the enhanced contact area by the pressure solution under hydrothermal conditions (e.g., Tenthorey and Cox, 2006). To test whether the hypothesis can quantitatively explain such a healing behavior, the diffusivity of dissolved ions through intergranular water (intergranular diffusivity) is required for predicting the deformation rate by the pressure solution. The intergranular diffusivity of dissolved ions is, however, poorly constrained (He et al., 2013) because of the difficulty of experimental evaluation. In this study, we calculated the intergranular diffusivity of dissolved Si between quartz surfaces by molecular dynamics (MD) simulations.
In the MD simulations, water molecules and dissolved Si were sandwiched between quartz (1010) surfaces terminated with Si-OH groups. We calculated the diffusivity of dissolved Si in the direction parallel to the quartz surfaces. MD simulations were performed for the thickness of intergranular water from 0.5 nm to 2 nm and temperature from 150 to 350˚C.
As the thickness of intergranular water decreases from 2 to 0.5 nm, the diffusion coefficient of dissolved Si decreases by more than one order of magnitude. The activation energy of intergranular diffusivity ranges from 14 to 30 kJ/mol. Using the obtained intergranular diffusivity with the kinetic model of pressure solution, the increase in grain-to-grain contact area of quartz gauge (ΔA (m^2) were calculated as a function of time. Assuming that the strength recovery ΔT(MPa) is proportional to ΔA, we can calculate ΔT by the relationship of $\Delta T = (\Delta A_r/A_{r0})C$ (A_{r0}: initial real contact area (m^2), C: cohesive strength (MPa)). Calculated t_c (9.4E+3 s at ˚C and 2.0E+2 s at 927˚C) by using the ΔT and time was roughly consistent with the experimental t_c in the SHS tests. The intergranular diffusivity obtained by this study is useful for extrapolating the relationship between time and strength recovery by SHS tests to natural systems and various time scales.

Keywords: Pressure solution, Frictional healing, Rate- and state-dependent friction law

Influence of swelling on frictional property of smectite gouge

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Smectite is a major component of shallow crustal fault gouges (Vrolijk and van der Pluijm, 1999), and is thought to have large influence on their slip behaviors (e.g., Moore and Lockner 2007; Oohashi et al. 2015). In this study we performed ring-shear friction experiments on water-saturated Na-montmorillonite powders to examine the influence of smectite swelling, one of typical features of smectite, on the frictional property of smectite gouges.
Experiments were conducted using a rotary-shear friction apparatus (Institute of Geology, China Earthquake Administration; Yao et al., 2011; Hou et al., 2012) wtih a variable electrolyte concentrations up to 3*M* NaCl under normal stresses of 1.0 and 2.0 MPa. The SWy-2 powder of 2.5 g and 0.75 g of waters with different salinities were placed and dropped between two solid-cylindrical specimens of Indian gabbro to make ~1 mm thick gouge layer, within a Teflon sleeve holding the gouge. Teflon friction was corrected using an intercept method (Mizoguchi et al. 2007).
The experiments demonstrate that the frictional coefficient shows a peak value at the onset of sliding (0.15~0.5), followed by a gradual decrease to less than 0.1 in all runs. The steady state frictional coefficient is dependent on salinity of pore water, and it is as low as ~0.01 when sheared with distilled water, whereas it increases to ~0.05 with 3*M* NaCl solution. According to the Gouy-Chapman (GC) theory (i.e., interparticle forces arising from the overlap of diffuse electric double layers between the charged plates), the higher swelling pressure is expected in lower salinity condition due to expansion of the diffuse double layers. The application of the extended GC theory proposed by Komine and Ogata (2004) predicts that in-situ swelling pressure of the present gouge sample saturated with distilled water reach as high as ~1.5 MPa, almost equivalent to the normal stress loaded during the test, while the interparticle force is rather attractive in the higher salinity conditions (1.0 and 3.0 *M*) caused by the enhancement of the van der Waals force. These results suggest that the swelling pressure can effectively reduce the effective normal stress exerting on the smectite platelets as argued by Chatterji and Morgenstern (1990), leading to the apparent reduction in the frictional coefficient at lower salinity conditions. Our experiments also indicate that frictional property of smectite-rich gouges is governed by pore fluid physico-chemical conditions in natural fault zones.

Keywords: smectite gouge, swelling, friction experiment

Evaluation of frictional melting in subduction-zone faults on the basis of geochemical analyses of fault rocks

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Pseudotachylytes (solidified frictional melts produced during seismic slip) found in exhumed accretionary complexes are considered to have formed originally at seismogenic depths, and help our understanding of the dynamics of earthquake faulting in subduction zones. The frictional melting should affect rock chemistry. Here, toward better understanding of the frictional melting using chemical means, we carried out detailed major and trace element and Sr isotope analyses for pseudotachylyte-bearing dark veins and surrounding host rocks. The samples collected from the Mugi area of the Shimanto accretionary complex, which were previously investigated by Ujiie et al. (2007 JSG), were used. About one milligram each of samples was collected from a rock chip along the microstructure by using the PC-controlled micro-drilling apparatus, and then analyzed by ICP-MS and TIMS. Host rocks showed a series of compositional trends controlled by mixing of detrital sedimentary components. Unaltered part of the pseudotachylyte vein, on the other hand, showed striking enrichment of fluid-immobile trace elements, consistent with selective melting of fine-grained, clay-rich matrix of the fault rock. Importantly, completely altered parts of the dark veins exhibit essentially the same characteristics as the unaltered part, indicating that the trace element composition of the pseudotachylyte is well preserved even after considerable alteration in the later stages. These results demonstrate that trace element and structural analyses are useful to detect preexistence of pseudotachylytes resulting from selective frictional melting of clay minerals. It has been controversial that pseudotachylytes are rarely formed or rarely preserved. Geochemical analyses on clay-rich localized slipping zones shed light on this topic.

Keywords: earthquakes, fault rocks, frictional melting, geochemistry, subduction zones

Estimation of frictional heating temperature of ancient mega-splay faults in the Cretaceous Shimanto accretionary complex, SW Japan

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Subduction zone earthquake is generated by activity of plate boundary megathrust and out-of- sequence thrust (OOST) which branch from the deep portion of the megathrust. It is very important to understand the mechanism of subduction-zone earthquake because most of earthquakes larger than M8 in the world are occurred around subduction zones. Although direct observation of fault rocks in seisomogenic zone is necessary to understand earthquake mechanism, collection of present days fault rocks of megathrust and OOST in seismogenic zone is technologically impossible. Recent study revealed that ancient seismogenic subduction faults are exposed on onland accretionary complexes such as Shimanto accretionary complexes. These faults will provide important information about the characteristics of fault rocks. Estimation of maximum temperature recorded in the fault rock provide us slip parameters during an earthquake because frictional heating temperature is directly related to shear stress and slip distance. Pseudotachylyte is discovered along an ancient OOST in the Shimanto accretionary complexes by previous study. Frictional heating temperature of pseudotachylyte is estimated to 650-1100˚C from mineralogical analysis. On the other hand, frictional heating temperature of most of “pseudotachylyte-less” OOSTs is not estimated because of lack of melted minerals. In recent years, Raman analysis of carbonaceous material (CM) in fault rock is used for estimation of frictional heating temperature of faults. The objective of this study is to estimate the frictional heating temperature of pseudotachylyte-less OOSTs in the Shimanto accretionary complex based on the Raman analysis of CM in the fault rocks. This study area is located on the southern coastal line of the Otsuzaki Peninsula, Kochi Prefecture, Japan. In this area, the Late Cretaceous Shimotsui Formation, Kure Melange and Nonokawa Formation is exposed. The Nonokawa and Shimotsui Formation consist of alteration layers of sandstone and shale. The Kure Mélange is composed of shale with blocks of sandstone, chert and basaltic rocks. More than 18 branched OOSTs are exposed along the southern coastal line of the Otsuzaki Peninsula. Strike of the OOSTs is generally NW and dip is 30~60˚ NE. Composite planner fabric of Y plane and P plane which indicates reverse fault shear sense is observed in each faults. Samples of fault rocks was collected from four faults (named F1 to F4) and polished slab and thin section of each faults is prepared for detailed observation and Raman analysis. Principal slip zone of each fault was selected for making thin section. Raman spectra analysis was conducted by Horiba Xplora Raman spectrometer installed in the Osaka University. CM in the fault zone and host rock was identified by the microscopic observation and Raman spectra of each CMs were measured. Raman parameter of intensity ratio of D and G bands (ID/IG) and area ratio of D and G bands (AD/AG) was determined for the temperature estimation. Shape of each spectrum was also carefully observed. Heating temperature was estimated by comparing the determined Raman parameter with reported values of heating experiment. Raman parameter of heating experiment reported by previous study show no significant ID/IG change below than 600˚C (in the range of 0.60 from0.57). In contrast, ID/IG values of experimentally heated CM higher than 700˚C drastically increased. Raman parameter of ID/IG and AD/AG of fault zone did not show any systematic change indicating measured faults were not experienced maximum frictional heating temperature higher than 700˚C. However, Raman spectra of host rock and fault zone of F1 fault show systematic change and these shape is similar with those of heating experimented CM of 600˚C.Thus we conclude that the F1 fault experienced a frictional temperature of 600˚C while sliding.

Keywords: Mega splay fault, Raman analysis

Detection of increased heating and estimation of coseismic shear stress from Raman spectra of carbonaceous material in pseudotachylytes

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Frictional heat generated during earthquakes provides insight into the coseismic fault strength. To detect increased heating associated with faulting at seismic slip rates, we analyzed the Raman spectra of carbonaceous material in natural and experimental pseudotachylytes derived from argillite. The results indicate that the increased carbonization in pseudotachylytes relative to the host rocks could be detected when the ambient temperature is lower than 280 ˚C. This increased carbonization can occur in ˜4–16 s and is preserved even after alteration of pseudotachylytes. The comparison between experiment and Raman data demonstrated that there is a correlation between the average shear stress and the Raman spectra in pseudotachylytes. The average coseismic shear stress estimated from the correlation was 1.8 MPa. The resulting apparent friction coefficient under hydrostatic conditions at depths of 4–6 km was ˜0.03–0.05. Raman analysis of carbonaceous material-bearing pseudotachylytes will be useful for estimation of coseismic fault strength.

Ito, K., K. Ujiie, and H. Kagi (2017), Detection of increased heating and estimation of coseismic shear stress from Raman spectra of carbonaceous material in pseudotachylytes, *Geophys. Res. Lett.*, in press.

Keywords: carbonaceous material, Raman spectra, pseudotachylyte, frictional heating, coseismic shear stress

Experimental evidence for effects of heating rate on thermal maturation process of carbonaceous materials during earthquake slip

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Quantitative estimation of frictional heat produced in the fault zone is one of the keys to understand the slip behaviors of an earthquake. Irreversible thermal maturation process of carbonaceous materials, which is very sensitive to maximum temperature, is reported to be a great indicator for frictional heat. In fact, such maturation process could be strongly affcted by not only ambient temperature but also heating rate. However, several previous studies have only conducted heating experiments with heating rate of ~1 °C s^{-1} to detect heat recorded in fault rocks, which is markedly lower compared to that of earthquake slip (several tens to several hundreds of degrees per second).
In this study, we have conducted heating experiments with two different heating rate (~1 and ~100 °C s^{-1}) on carbonaceous materials retrieved from an ancient plate-subduction fault, and carried out IR and Raman spectroscopies, and py-GC/MS analysis to examine whether heating rate could affect the maturation process of carbonaceous materials. Results showed that maturity of carbonaceous materials after heating with 100 °C s^{-1} is lower than that after heating with 1 °C s^{-1}. By performing numerical simulation based on one-dimentional thermal diffusion equation, we have re-evaluated maximum temperature of the targeted fault to possibly reach 900 °C during past earthquakes, which is much higher than that estimated in the previous study (600 °C). We concluded that maturation of carbonaceous materials is strongly affected by heating rate, and such effects must be considered when we estimate maximum temperature from carbonaceous materials.

Keywords: Frictional heat, Carbonaceous materials, Heating rate, Spectrometry

Mechanochemical effects on maturation of carbonaceous materials in faults during earthquakes

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Frictional heating is thought to occur during an earthquake and the shear stress can be estimated from the temperature recorded in the fault. A new temperature proxy for maturity of carbonaceous materials by using infrared and Raman spectroscopies was recently proposed, but intra-crystal change by shear damage may affect on the maturation. Here we focus on the mechanochemical effect in the process by performing low-velocity friction experiment and spectroscopic analyses.

We performed the friction experiments at 3.0 MPa normal stress and 1 mm/s slip rate, and 10 m slip distance by using the mixture of 90 wt.% quartz and 10 wt.% coal. To reproduce heating during earthquake slip, we heated the samples after experiments at 100-1000 °C. By comparing the spectra on these samples, we confirmed that some reactions, such as breakage of aliphatic chain, occurred at relatively low temperature on sheared samples. Thus, the mechanochemical effect should be considered for deterring the temperature recorded on the basis of the maturation.

Keywords: Fault, Carbonaceous materials, Spectroscopic analysis

Sintering on a fault during an earthquake

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Frictional heating on a fault during earthquale slip induces various phenomena such as melting, thermal decomposition, and so on. In the case of the Taiwan Chelungpu fault which slipped at the 1999 Chi-Chi earthquake, disk-shaped black material was discovered within the fault zone, and was considered as a pseudotachylite on the basis of the development of hourglass and bubble structures. However, such structures are commonly observed in ceramisc. Here we demonstrated experimentary the sintering phenomenon on the syntetic and natural samples (montmorillonite, illite, and sedimentary host rock nearby the Chelungpu fault). We observed similar structure in the sample that heated at 800 C to those in the fault material. Thus, frictional heating induces not only melting but also sintering, which might affect the frictional behavior and strength recovery of a fault.

Keywords: Sintering, Fault

Experimental measurements and numerical analyses about the temperature change of rocks with stress chang

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The temperature responses of rocks to stress changes are key to understanding temperature anomalies in geoscience phenomena such as earthquakes. We developed a new hydrostatic compression system in which the rock specimen center can achieve adiabatic conditions during the first ~10 s following rapid loading or unloading, and systematically measured the representative lithologies of several sedimentary, igneous and metamorphic rocks sampled from two seismogenic zones (the Longmenshan Fault Zone in Sichuan, and the Chelungpu Fault Zone (TCDP Hole-A) in Taiwan), and several quarries worldwide. And we built a finite element model of heat conduction to confirm the measured results of temperature response of rocks to stress change. The results show that: (1) the adiabatic pressure derivative of the temperature (β) for most crustal rocks is ~1.5 to 6.2 mK MPa^{-1}, (2) the temperature response of sedimentary rocks (~3.5 to 6.2 mK MPa^{-1}) is larger than that of igneous and metamorphic rocks (~2.5 to 3.2 mK MPa^{-1}), and (3) there is a good linear correlation between β (in mK MPa^{-1}) and the bulk modulus K (in GPa): β=(-0.068·K+5.69)±0.4, R^2=0.85. This empirical equation will be very useful for estimating the distribution of β in the crust, since K can be calculated when profiles of crustal density (ρ) and elastic wave velocities (V_p, V_s) are obtained from gravity surveys and seismic exploration.

Keywords: Adiabatic pressure derivative of temperature (β), Temperature response, Stress change, Hydrostatic compression system, Numerical simulating

Scaly fabrics and veins of the Mugi and Makimine mélanges

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Ancient subduction fault zones provide a microstructural record of the plate boundary deformation associated with underthrusting. The Mugi and Makimine mélanges of the Shimanto Belt exhibit many of the characteristics associated with exposed ancient subduction fault zones worldwide, including: (1) σ_1 that is near orthogonal to the deformation fabric (2) microstructurally pervasive veins that record hydrofracturing and act as sinks for silica, calcite, and albite (3) cyclic fracturing and sealing recorded through crack-sealing and (4) evidence for local diffusion of silica sourced from web-like arrays of slip surfaces (i.e., scaly fabrics). We present microprobe observations of scaly fabrics and veins from two ancient subduction-related shear zones that represent the full temperature range of the seismogenic zone: 1) Mugi mélange lower (~130-150°C) and upper (~170-200°C) sections and 2) Makimine mélange (peak temperatures of ~340°C). The Mugi mélange is an underplated duplex consisting of two horses separated by an out of sequence thrust fault. The upper section is bounded at the top by a pseudotachylite-bearing paleodécollement. The Makimine mélange was underplated at the downdip limit of the seismogenic zone. The scaly fabrics and veins associated with these shear zones exhibit evidence for different geochemical reactions occurring as a function of depth and temperature. Upper Mugi (170-200 °C) has evidence for the incongruent pressure solution reaction of coarse grained albite in the matrix breaking down into illite in the shear zone (i.e. scaly fabric). Makimine (up to ~340 °C) has evidence for a different set of reactions that result in rutile and iron-oxide phases concentrated in the shear zone. Microstructural analyses of ancient subduction-related faults show differences with temperature that highlight the importance of establishing the geochemical processes and activation energies that contribute to slip, fracturing, and healing of rocks that underthrust the subduction interface.

Keywords: tectonic mélange, hydrofractures, seismogenic zone, earthquakes

Earthquake magnitude and moment magnitude: Apparent fracture energy and damage zone thickness of faults

*Kiyohiko Yamamoto

Introduction: The relationships between the seismic energy E_s and the magnitude M_s and between the seismic moment M_o and the moment magnitude M_w, respectively, are usually expressed by the following equations.
Log E_s=1.5M_s+4.8 (1)
Log M_o=1.5M_w+9.1 (2)
Hereafter, we call the earthquake that almost follows these equations as the standard earthquake.
M_s is smaller than M_w for the relatively large earthquakes along the Japan Trench. In the previous conference, Yamamoto shows the possibility that this difference is elucidated in terms of the seismic efficiency η. On the other hand, (M_j-M_w)>0.2 is found for many intra-earthquakes. For example, (M_j, M_w) is (7.3, 6.9) for the 1995 Hyogo ken Nanbu Earthquake, (7.3, 6.8) for the 2000 Tottori ken Seibu Earthquake, and (7.2, 6.8 to 6.9) for the 2008 Iwate-Miyagi Nairiku Earthquake. For these earthquakes, (M_s-M_w)>0.2, provided M_j = M_s. According to the uniform DMF-model, M_w>M_s when the seismic efficiency η is 0.8 or less, M_ws for η>0.8, and (Ms-Mw)=0.2 at η=1, for the standard earthquake. This implies that the earthquakes of M_s-M_w>0.2 cannot be explained as the standard earthquake. In the present study, we will investigate the causes of (M_s-M_w)>0.2 besides η.
Apparent fracture energy: The damage zone fault (DMF)-model means that a fault has a finite thickness and consists of a damage zone (DZ) area and an asperity (AS) area. In the model, as a slip plane propagates in a DZ area, rotation of the DZ takes place. The apparent fracture energy is equivalent to the work done against the normal stress by the normal displacement to the fault plane due to the rotation. It is assumed that AS has the same rigidity μ and shear fracture strength t_f as the matrix and that DZ is completely relaxed. The uniform DMF model means the fault that has infinite length and uniform thickness. The non-uniform DMF model does the fault with a finite length and non-uniform thickness.
Results: From the uniform DMF-mode, the followings are obtained: 1) Es=(δt/2μ)M_o at η= 1. Here, δt is the stress drop amount. 2) The fraction ϕ of AS area in the fault plane is determined only by the critical strain e_f=t_f/μ and η. Thus, ϕ=(2xe_f) and δt is (2xe_f)x(t_f) at η=1. When e_f is set to 1.5×10^{-2}, (M_s-M_w) becomes approximately 0.2 at η=0.8. A larger value of t_f may be a possible explanation of (Ms-Mw)>0.2 in the case of uniform DMF-model.
Generally, a fault zone has a finite length and non-uniform thickness. The slip propagation requires the stress concentration at the tip of slip plane. It is assumed that the slip amount required for the slip propagation is equal to that of the critical weakening displacement that is necessary for the fracture of AS, and that the slip amount is constant throughout DZ. It is found that as the DZ thickness decreases to zero, the apparent fracture energy approaches twice the strain energy accumulated in AS, per unit area. This suggests that the slip propagation most likely is suppressed when the tip of the slip goes into the DMZ thinner than that around AS. This makes the fault area small compared with that of a standard earthquake for the same AS size, and this makes δt larger. This is another explanation.
Conclusion: (Ms-Mw)> 0.2 occurs in the following cases. 1) For a standard earthquake, the seismic wave efficiency is 0.8 or more. 2) The average stress drop amount is larger than that of a standard earthquake. The larger stress drop amount is caused by the reasons as follows 2-1) the shear fracture strength of AS is larger than the case of standard earthquake, 2-2) the damage zone thickness is small outside the AS area. This means a case where the fault plane is geometrically non-uniform. The reason for the (Ms-Mw)>0.2 in the inland earthquake is that the earthquakes occur on the faults of more complicated structure than the

faults at the plate boundary. In order to draw a conclusion, it is necessary to know the structure of a fault, especially around its tips.

Keywords: fracture energy, seismic efficiency, magnitude, moment magnitude, damage zone fault model , critical weakening displacement

Early recurrence of M˜6 intraplate earthquake (5.8 years) observed in northern Kanto region, Japan

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On 28 December 2016, an M˜6 normal fault earthquake occurred in the northern part of Ibaraki prefecture in Kanto region, Japan (hereafter called event B). This event was observed by the Japanese ALOS-2 satellite equipped with PALSAR-2, an L-band synthetic aperture radar (SAR). Interferometric SAR (InSAR) processing indicates clear displacement discontinuity line, directing approximately NW-SE. The amount of discontinuity is ˜30cm in the line-of-sight (LOS) direction (approximately from East with incidence angle of 36 degrees). A preliminary inversion found a dip angle of 42 degrees with fault slip confined in the upper-most 5km in the crust.

The region has experienced swarm-like normal faulting activities after the occurrence of the 11 March 2011 Mw9.0 Tohoku-oki earthquake including an Mw6.6 event composed of complex ruptures on multiple faults (e.g., Fukushima et al., 2013, BSSA). One of such events was an M˜6 event on 19 March 2011 (hereafter called event A).

We performed InSAR analysis also for the event A using the data acquired by the ALOS satellite equipped with PALSAR radar. After removing the displacements caused by the Tohoku-oki earthquake, we obtained a remarkably similar displacement pattern for the event A as compared with the event B. Specifically, the locations of displacement discontinuity lines were almost identical, and the amount of displacement discontinuity was up to ˜45cm for the event A and ˜30cm for the event B. The displacement patters were similar, both indicating southwestward normal faulting on a NW-SE striking fault, suggesting that the same fault ruptured. The slight larger displacement for event A indicates that this event was associated with slightly larger slip on the fault at least close to the ground. The InSAR data for the event A presumably includes the displacements associated with an Mj 5.7 event, which should be taken into account for further comparison.

Our result indicates that the same M˜6 fault can re-rupture in a very short time interval of 5.8 years. Two interpretations are possible as to the mechanism of the extremely early recurrence: 1) rapid loading of the fault occurred after the event A, possibly associated with the postseismic deformation due to the 2011 Tohoku-oki earthquake, and 2) stress level on the fault remained high after the event A, enabling further slip on the fault, without significant loading.

Keywords: InSAR, crustal deformation, earthquake recurrence, intraplate earthquake

Development of trans-dimensional source inversion with geodetic data

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In this study, we develop a new approach to estimate the static slip distribution from geodetic data by the trans-dimensional inversion, which estimates the dimension of model parameters as well as values of model parameters. The trans-dimensional inversion has been recently applied in the geophysical field (e.g. Agostinetti and Malinverno 2010; Bodin et al. 2012; Hawkins and Sambridge 2015; Kubo et al. 2016 JpGU) including the source inversion (e.g. Dettmer 2014). An advantage of this approach on the source inversion is that it does not require the smoothing constraint on slips as the prior information. The smoothing constraint is widely used in the source inversion to obtain stable and physically reasonable solutions; however, the use of the smoothing constraint significantly reduces the resolution of the source inversion. In the case of the biased and/or sparse station distribution, the source inversion with this constraint is likely to produce the solution largely affected by the prior information. Another advantage is that the posterior distributions of model parameters directly produced by sampling methods such as Markov chain Monte Carlo (MCMC) method are useful for the estimation of model uncertainties.
We assume the linear observation equation: the static slips on fault are linearly related to the static displacement at receivers via Green’s functions. For simplicity, the errors of the observation equation are assumed to follow a Gaussian distribution and to be independent of each other. We model the static slip distribution on fault by a variable number of Voronoi cells. Unknown parameters are the number of Voronoi cells, the locations of Voronoi cells on fault, and slip values of Voronoi cells. We impose the non-negative constraint on this inverse problem following the procedure of Fukuda and Johnson (2008) and Kubo et al. (2016 GJI). To obtain the distribution of the model parameters, we employ the reversible jump MCMC method (Green 1995), which selects the action in each sampling step from four candidates: birth of Voronoi cell, death of Voronoi cell, move of Voronoi cell, and slip change of Voronoi cell. To improve the efficiency of the probabilistic sampling and the search range of parameter spaces, we use the parallel tempering algorithm (e.g. Sambridge 2013) in the ensemble sampling. For Green’s functions, we calculate the theoretical static displacements caused by a unit slip on each subfault assuming a homogeneous elastic half-space (Okada 1992).
We apply this newly-developed approach to real GNSS data of the 2015 Gorkha, Nepal, earthquake (Galetzka et al. 2015; Kubo et al. 2016 EPS). Because the station distribution is sparse in this event, the GNSS data are expected to have a limited resolution of fault slips. We found that the conventional source inversion with the smoothing constraint produces the unsharp slip distribution where slips are widely distributed over the assumed fault. On the other hand, our new approach produces the sharp slip distribution that has large slips north of Kathmandu and no slip at the other places. The data fit of this approach is better than that of the conventional approach. This result demonstrates that the introduction of the trans-dimensional approach to the source inversion leads to the acquisition of the source model composed of only meaningful slips that are necessary to explain the data. The estimated posterior distributions in the large slip region suggest that the variation of slips is small in the area surrounded by several stations and large in the area far from stations, which is consistent with our intuitive understanding of the source process inversion.

Keywords: Source inversion, Trans-dimensional inversion, Geodetic data

Potency Backprojection

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The backprojection (BP) method has been used as a tool to image the rupture propagations of the M8–9 megathrust earthquakes since its successful application to the Mw 9.1 2004 Sumatra-Andaman earthquake. The BP method back-projects waveforms onto a point of a source area by stacking them with theoretical travel time shifts between the point and the stations. The hybrid backprojection (HBP) method, an alternative BP technique, resolves a spatiotemporal distribution of waveform-radiation sources by stacking cross-correlation functions of the observed waveforms and theoretically calculated Green's functions. As the Green's function contains information of the direct P-phase as well as the later phases (pP and sP phases), the HBP method enhances the depth-resolution of the image and mitigates the dummy-imaging of the later phases, which had been the shortcomings of the conventional BP method. Both methods are able to track high-frequency (HF) radiation sources, which are hard to be resolved with the waveform inversion method. The HF waves are radiated when rupture velocity and/or slip rate abruptly change, and contain rich information of a heterogeneous rupture evolution. Thus, an integrated analysis with the BP/HBP method and the waveform inversion provides us fruitful information to understand the rupture process of a megathrust/large earthquake.

The intensity at a point of the BP/HBP image represents how much wave radiated from the point accounts for the observed waveforms. Since the amplitude of the Green's function associated with unit slip-rate increases with depth as the rigidity increases with depth, the intensity of the BP/HBP image inherently has a depth dependence. To make a direct comparison of the BP/HBP image with a slip distribution inferred from the waveform inversion, and discuss the rupture properties of the fault, it should be required the BP/HBP image to represent the slip-rate distribution that corresponds to the potency rate density distribution.

Here we propose new formulations of the BP/HBP methods, which image the potency rate density distribution by refining the normalizing factors in the conventional formulations. For the BP method, the observed waveform, that is shifted with the relative travel time, is normalized with the maximum amplitude of P-phase of the theoretically calculated Green's function. For the HBP method, we normalize the cross-correlation function of the observed waveform and the Green's function with the squared-sum of the Green's function. The normalized waveforms and the cross-correlation functions are then stacked for all the stations to enhance the signal to noise ratio, and the back-projected image now represents the potency rate density distribution.

We tested the new formulations against synthetic waveforms and the real data of the Mw 8.3 2015 Illapel Chile earthquake. We back-projected the synthetic waveforms originated from randomly distributed synthetic source points possessing a uniform potency. The resulting image intensity at the shallow parts of the fault was increased compared to that from the conventional formulations, reproducing the potency distribution of the input model. The intensity, however, were still weak at the very shallow parts, where the relative travel time between the P-phase and the later phases are very close. We also applied the new formulations to the real data, and found that the intensity of the image at shallower than 25 km depth was also slightly increased, compared to that from the conventional formulations.

Keywords: Backprojection, Imaging of rupture evolution, Depth dependence, Seismic source process, Potency

Analysis of seismic source process during the 2016 Kumamoto earthquake by jointly using surface ruptures and teleseismic waveforms

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Waveform iversion of teleseismic body waves has been applied to earthquakes to analyze an earthquake source process. However, it is difficult to resolve fault slip near the surface because the relative travel time between the direct P-wave and the reflected waves becomes short and the waveform signal generated by a near-surface slip becomes small with increasing of the slip duration. On the other hand, we can measure relative displacement along surface ruptures with high accuracy after an occurance of the earthquake. By jointly using the teleseismic waveforms and the surface rupture observations, it is possible to estimate a source process of an earthquake, even for the past earthquakes which we do not have enough data with recent developed techniques such as InSAR or GPS. In this study, we demonstrated the utility of the joint inversion of teleseismic data and field survey data through analysis of the 2016 Kumamoto, Japan earthquake (M_{JMA} 7.3).
We used vertical components of teleseismic P body waves observed at 27 stations of the Global Seismographic Network (GSN) and relative displacements of surface ruptures at 408 measurement points (Kumahara et al. 2016, JpGU). It is difficult to uniquely determine variance of the field survey data since measurement errors of the data depend on the appearance-clarity of each measurement object (e.g., water channels, furrows on rice fields). We determined the relative weights among the teleseismic body waves data, the field survey data, and prior information using the Akaike's Bayesian information criterion (ABIC). We assumed a planar single fault model (strike: 234°, dip: 64.0°) along the Hinagu-Futagawa fault zone based on the focal mechanism, aftershocks distribution, and the surface ruptures. To describe in detail a slip behavior around a junction of the two fault zones, we discretized the fault model into 2 km ×2 km sub-faults and deployed 49 B-spline functions expressing source time functions of each sub-fault at intervals of 0.3 s. We projected the field survey data to the uppermost sub-faults on the fault model.
Main rupture can be seen in the Hinagu fault area from rupture initiation to 8 s where a right-lateral slip is dominant. The rupture then shifts to the Futagawa fault area, and gradually propagates to the surface with a right lateral slip involving normal faulting. The rupture terminates southeast side of Mt. Aso caldera at about 15 s after rupture initiation. From the total slip distribution, we can see a maximum slip of around 3 m along the Futagawa fault area, and a right lateral motion is dominant along the entire Hinagu fault area, while a right lateral slip with a normal faulting prevails along the entire Futagawa fault area.
Comparing the result with one estimated by using only the teleseismic body waves, we can see clear differences in spatiotemporal distributions of slip-rate near the surface. In the result from only the teleseismic records, the slip at the shallower than 1 km depth occurs at 7 s after rupture initiation and continually occurs along both the Hinagu and Futagawa fault areas until 15 s. In the result of the joint inversion, however, the time of occurrence of the slip is about 10 s after initiation, which is later than that by solely using teleseismic body waves. Synthetic waveforms of both the joint analysis and the teleseismic analysis well capture the characteristics of the observed waveforms, while the total slip and the slip directions near the surface estimated by the joint analysis are more consistent with the surface ruptures, compared with those from the teleseismic analysis. The path of the rupture propagation, the rupture transition from the Hinagu fault to the Futagawa fault, and the spatial pattern and the depth of maximum slip are consistent with the results from the strong motion records based on the detail fault geometry and

the InSAR data. The result in this study suggests that we can acquire the detailed slip distribution even if we use a simple planar fault model by using the field survey data together with the teleseismic body waves.

Keywords: Joint inversion using ABIC, Field survey data, 2016 Kumamoto earthquake

3D seismic velocity structure in the lower crust beneath the San-in district

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Introduction

In the San-in district, a linear distribution of epicenters is seen along the Japan Sea coast. The linear distribution of epicenters is called the seismic belt along the Japan Sea coast. Large earthquakes also occurred in and around the seismic belt. What localizes the distribution of earthquakes in the San-in district far from the plate boundary? We thought that we could explain the reason by the model proposed by Iio et al. (2002, 2004). The model is as follows. A part of the lower crust has low viscosity. The low viscous part was called 'weak zone'. The stress and strain in the upper crust are concentrated right above the weak zone and earthquakes occur there. We estimated the seismic velocity structure in the lower crust beneath the San-in district in detail by carrying out seismic travel time tomography to verify whether the weak zone exists there.

Seismic travel time tomography

We carried out the tomography with FMTOMO (Rawlinson et al., 2006). FMTOMO implements wavefront tracking (de Kool et al., 2006), which can trace rays robustly. We set the study area shown in Figure 1. We used travel times picked by JMA for earthquakes that occurred in the study area (Figure 1), as well as with the travel times manually picked for earthquakes that occurred within the Philippine Sea Slab (PHS). Because seismic waves from these earthquakes to stations in the San-in district pass through the lower crust beneath the San-in district, we can expect that those data improve the resolution at the lower crust. Because those seismic waves also pass through the PHS, the velocity structure in and around the PHS plays an important role in this study. However, the dataset used in this study is not enough to estimate accurately the velocity structure. For this reason, we estimated in advance rough velocity structure in a wider area shown in Figure 2, and used the velocity structure as an initial velocity model.
In this study, we revealed that the lower crust beneath the seismic belt in the San-in district has low velocity anomalies. Since velocities of rocks decrease with temperature or fluid content, the lower crust beneath the San-in district might have low viscosity (weak zone). Therefore, the results of this study support the model proposed by Iio et al. (2002, 2004).

Acknowledgement: We used JMA's earthquake catalogs. We also used waveform data from permanent stations of NIED.

Keywords: tomography, San-in district, lower crust, intraplate earthquake

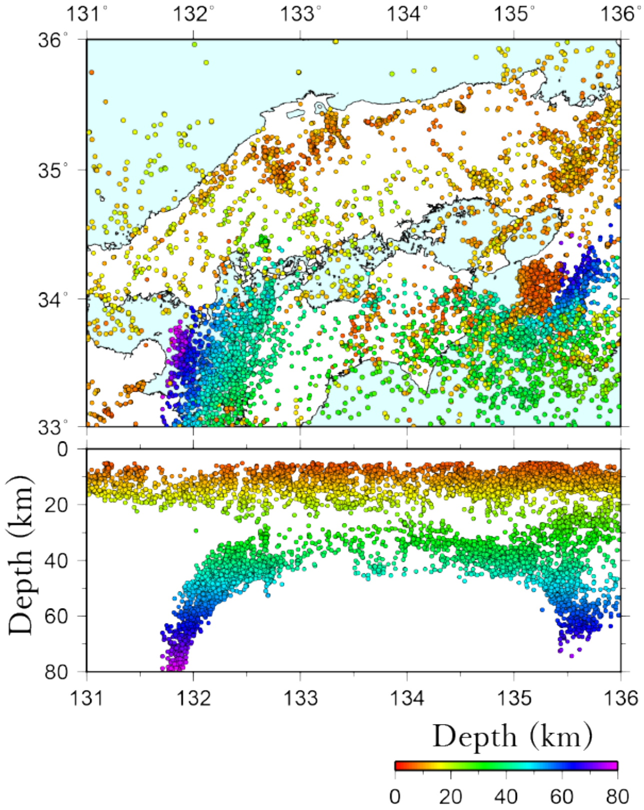

Figure 1 The distribution of earthquakes used in the tomography.

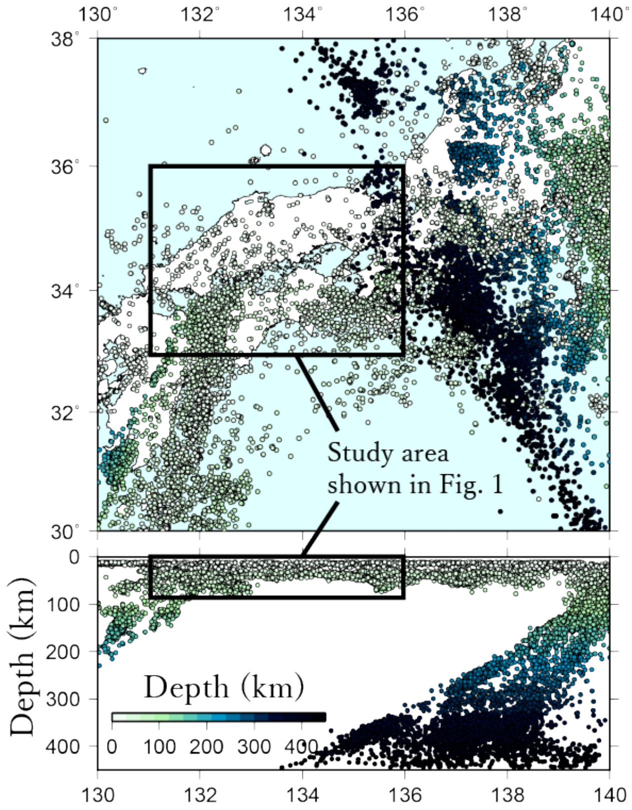

Figure 2 The distribution of earthquakes used for estimating rough velocity structure of an wide region which is used as an initial velocity model.

Swarm activity beneath Sendai-Okura Dam, NE Japan, induced by the 2011 Tohoku-Oki earthquake - Precise hypocenter distribution and fine fault structure

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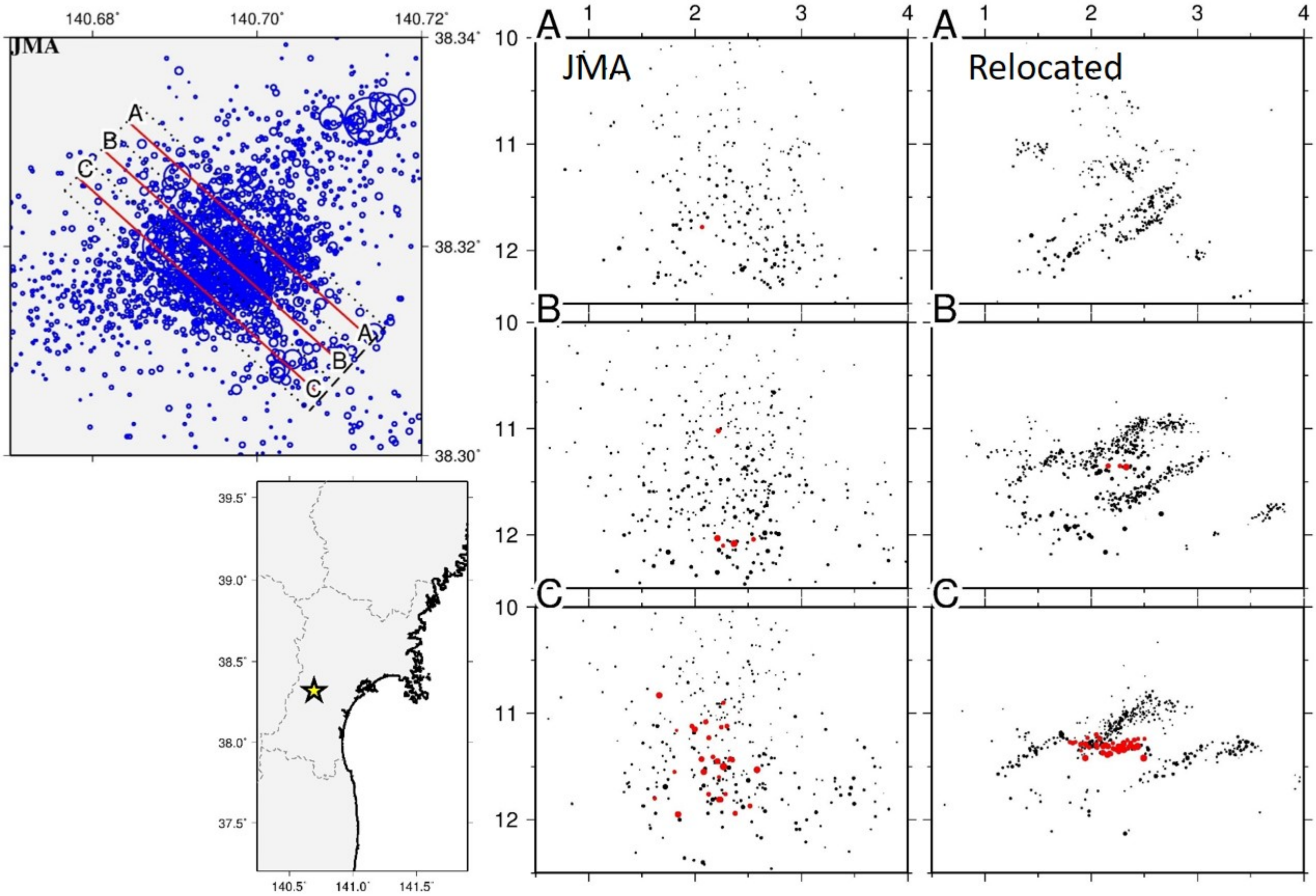
An earthquakes occurs when shear stress acting on a weak plane reaches its frictional strength. Therefore, we can roughly divide the cause of earthquake occurrence into two: increase in shear stress and reduction in frictional strength.
There occurred several earthquake swarms in NE Japan induced by the 2011 Tohoku-Oki earthquake, regardless of the reduction in ΔCFF. Since they commonly show the migration behavior of hypocenters as well as the delay of the their initiation of a few days to a few weeks after the Tohoku-Oki earthquake, several studies suggested that these swarms were caused by the reduction in frictional strength due to the increase in pore pressure by fluids rising from below [Yoshida et al., 2012; Terakawa et al., 2013; Okada et al., 2015; Yoshida et al., 2016].
In order to know detailed behavior of crustal fluids, we investigated spatio-temporal distribution of hypocenters in an earthquake swarm beneath Sendai-Ohkura Dam that was induced by the Tohoku-Oki earthquake. Approximately 10 km southeast of this swarm, an M5.0 earthquake took place in 1998. Subsequent studies showed that there exist a remarkable S-wave reflector in the middle crust [Umino et al., 2002]and a prominent low-velocity zone in the lower crust right beneath the source area [Nakajima et al., 2006].
Spatial distribution of earthquake hypocenters listed in JMA catalogue shows a slightly east-dipping cloud-like distribution with ~4km width, probably due to the errors in hypocenter locations, which makes it difficult to understand the detail of hypocenter migration. We relocated hypocenters by using the cross-correlation of waveforms to obtain a clearer image of hypocenter migration.
First, we classified earthquakes based on waveform similarity. When there is an event pair with correlation coefficient >0.92 at least at three stations within 20 km from the swarm region, we regarded them as similar earthquakes. We then searched for other similar events. Repeating the same procedure, we produced groups of similar events. As a result, we obtained 7 similar earthquake groups involving >30 events.
Second, we computed cross correlations of P- and S-waves of the event pairs with their epicenter separations less than 2 km, and obtained normalized cross correlation coefficients and differential times. By using differential times with normalized cross correlation coefficient higher than 0.9, scatter of S-P times reduced from 0.2s to less than 0.05s. By adding the differential time data thus obtained to the manually picked arrival time data, we relocated hypocenters by the Double-Difference method [Waldhauser & Ellswoth 2002]. The residuals of differential time reduced from ~120 ms to ~10 ms after 30 times iteration.
Hypocenter distribution drastically changed from the original east-dipping cloud-like scatter to the distribution on several sharp planes. Similar earthquakes in one group concentrate on a common fault plane. Most of the hypocenter alignments are dipping to the west. However, there exist some subhorizontal alignments. Their focal mechanisms are consistent with this alignments, which are unfavorably-oriented from the regional stress field. This suggests that the strength of fault planes decreased as suggested from the hypocenter migration. The relocated distribution of hypocenters shows that the hypocenters migrated along the fault planes mainly from deeper to shallower parts.

Keywords: crustal fluid, frictional strength, 2011 Tohoku-Oki earthquake, swarm



Record of slow slip instabilities in rocks: the role of silica redistribution in the behavior of subduction interfaces

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We present observations from nine regional fault zones exposed in the ancient, sediment-dominated Kodiak and Shimanto accretionary complexes. There are characteristics common to all these examples that suggest a record of slow slip instabilities that deform the underthrusting footwall at a range of depths within and around the seismogenic zone. These fault zones, in some cases 10's of m's thick, have a block-and-matrix fabric but are structurally systematic, with evidence for a compactive strain path and simple shear along a web-like array of scaly slip surfaces in fine-grained lithologies. These slip-related microstructures are coincident with silica redistribution, with silica depletion along slip surfaces and precipitation of quartz and other silicates in veins within coarser clasts and along extensional jogs in slip surfaces.

The fault rocks contain several features that suggest a record of slow slip and quasi-dynamic fault motion: 1) scaly shears represent locations of diffusive mass transfer, suggesting linear viscous flow, a rheology favored by low strain rates, 2) there is clear evidence for repeated antitaxial and syntaxial cracking and sealing, in some examples directly related to slip on shear surfaces—an observation that is consistent with slip instabilities as it requires cyclic behavior rather than continuous creep, 3) the zone of deformation is wide, indicative of distributed shearing on many slip surfaces, with large slip distances and a strain hardening process on individual features, and 4) small (10's of microns) magnitudes of slip during cracking and slip.

We propose a conceptual model for propagating, slow ruptures that move at rates dictated by shear processes within a zone of finite thickness. The fault rocks suggest that stress rises at the propagating front of a slow slip instability, leading to quasi-plastic failure in the form of scaly slip surfaces in the footwall. Development of slip surfaces represents a weakening mechanism due to loss of cohesion or alignment of phyllosilicates, but each slip surface subsequently hardens because of increases in normal stress associated with hydrofracturing or by the activation of a hardening mechanism such as pressure solution and ensuing reduction in fracture porosity. Thus, the development of a distributed scaly foliation and vein system leads to initial softening but has an inherent stabilization mechanism for putting on the breaks and keeping things slow.

Based on these observations, we construct a kinetic model to estimate the time required to seal fractures. This model accounts for the interplay between spatial gradients in chemical potential and pressure within a vein-rock system. Vein sealing is driven by diffusive redistribution of Si from solid-solid surfaces to undersaturated veins. The model predicts that healing of cracks in subduction zones occurs on secular time scales. Temperature exerts a primary control on healing rate and variations in the temperature structure of different convergent margins leads to a wide variability in sealing times. Correlation between plate age and the b-value of earthquake size distributions could reflect temperature through the kinetics of reactions and the healing rates of fractures. The evidence from ancient rocks for stress cycling, repeated fracturing, and thermally activated crack healing in underthrusting sediments could play an important role in modulating the behavior of the footwall of the subduction interface, and the spatial roughness in this behavior for different subduction zones could be an important control on seismicity.

Keywords: Slow slip, silica kinetics, earthquakes

Constraining the thickness of tremor source region on the basis of seismological and geological observations in southwest Japan

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Recent studies have shown that slow earthquakes such as tremors and slow slips along subduction zones are shear slips on the plate interface of subducting oceanic slab (e.g. Ide et al., 2007). Although the seismologically determined depth range of tremors is several km and still has large uncertainties, such tremor zone is usually treated as a flat fault plane with no thickness. On the other hands, the recent geological observation has discovered the records of past tremors and suggested that tremors occur in the deformation zone with the thickness of tens of meters (Ujiie et al., 2016, AGU Fall Meeting). Here we try to reconcile these two observations by estimating the thickness of the tremor zone based on both the seismological and geological approaches.
For the seismological approach, we focus on the thickness of the hypocenter distribution of tremors in Shikoku region, southwest Japan. As representatives of tremor sources, we use the deep low frequency earthquakes (LFEs). By applying the NCC hypocenter determination method (Ohta and Ide, 2011) based on the summed cross-correlation coefficients across the network (NCC) to Hi-net velocity seismograms, we accurately relocate 2450 LFEs in the catalog of Japan Meteorological Agency from 2004 to 2011. Relocated hypocenters of LFEs are highly concentrated in the depth direction and show gradual inclinations consistent to the geometry of the oceanic Moho of the subducting Philippine Sea Slab (Shiomi et al., 2008). We fit a polynomial surface to the distribution for each cluster by minimizing the vertical offsets in the least-squares sense and measure the thickness as their deviation. The thickness of each cluster ranges from ˜50 m to ˜1700 m.
For the geological approach, we examine the vein distribution in the Makimine tectonic mélange in the Shimanto accretionary complex in southwest Japan. The mélange is considered to be shear zone along subducting plate and preserve numerous shear veins accompanied by extension veins. We regard the shear vein concentration zone as the tremor zone and measure its thickness along the transect perpendicular to the foliation. We further examine the number and length distribution of the veins. Within the entire exposure of ˜120 m thickness, shear veins are concentrated in the zone of ˜60 m thickness. We observed numerous shear veins as well as foliation parallel extension veins. The number of veins along the transect is 1147 in total. The lengths of the shear veins are from 1 to 7 m and most are around 1 m.
The geologically determined thickness (60 m) of the tremor zone is within the range of the seismologically determined thickness (50-1700 m), which supports the idea that the observed shear veins are the faults of tremors. The lengths of veins (˜1 m) are much smaller than the fault size of tremor and other slow earthquakes (>100 m). However, a cascading failure of the faults caused by the entire zone deformation can possibly produce larger events. The coexistence of the shear veins and foliation parallel extension veins indicates high pore pressure in the tremor zone that exceeds the least stress. We further expect extension components associated with extension veins in the focal mechanism of slow earthquakes.

Keywords: tremor, low frequency earthquake, Makimine tectonic mélange, subduction zone

Microscopic derivation of rate- and state-dependent friction and its scaling properties

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In this talk, a scaling argument is given for the the length constant in the rate- and state-dependent friction law.
In general, the dynamic friction coefficient is not the single-variable function of the sliding velocity, as friction involves some aging processes such as frictional healing. Therefore, one needs additional variables to describe the behavior of friction coefficient. In the simpleset case, a single "state variable" is introduced to describe an aging process and the friction coefficient is described with the two variables: the sliding velocity and the state variable. This formulation is referred to as the rate- and state-dependent friction (RSF) law. It includes three important parameters and they determine the frictional stability/instability. Thus, it is widely used to understand earthquakes as the frictional instability. Unfortunately, to this date, the RSF is purely empirical and therefore one cannot judge its applicable limit. In addition, it is not clear at all how these important parameters are determined from (or related to) the physical entity of the fault surface.
Because the macroscopic friction force is supported by microscopic junctions of protrusions, any macroscopic friction law should be derived from constitutive laws of such microscopic junctions. With this procedure one can overview the micro-macro correspondence in friction and understand the physical meaning of phenomenological parameters in an macroscopic friction law. Here we carry out this program for the RSF law; i.e., we derive the RSF from constitutive laws of the microscopic junctions. Consequently, the microscopic expressions are given of the RSF parameters such as the relaxation length Dc. The system-size dependence of the relaxation length is discussed.

Keywords: friction law, critical slip distance

Deformation experiment on quartz aggregates with high water contents at high pressure and temperature

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Large earthquakes typically nucleate near the depth limit of seismogenic zones. In these areas, high V_p/V_s ratios are commonly observed, indicating the presence of high pore fluid pressures. Thus, it is important to understand how the water content (both water in the crystal and in the pores) and the pore structure affect the rheology of polycrystalline materials.

We conducted deformation experiments on quartz aggregates using a Griggs-type deformation apparatus. Samples were hot-pressed from silica gels, which contain ~9 weight percent water within the amorphous structure and absorbed on the surface. Hydrostatic experiments within the alpha-quartz stability field at a pressure of 1.5 GPa and 900oC indicate that hot-pressed samples are composed of quartz and no relict of amorphous material is present. The average grain size and porosity of the hot-pressed aggregates is about 6 um and 0.23, respectively. The grain shape is equigranular and no crystallographic preferred orientation (CPO) is observed.

Initial results from general shear experiments on the hot-pressed quartz aggregates at the equivalent strain rate of 1.5 x 10^{-4} 1/s, a pressure of 1.5 GPa and 900°C show very low strength (equivalent stress of 140 MPa) and nominally steady state flow at shear strains up to 3.5. The samples show weak CPO; a-axis of quartz aligned parallel to the P direction. We also found an evidence for strain localization along R_1 riedel shears, which structure is characterized by high porosity zones. In contrast, deformation experiments on cores of quartzite show dislocation creep at this pressure/temperature condition.

The stress exponent *n* is 2.8–3.4 indicating that the dislocation creep of quartz presumably controls the overall rate-behavior in the quartz shear zone. The measured stress from the new experiments is significantly lower than predicted by the wet quartz flow law (e.g., Hirth et al., 2001). The low flow stress and R1 reidel shear zones suggest that the stress enhancement process (Hirth and Kohlstedt, 1995) is activated by the high volume amount of water or perhaps the effective pressure law is still applicable and the sample deforms by a semi-brittle flow process.

Keywords: brittle-ductile transition, strain localization, earthquake

Determination of the deformation conditions of the shear zone using fault rocks: an example for the Asuke Shear Zone

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The Asuke Shear Zone (ASZ) transects the Inagawa Granodiorite in the Ryoke Belt, and it extends NE–SW for ~14 km and is several tens to hundreds of meters wide around Asuke Town, Aichi Prefecture. Cataclasites constitute entirely the ASZ, whereas pseudotachylytes and mylonites are also observed in the central segment of about 4.5 km along the ASZ (Sakamaki et al., 2006). The ASZ is considered to be deformed in cataclastic-plastic transition regime of granitic crust (Sakamaki et al., 2006). Kinematic indicators and stretching lineations in the mylonites indicate a sinistral–normal shear. In this presentation, I will summarize (1) the paleostress orientations during the formation of mylonite using slip data of the shear zone and healed miocrocracks in quartz grains in the protolith granite, and (2) those just after the formation of pseudotachylyte using microstructure of calcite infilling amygdales. I will also summarize the deformation conditions of the ASZ using microstructures of recrystallized quartz grains and those of calcite grains.
In the high strain area such as the central part of the shear zone, it is believed that the mylonitic lineation defined by the stretching lineation is parallel to the displacement direction of the shear zone (Simpson, 1986). Assuming that the Wallace-Bott hypothesis that the displacement direction is parallel to the direction of the shear stress acting on the slip surface, the combination of the mylonitic foliation and lineation of mylonite which can judge the shear sense can be used for paleostress analysis as well as fault slip data. The mylonites strike NE–SW to ENE–WSW and dip 50–70° to the N, and mylonitic lineations plunge 40-50° to the NW. As a result of the Hough-transform-based inversion method (Yamaji et al., 2006), the optimum estimated σ_1 axis trends 183° and plunges 63°, whereas the σ_3 axis trends 310° and plunges 14°. The stress ratio is 0.56. Kanai and Takagi (2016) reported the Z-maximum quartz *c*-axis LPO patterns from the mylonitized pseudotachylyte that was used for the paleostress analysis this time, and the deformation temperature was estimated of 300-400 °C. Moreover, differential stress is estimated to have been 110–130 MPa based on the recrystallized grain size.
Paleostress orientation analysis using calcite *e*-twins in the amygdales of the pseudotachylytes has been carried out (Kanai and Takagi, 2016). The optimal estimated σ_1 axis trends 228° and plunges 55°, whereas the σ_3 axis trends 320° and plunges 1°. The stress ratio is 0.78. The deformation temperature and differential stress estimated by the morphology of the *e*-twins (Burkhard, 1993) and the twinning ratio (Yamaji, 2015) give 150-200 °C and 40-80 MPa, respectively. The misfit angle of the stress tensor estimated from the mylonite and the calcite *e*-twin is 23.1°. Although deformation temperature, differential stress and deformation scale are different in recrystallized quartz in mylonite and calcite amygdales in pseudotachylyte, the principal stress axes orientation estimated from mylonite and calcite are similar. The timing of mylonitization and calcite twinning is about 70 and 50 Ma, respectively, on the basis of the deformation temperature of mylonites, cooling curve of the Inagawa Granodiorite (Yamasaki, 2013) and fission-track zircon age of pseudotachylyte (Murakami et al., 2006). The ASZ is considered to have been activated under the single paleostress filed that involves the orientation of NW-SE subhorizontal $\sigma 3$ axis and $\sigma 1$ axis plunging 60° S~SSW during 70-50 Ma.

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Keywords: Asuke Shear Zone, mylonite, paleostress analysis

