Seismic and tsunami waveform analyses for the 1938 and 2016 Off Fukushima earthquake sequence

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The 1938 Off Fukushima (Shioya-oki) earthquake sequence, which consists of five earthquakes of M_{JMA} ranging from 6.9 to 7.5, occurred in the southern part of the 2011 Tohoku earthquake source area. In this region, a normal fault earthquake occurred on November 22, 2016 (M_w 6.9) . To understand their source processes, we re-examined seismic and tsunami waveform records. Murotani et al. (2004, SSJ Fall Meeting) estimated slip distributions for event 1 on May 23 (M_w 7.6, Fault size 60 km x 70 km), event 2 on November 5 (M_w 7.9, Fault size 80 km x 60 km), and event 3 on November 5 (M_w 7.8, Fault size 90 km x 60 km) from inversion analyses of near field seismic waveforms at Sendai, Niigata, Maebashi, Mito, and Hongo (Tokyo). In this study, we compared the observed teleseismic waveforms at Christchurch (CHR), De Bilt (DBN), Pasadena (PAS), and Pulkovo (PUL) with the calculated waveforms from the above slip distributions. The result showed that the amplitudes of computed waveforms for all events were several to several tens of times larger than the observations. We also calculated the tsunami waveforms using the slip distribution for Event 2, and compared with the observations at Hachinohe, Ayukawa, Miyako, Ojima, and Onahama. The amplitudes of calculated tsunami waveforms were also larger than the observations. These indicate that the slip amount and M_w obtained from the near field seismic waveforms inversion were over-estimated. Then, we compared the normal fault event of 1938 (event 4 on November 6) with the 2016 (M_w 6.9) event. Although there were only a few tsunami records from the same stations, the waveforms are not similar. The teleseismic waveforms of event 4 is similar to those of 2016 event. The re-analyses of near field seismic data using the heterogeneous velocity model will be also presented in the presentation.
This study was supported by JSPS KAKENHI Grant Number JP16H01838.

Keywords: 1938 and 2016 Off Fukushima earthquake, Source process, seismic and tsunami waveforms

Fault Slip Distribution determined by Automated Source Process Analysis with Teleseismic Body-Wave based on Scaling Relationships Derived from Fault Slip Distributions

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1. Introduction
We have examined optimized preset parameters for automatic source process analysis with teleseismic body-wave. First, we set size of fault and subfault based on scaling relationships derived from fault slip distribution studies, and we investigated that fault plane included rupture area for many events. Then, we set sampling rate and rise time of basis function based on subfault size, and we investigated that we could avoid instability of the solution caused by setting too high-resolution temporal or spatial parameters for many events. Finally, we set other parameters by using experiential knowledge, and we investigated that we could set all parameters for automatic source process analysis based on hypocenter data and focal mechanism data.
This time, we set parameters more precisely based on event magnitude, we selected stations automatically by using signal-to-noise ratio of waveforms, and pick P-wave onset time automatically by using an auto-pick program for hypocenter determination. Thus we have become to do source process analysis automatically.
In this report, we investigated fault slip distributions of large earthquakes (M7.5) determined by automated source process analysis. And for verification, we compared fault slip distributions and aftershock distributions, and others.

2. Analysis Methods
We used the same program package as Iwakiri et al. [2014] for analyzing source process with teleseismic body-wave. This program package is modification of the program package by Kikuchi and Kanamori [2003]. We used broadband waveform data which were downloaded from IRIS DMC HP, and set sampling rate and band-pass filter band based on event magnitude. We used hypocenter data of JMA for events in and around Japan, and USGS for events in other areas. We used focal mechanism data of JMA for events in and around Japan, and W-phase moment tensor of USGS for events in other areas. Hypocenter was assumed as the center of fault plane, and subfault size was set based on event magnitude (number of subfault were fixed). Source-time function was set as triangle functions, and rise time was set based on event magnitude (number of basis function were fixed). Preset source time duration was assumed as the sum of rupture front arriving at the most distant subfault from hypocenter and the source duration of a single subfault (source duration of a single subfault was determined from average slip based on scaling relationships and experiential slip velocity). Velocity structure for Green’ s functions were set based on the IASP91 model and the CRUST2.0 model. We used the ABIC [Akaike, [1980]] for temporal and spatial smoothing constraints, and the hyperparameters were set so that ABIC value becomes minimum. Maximum rupture speed was set experientially at 0.70 times of S-wave velocity of near hypocenter. Event magnitude for preset parameters based on scaling relationships was selected from the magnitude +0.0, +0.1, +0.2, +0.3 of Mw (by JMA CMT solution) or Mww (by USGS W-phase moment tensor), and finally we selected event magnitude for preset parameters so that ABIC value become minimum.

3. Verification Methods
(1) We compared aftershock distribution with slip distribution.
(2) We compared seismic moment estimated by aftershocks with slip distribution (seismic moment release).
(3) We compared tsunami source area with slip distribution.

4. Results
Rupture area analyzed by automatic source process analysis located in and around aftershock area for many events. Large aftershock tended to occur adjacent to rupture area. Seismic moment estimated by aftershocks and seismic moment release from main shock were complementary to each other for some events.

Acknowledgement
We thank IRIS for providing the broadband waveform data and IASP91 model. We also thank USGS for providing event parameters. We also use the CRUST2.0 model.

Keywords: Automated Source Process Analysis, Scaling Relationships, Aftershock Distribution

Dynamic rupture simulations for the 2016 Tottoriken-chubu earthquake

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In this study, we performed dynamic rupture simulations for the 2016 Tottoriken-chubu earthquake (M6.6). We used a boundary integral equation method, and supposed slip-weakening law as a frictional constitutive law. We assumed a vertical rectangular fault plane whose depth of the upper edge is 0.5 km, the fault size is 19.5 km (along strike)×18 km (down dip), and left lateral faulting. We also assumed a rupture initiation point coincided with its hypocenter (Hi-net automatic processing hypocenter), and the rupture spread from this point. In this study, we attempted to obtain spatial distributions of initial stress and critical slip weakening distance in the slip-weakening law, which can fit better the slip distribution obtained from inversion analysis of the observed seismic waveforms performed by Kobayashi et al. (2016). The final slip distribution obtained from the inversion analysis has an area whose slip amount is very large just above the hypocenter, reaching 1.3 m. In addition, the large slip, reaching 1.27 m, has completed within 1 s (0 s is rupture initiation time).
Firstly, we performed a simulation, assuming uniform dynamic parameters on the fault plane with initial stress of 10 MPa, critical slip weakening distance of 0.25 m, peak stress of 20 MPa, and residual stress of 0 MPa. The simulation shows that the whole area slipped, reaching 4.4 m. We found that it was impossible to explain the inverted slip distribution using uniform dynamic rupture parameters. Therefore, we introduced heterogeneity of dynamic rupture parameters on the fault plane.
We divided the fault plane into two areas, referring to the inverted slip distribution; one is the area with a large slip amount, and the other is the surrounding one with a small slip amount. We assumed that residual stress was 0 MPa, and peak stress was 20 MPa in both areas. Here, we estimated initial stress in these two areas, by fixing the values of critical slip weakening distance. For this purpose, we assigned initial stress of 2 MPa in the surrounding area of small slip, and varied initial stress value from 5 MPa to 15 MPa in the area of large slip. We attempted to obtain an initial stress value so as to minimize the residual between the simulated and inverted final slip distributions by a try-and-error method. As a result, we obtained 10 MPa as the optimal initial stress value in the area of large slip.
Next, we attempted to estimate spatial distribution of critical slip weakening distance values. For this purpose, we assumed the value to be 0.25 m in the surrounding, and divided the area of large slip into four areas in the depth direction (the deepest one included the rupture initiation point). We varied critical slip weakening distance value from 0.25 m to 0.30 m in these four areas. We attempted to obtain critical slip weakening distance values so as to minimize the residual between the simulated and inverted slip distributions at every 1 second by a try-and-error method. As a result, we found there are a trend that the value of critical slip weakening distance become larger toward the direction of the ground surface.
Comparing the inverted slip distribution with obtained heterogeneity in initial stress and critical slip weakening distance on the fault plane, we found that an initial stress value in the area of large slip was larger than that of the surrounding, and a critical slip weakening distance value was the smallest in the area including the rupture initiation point than the other upper three areas.

Keywords: dynamic rupture simulation, Tottoriken-chubu earthquake

Simulation of Great Earthquakes along the Nankai Trough: An Attempt at Simulation of Heterogeneous Slip Deficit Rate Distribution and Slip Distributions of the Showa Tonankai / Nankai Earthquakes

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1. Introduction

Recently, Yokota et al. [2016, Nature] and Nishimura et al. [2016, AGU] estimated heterogeneous slip deficit rate distributions on the plate boundary along the Nankai trough using both land based GNSS and offshore GPS/A data. We intend to simulate not only the heterogeneous slip deficit rate distribution but also slip distributions of the Showa Tonankai / Nankai earthquakes relatively well known [Baba & Cummins, 2005, GRL] using a three-dimensional earthquake cycle model based on the rate- and state-dependent friction law with heterogeneous frictional parameters on the plate interface along the Nankai trough.

2. Parameter setting

We set frictional parameter a = 0.005 in reference to Sawai et al. [2016, GRL]. The seismogenic zones for which (a-b) is negative are within the depth ranging from trough to 30 km. We used larger effective normal stresses (35-60 MPa) at the plate interface off Shikoku and Tokai districts than the 30 MPa we used elsewhere. We set characteristic displacement L in 0.05-0.20 m on slip distributions of the Showa Tonankai / Nankai earthquakes and in 7.5 m on regions corresponding to small slip deficit rate distributions. The plate convergence rate we used was 5.5 cm/y in the western part of the study area, decreasing eastward from the Kii Peninsula to 1.0 cm/y in the eastern part of the study area [Nishimura et al., 2016, AGU].

3. Results

Preliminary results showed that Mw7.9-8.6 great earthquakes occur with recurrence interval of 90-120 years. We found various rupture patterns as follows, 1: stop off Omaezaki (Hoei eq. type), 2: whole (Ansei Tokai eq. type), and 3: stop off Lake Hamana (Showa Tonankai eq. type) in eastern area, and 4: whole including Hyuganada (Hoei eq. type), 5: off Shikoku district (Ansei Nankai eq. type), and 6: beneath coast of Shikoku (Showa Nankai eq. type) in western area. Occurrence interval between Tonankai and Nankai earthquakes were 0.7-1.6 years. We also found small slip deficit rate distributions off Kii peninsula and off eastern Shikoku district during interseismic periods. Thus, we could roughly simulate the heterogeneous slip deficit rate distribution and slip distributions of not only the Showa Tonankai / Nankai earthquakes but also other historical earthquakes. However, it is necessary to try parameter tuning further because we could not simulate historical occurrence timing.

Keywords: Nankai trough, Simulation, Slip deficit rate distribution, Showa Tonankai / Nankai Earthquakes

Afterslip distribution of the 2003 Tokachi Earthquake and the 2004 Kushiro Earthquakes using poroelastic and viscoelastic media

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1. Introduction
It is important for obtaining frictional properties of plate boundaries to estimate coseismic and afterslip distributions of large interplate earthquakes. Afterslip may trigger another earthquakes, such as the 2004 Kushiro Earthquakes after the 2003 Tokachi Earthquake, and 3/11 main shock of the 2011 Tohoku Earthquake after 3/9 pre-shock. Surface deformation after large earthquakes includes displacements due to afterslip, viscoelastic relaxation, and poroelastic rebound. To determine afterslip distribution correctly, we need to estimate effects of viscoelastic and poroelastic responses. This presentation will show afterslip distribution of the 2003 Tokachi and 2004 Kushiro Earthquakes estimated from GNSS data using viscoelastic and poroelastic media, and discuss relationship between afterslip of the 2003 event and the 2004 events.

2. Data and method
We used daily F3 coordinate values of GNSS control stations from the GSI. We calculated the poroelastic deformation from the surface deformation under two conditions, drained and undrained, in terms of the elastic properties. We consider not only viscoelastic responses of coseismic slip but also viscoelastic responses of afterslip (for detailed method, see Lubis et al. GJI, 2013).

3. Results
The afterslip with poroelastic and viscoelastic media concentrates deep and shallow parts of plate interface at the eastern adjoining area of 2003 Tokachi Earthquake. This distribution of the afterslip spreads eastern side of the coseismic slip area of the 2004 Kushiro Earthquakes, and avoids the 2004 coseismic slip area. No slip area exists at the western side of the 2004 coseismic area. This area has no slip even after the 2004 events.

Acknowledgements
We used daily F3 coordinate values of GNSS control stations from the GSI.

Keywords: Afterslip, poroelasticity, viscoelasticity, 2003 Tokachi Earthquake, 2004 Kushiro Earthquakes

Comparison between postseismic slip immediately after large earthquakes in northeastern Japan

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In general, postseismic deformation after large earthquakes consists of afterslip and asthenospheric viscoelastic relaxation. Many studies have estimated both effects from year-scale data. Alternatively, we focus on temporal evolution of postseismic deformation, which is almost due to afterslip, following large interplate earthquakes in northeastern Japan (2003 Tokachi-oki, 2005 Miyagi-oki, 2011 Tohoku-oki (March 9), and 2011 Tohoku-oki (March 11)). We obtain surface deformation data at an interval of 30 seconds about 2 days after the earthquakes, from RINEX files of GNSS data, using GSILIB. We invert slip velocities of sub faults at the plate interface from the surface deformation data. First, we find that early afterslip velocities positively correlate with magnitude of the mainshock. Second, we find that the early afterslip velocities are approximately 4 orders of magnitude lower than mean seismic slip velocities of their mainshock. Next, the early afterslips tend to decay almost linearly with time during the investigation periods.

Keywords: afterslip, GNSS, slip velocity

Reestimation of pore fluid pressure fields in the region with intensive swarm activity around Mt. Ontake volcano

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Overpressurized fluids in the Earth's crust have been increasingly implicated to play an important role to earthquake generation by decreasing fault strength (e.g., Hubert and Rubey, 1959). However, it is difficult to directly measure pore fluid pressures in the crust. The focal mechanism tomography (the FMT) is an inversion method to estimate 3-D pore fluid pressure fields by mapping focal mechanism solutions (fault strike, dip angle, and slip angle) of seismicity on the 3-D Mohr diagram for a given tectonic stress field (Terakawa et al., 2010). Validity and applicability of the method are demonstrated by analyzing seismicity induced by fluid injection experiments (where the history of fluid pressures is known) in the Basel Enhanced Geothermal System, Switzerland (Terakawa et al., 2012; Terakawa 2014). On the other hand, in applications of the method to natural earthquakes there was no way to validate results of pore fluid pressures (Terakawa et al., 2010; Terakawa et al., 2013).
In this study we reevaluated the 3-D pore fluid pressure field in the frank of Mt. Ontake in Terakawa et al. (2013). The previous study applied the FMT method to microseismic activity around Mt. Ontake, and estimated overpressureized fluid reservoirs with a peak of 100-150 MPa (with estimation errors of 20 MPa) at depths between 5 and 12 km in the southeast and east franks of the mountain, assuming a tectonic stress field with 10-20 km resolution inferred from events with M > 3 (Terakawa and Matsu'ura, 2010). In this study we analyzed the same data set as that in Terakawa et al. (2013), assuming a regional stress field with 5 km resolution inferred from smaller events with M > 1 (Terakawa et al., 2016). The pore pressure field obtained in this study is consistent with the former one in the north frank of Mt. Ontake, but discrepancy is large in the southeast and east franks. The peak pore fluid pressure in this study is by > 30 MPa smaller than the former one. In the southeast and east franks difference of the two stress pattens assumed in the two analyses is the largest, although in the two stress patterns the maximum compressive principal stress axes are commonly in the direction of the northwest-southeast. The estimation errors in pore fluid pressures are attributed to both accuracy of the stress pattern and focal mechanism solutions. The level of the pore fluid pressures in the previous study may be overestimated. We reconsider the estimation errors of the stress patterns, and estimate appropriate pore pressure triggering swarm activity.

Keywords: pore fluid pressures, earthquake, stress field

Stress condition around M6.5 earthquake fault of the 2016 Kumamoto earthquake sequence

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The 2016 Kumamoto earthquake sequence occurred at Hinagu and Futagawa fault zones under tectonic stress condition of strike slip or normal fault type. First large earthquake with magnitude 6.5 on April 14, 2016 was located at Hinagu fault zone with high seismic activity prior to the event. The stress condition around the fault zone is important to understand the generation of the earthquake. Especially, it is a key factor estimating the spatial variation of stress field at the depth of the hypocenter.
In this study, we estimated the deviatoric stress field and the stress ratio around Hinagu fault zone from focal mechanisms. We used the method estimating it from seismic moment tensor data (Matsumoto, 2016). The data were selected from focal mechanisms of earthquakes occurring from May 2016 to December 2016 at a depth range of 0-20km. We found that the stress field with strike-slip fault regime at the 0-5km depth area. This principal direction is similar to commonly observed in Kyushu Island, Japan. However, the stress field in the area deeper than 5km was in normal fault regime. The maximum principal compressional stress was close to the moderate one at the area. This area corresponds to the co-seismic large slip area estimated from the kinematic waveform inversion of strong motion data (Asano and Iwata, 2016). This suggests that the spatial change in the stress could be caused by decreasing the differential stress at the area deeper than 5km. The stress field around Hinagu fault zone was in strike-slip regime before the occurrence of the M6.5 event and changed to normal fault stress type due to the slip of the event.

Searching significant displacement zone of Orkney earthquake fault by forward and inversion analysis with strain data observed at very close distance

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The largest event recorded in a South African gold mining region, a M5.5 earthquake took place near Orkney, South Africa on 5 August 2014. This is one of the rare events as the main- and after-shocks were recorded by 46 geophones and 3 Ishii borehole strain meters at 2 - 3 km depths with epicentral distances, delta < several km, and 17 surface strong motion meters with delta < 20 km. The upper edge of the planar aftershock activity dipping almost vertically was only some hundred meters below the sites where the strainmeters were installed. As the M5.5 seismic rupture is located within a range drillable from gold mine workings at depth, ICDP approved a project to drill into the seismogenic zones. Moyer et al. (2016 SCEC) inverted surface strong motion data, suggesting significant fault slip even at the mining horizon, while there was no seismic rupture mapped or there were three strainmeters installed. So, the three strainmeters can contribute to constrain the configuration of the seismic rupture. As population of the aftershocks varies in space significantly, we expect a possibility to discuss a relationship the fault slip and the aftershocks.
These strainmeters were apart each other about 150 m only. However, their strain changes had different polarities while the other M4 strain changes with a similar hypocentral distance was the same. So, this information can constrain the location and configuration of the M5.5 fault critically.
First, we conducted a forward analysis by assuming a point source with the mechanism same as macroscopic one of the M5.5 faultingat a distance of a few km. However, no difference in polarity in strain change was seen, suggesting that the effect of a finite size of the source with an edge much nearer than the point source had to be taken into account. We are attempting to invert the slip distribution on a source with a finite size together with surface strong motion data. We will report on the results at the meeting.

Keywords: South Africa, induced earth quake, inversion

Terzaghi's theory of consolidation and precursory time of earthquakes

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In general, the greatly repetitive shearing stress during earthquakes causes ground deformation and subsidence. As a result, severely ground deformation and liquefaction were induced during the 1995 Kobe earthquake (M 7.2) and Tokachi-Oki Earthquake (M 8.0). Settlement of ground can be explained by Terzaghi’ s theory of consolidation in the field of soil mechanics. Terzaghi introduced the concept of strain to the consolidation equation in the theory. On the other hand, the diffusion-like equation for earthquake prediction can explain precursory phenomena such as crustal movement and electrical resistivity closely link to the relationship between magnitude and precursor time. However, the reason is obscure why derived from the diffusion-like equation in spite of given seismological impact. Accordingly, we noticed the void ratio from the point of view of consolidation rather than the equation by the concept of hydrostatic pressure. In the beginning, we referred on the assumption that the critical state soil mechanics. Therefore, this consolidation idea (to relate void ratio and dilatancy) can effectively explain the electrical resistivity composed in saturated ground. Conventionally, the field of earthquake and consolidation is independently, however we would like to receive the baton from both fields and previous research for the goal of earthquake prediction from this study. Here, we indicate essence on saturated ground settlement process links to above.
The part of the present study is published in Kaneko, N., and Nagahama, H. (2016), Theory of consolidation and precursory time of earthquakes, IOSR Journal of Mechanical and Civil Engineering, 13(4), Ver. V, pp. 44-46., doi: http://dx.doi.org/10.9790/1684-1304054446

Keywords: Consolidation, Dilatancy, Earthquake, Porous medium equation, Precursory time

Moment tensor analysis of acoustic emissions induced by hydraulic fracturing in laboratory experiments

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Hydraulic fracturing has been used for the development of Enhanced Geothermal reservoirs and Shale Gas/Oil reservoirs in order to stimulate reservoirs by producing artificial fractures. Microseismic observation is often employed to monitor the hydraulic fracturing. Some field observations suggested that shear events were dominated (e.g., Maxwell, 2013), although an open crack along the maximum compression axis is predicted by stress concentration around a circular hole in elastic medium. Focal mechanisms of earthquakes induced by hydraulic fracturing is important because, for example, proppants are injected so as to prevent closing cracks in Shale Gas/Oil Reservoirs and they should enter open cracks more easily. It is however difficult to constrain focal mechanisms of induced earthquakes in such fields due to insufficient network coverage.
In the present study, we conducted hydraulic fracturing laboratory experiments under uniaxial loading by using 7 granite samples, and monitored acoustic emissions (AE) by a 16-channel AE monitoring system, estimating their seismic moment tensors. Generally, moment tensor analysis, in which accurate measurements of waveform amplitudes are necessary, is difficult for AE data owing to unknown and complex sensor characteristics such as sensor sensitivity depending on sensor coupling. In this study, we estimated the influence of coupling of individual AE sensors in each experiment by using an approach similar to Kwiatek et al. (2013), and estimated moment tensors by using calibrated AE amplitudes. We classified the obtained moment tensor solutions into isotropic, double couple and CLVD dominant solutions on the basis of the decomposition method of Knopoff and Randall (1970). The shear-dominated events occupied 20%-55% whereas CLVD dominated events indicating open-mode cracks occupied 10–20%. In addition, T-axes of the CLVD dominated events (corresponds to open axis of the corresponding open cracks) were consistent with that of the open cracks predicted by stress concentration nearby a circular hole.

Keywords: Acoustic Emission, Hydraulic fracturing, Moment tensor

Response of Transmitted-wave Amplitude to a Biaxial Compressive Experiment

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Active and passive seismic monitoring approaches, such as active seismic survey and seismic interferometry, for phenomena on subducting plate interfaces, especially slow earthquakes, are one of technically feasible ways to measure strain accumulation and release in subduction zones. A laboratory experiment is one of the effective approaches to unravel the mechanism. Some previous studies, reporting on laboratory experiments using rocks, have described results on the response of amplitude and velocity reductions to failure occurrence (e.g., Lockner et al., 1977; Yoshimitsu et al., 2009). Additionally, some previous studies, which imitated slow slip events in the laboratory setting, have reported on velocity reductions before and after a slow stick-slip event (Nagata et al., 2008; Scuderi et al., 2016). Here we show a response of amplitude in transmitted waves to the occurrence of slow slip in a biaxial compressive experiment.

We used three stainless steel blocks (a center block and side blocks) and held Ca^- montmorillonite powder as simulated fault gauge between each of the center blocks and the side one. We used piezoelectric elements as transmitters, putting them on the center block, while putting three receivers on the side blocks, which are aligned along the loading direction and placed at an interval of 10 mm. We ran a series of slide-hold-slide experiments. In the initial run, the center block slid first at 1.5 μm/s for 5 mm, and the block was then held stationary for 1000 s. In the second run and the third run, the block was held stationary for ~3600s and ~32500s on second and third runs, respectively. The sliding was resumed with the same velocity and the same displacement as the first run. After the third hold, the sliding was continued with the same velocity until reaching 2mm of displacement, thus achieving 17 mm displacement in total. We recorded the transmitted waveforms for every 1mm displacement during the sliding period, and every 100 seconds during the holding period, as well as just before and after the holding period.

The preliminary results show that the transmitted-wave amplitude recovered in accordance with the logarithm of the elapsed time during the hold, and that the rate of amplitude reduction is on average about ~10% just after holding periods at all the receivers. The recovery and reduction of amplitude observed for the transmitted waves could be due to change of frictional contact on interface due to the occurrence of sliding.

Keywords: biaxial compressive test, slow slip

Temperature-dependent frictional strength of dolerite in an argon atmosphere

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Since 1990’s, high velocity friction experiments (up to several m/s) on many types of rocks have revealed that frictional strength significantly decreases with increasing slip rate at seismic slip rates (e.g., Tsutsumi and Shimamoto, 1997; Di Toro et al., 2011). Coseismic weakening mechanisms are due to temperature rise including flash heating, melt lubrication or thermal pressurization (e.g., Rice, 2006; Hirose and Shimamoto, 2005). Although the important role of temperature rise in fault motion are widely recognized, there is just a few studies which investigated the effect of temperature on frictional properties at intermediate to high slip rates (e.g., Noda et al., 2011). Yao et al. (2015) conducted the high velocity friction experiments using host blocks with different thermal conductivity values, and reported that the amount of slip-weakening increases with decreasing thermal conductivity values of host blocks. This implies that an ambient fault temperature has a large effect on the frictional strength at the coseismic slip rates. We therefore performed friction experiments at a wide range of temperatures and slip rates, and investigated the effect of temperature on the friction coefficient (μ).
Experiments were conducted on dolerite (Belfast, Northern Ireland) using a rotary shear deformation apparatus at Chiba University. Dolerite samples were sheared at a normal stress of 1 MPa, slip rates of 1 to 300 mm/s, slip displacements of 10 - 20 m at each slip rate and temperatures of 20 - 500°C in an argon atmosphere with an oxygen concentration of 0.2 %. A high-frequency induction coil surrounding the sample holders is used to heat up the sample holders and the rock samples.
At 20°C and 100°C, the dolerite showed velocity weakening at the range of slip velocities 1 - 30 mm/s with μ ranging 0.81 - 0.83 at 1 mm/s and of 0.73 at 30 mm/s. Whereas at high temperatures >300°C, friction is almost constant (μ = 0.81 - 0.85) at < 30 mm/s. At 100 mm/s, the behavior is slight velocity strengthening at 20°C and 100°C with μ = 0.75 - 0.79 and clear velocity-weakening at more than 300°C with μ = 0.67 - 0.76. At 300 mm/s, the dolerite showed strong velocity weakening at all temperatures investigated. The amount of weakening (i.e., the drop in friction, $\Delta\mu$) increases with increasing temperature ($\Delta\mu$ = 0.1 - 0.38). Thus, the frictional properties of dolerite are affected by not only slip rate but also the ambient temperature. Our results suggest that rocks at depths are energetically favored for earthquake ruptures to propagate deeper.

Keywords: friction, temperature dependence, dolerite

Dynamic water permeability change of simulated fault induced by moderate velocity friction

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Co-seismic events induce sudden changes in pore pressure, flow rate, and fluid chemistry at depth. These temporal transitions could be explained by water permeability changes of fault zones at depth during earthquakes, and change in permeability in fault zone also plays an important role in dynamic processes. Considerable change of permeability may occur during the transition from coseismic to post-seismic period, though the change is not well documented. Therefore, I designed the laboratory system to measure the change of water permeability during low to high velocity friction tests using simulated fault rocks. Similar permeability-friction tests were conducted in the past studies (Tanikawa et al., 2012, 2014). However, the previous tests were conducted by using nitrogen gas as pore fluid, and slip rate was not so high compared to dynamic fault motions.
In this study, Belfast dolerite and Aji granite were used as test specimens. For each experiment, two 20-mm-long hollow cylindrical specimens with 40 mm and 16.5 mm outer and inner diameters, respectively, were used. To measure the permeability, radial flow from the inner wall to the outer wall of the specimen was induced by applying a differential pre pressure between inner and outer walls. 0.1 to 0.8 MPa of constant pore pressure was applied from the inner wall, and water flowing out from the outer wall was released to the atmosphere. I applied constant normal stress of 2 MPa and constant rotation speed from 0.1 to 100 rpm (0.001 to 0.1 m/s) for a slip displacement of 1 to 10 m.
The result shows that permeability (flow rate) increased suddenly at the onset of sliding by a factor of more than two, and the rate of increase was nearly proportional to permeability before sliding. After sliding, permeability was decreased gradually with time, and had almost stabilized within few minutes. To compare the permeability before and after sliding, higher velocity friction (>0.03 m/s) results in the increase of permeability, and slower velocity friction induced the permeability reduction. This transition appears to be related to velocity dependent friction behavior, as velocity weakening was observed at above 0.03 m/s of slip velocity. Permeability reduction and velocity weakening behavior at slower velocity regime is probably explained by gouge compaction and gouge friction. On the other hand, high velocity friction will produce thermal pressurization, flash heating, and thermal cracking, therefore, the transition process of water permeability for high velocity friction would be more complicated than slow velocity friction.

Keywords: permeability, friction coefficient, fault

Frictional strength of agate at intermediate slip rates in air and argon atmospheres

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Frictional strength of quartz rocks is known to be extraordinary low at subseismic slip rates ranging from 1 mm/s to 10 cm/s, and this weakening has been ascribed to the hydration of comminuted material, i.e., silica gel formation (e.g., Goldsby and Tullis, 2002; Di Toro et al., 2004; Hayashi and Tsutsumi, 2010). If so, frictional strength of quartz rocks at dry conditions would not significantly decrease at those slip rates, because the hydration of comminuted material would be prevented. In order to testify this hypothesis, we conducted rotary-shear friction experiments on agate samples at a normal stress of 1.5 MPa and intermediate slip rates of 1 cm/s and 10 cm/s, i.e., at the same conditions as those of experiments done by Hayashi and Tsutsumi (2010), but in humid-air and dry-argon atmospheres, and compared frictional strengths in humid and dry conditions.
At a slip rate of 1 cm/s, frictional strength in both atmospheres did not change much with displacement so that friction coefficients after displacements of ≈180 m were as high as ≈0.7. In contrast at a slip rate of 10 cm/s, frictional strength in both atmospheres significantly decreased with displacement, and friction coefficients after displacements of ≈250 m became as low as ≈0.25, although significant fluctuations in frictional strength were observed throughout the experiments. Thus our results show that frictional strength of agate at a given slip rate does not differ between humid and dry conditions, and therefore cast doubt about weakening of quartz rocks caused by the hydration of comminuted material. Since we observed flashes along the slip surface during experiments at a slip rate of 10 cm/s, significant weakening of agate at this slip rate is likely due to the flash heating of asperities. We monitored thermal images during experiments in air at both slip rates of 1 cm/s and 10 cm/s, and will also report the relationship between frictional strength and the slip-surface temperature.

Keywords: frictional strength, agate, in air, argon atmosphere

evolution of localized shear texture on a simulated fault surface of quartz rocks during slip-weakening process at a intermediate slip velocity

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Siliceous rocks such as novaculite and quartzite display dramatic weakening of frictional strength at slip velocities of >1 mm/s [Goldsby and Tullis, 2002; Di Toro et al., 2004]. It is known that hydrated amorphous silica gouges form on the fault surface in the intermediate-high velocity frictional slip [Hayashi and Tsutsumi, 2010]. Goldsby and Tullis [2002] suggested that the silica gel layer made of very fine amorphous silica particles causes the frictional weakening. However, there are few reports focused on the state of these silica gouges during the slip-weakening process. In this study, to better understand the state of the fault surface during the slip-weakening, SEM observations of the fault surface and section and XRD analyses of the silica gouge were performed.
All the experiments in this study were conducted using a rotary-shear, intermediate-to high-velocity friction testing machine in Kyoto University. The samples used for the friction experiments were single crystal of quartz (a synthetic crystal). A pair of solid cylinders with a ring-shaped end surface (inner and outer diameter of 5 mm and 25 mm) was cored from the samples. Experiments were carried out at a constant normal stress of 1.5 MPa and a slip velocity of 105 mm/s condition.
As an experimental result, slip-weakening occurred at the initial 0.2–0.3 m of the sliding and the value of friction coefficient dropped from the peak value 0.6 to residual value 0.2. The peak friction showed log(t) healing [Dieterich, 1972]. Whole of the fault surfaces of the specimens were completely covered with white, fine-grained gouges after the experiments. SEM observations showed that 100–300 μm size of plate-like structures had been formed on the surface. The surfaces of these structures were very smooth and flat. These structures were teared from the surface into a shear direction. SEM observations of the fault section revealed that a continuous shear plane had been formed at the center of the fault zone. Along and parallel to this shear plane, approximate 1.5 μm-thick layers had piled up and formed foliation structures. Similarities in size and direction of the planes suggest that these piled layer structures should correspond to the plate-like structures found on the fault surface.
XRD analyses of the fault gouge revealed that amorphization of gouges had already been occurred during the slip-weakening.

Keywords: quartz, weakening, structure, amorphous, healing, gouge

Cathodoluminescence spectra properties of recrystallized quartz in mylonite.

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Quartz has characteristics of cathodoluminescence (CL) emission due to structural defects in the crystal and presence of impurity elements. Previous studies have been reported that emission intensity decreases due to mylonitization based on the observation of CL images (Shimamoto et al., 1991; Morales et al., 2011; Kidder et al., 2013). However, no research has been reported on examining the influence of mylonitization by separating the CL spectrum for each emission factors. In this study, CL spectra of quartz grains in mylonite were measured using SEM-CL in order to elucidate the influence of quartz on the CL spectrum by shear deformation. CL spectra of quartz grains in the mylonites from Iragawa mylonite zone (Aomori Prefecture, NE Japan) and along the Median Tectonic Line (MTL) in Mie Prefecture, SW Japan were measured and examined characteristics of each separated spectra. Spectra of quartz grains have two peaks (around 420 nm and 620 nm) or only one peak (around 620 nm). Principal component analysis (PCA) of CL spectra data was examined in order to extract potential factors which influence the CL spectra. As the result of the PCA, the first principal component (PC1) and the second principal component (PC2) represent the emission intensity and the intensity ratio between the blue side (380–450nm) and the red side (580–650nm), respectively. Since the PC2 score is influenced by the overall emission intensity, the spectra of each sample are normalized as the areas become equal. The normalized spectrum was multiplied by the eigenvector of PC2 to obtain the score (PC2') as PC2 score. After that, measured spectrum was fitted by nine Voigt functions (mixed Voigt function) and parameters of each Voigt functions were estimated by the least squares method and calculated mixing coefficients for each peak. The center wavelength of each Voigt function was set to nine (380, 420, 450, 500, 580, 620, 650, 705 and 730-800 nm) whose emission factors are summarized by Hunt (2013).
PC2’ score and the mixing coefficients indicated that the emission intensity on the red side are increasing together with decreasing grain size of recrystallized quartz across the Iragawa mylonite zone and the MTL mylonite zone. The deformation temperatures estimated by quartz LPO do not show conspicuous change across the Iragawa mylonite zone (Watanuki et al., 2017), so the clear change of PC2’ does not depend on the change in the deformation temperature. The PC2’ results can be therefore interpreted by the effects of the lattice defects (e.g. Al or Ti substitute decrease, or non-brigding oxygen hole center: NBOHC increase associated with strengthening mylonitization. Especially NBOHC is attributed to OH^- bonding defect (Götze et al, 2001). Therefore, this defect was presumably increased by mylonitization. We need to clarify exact kind of lattice defects in recrystallized quartz in strongly deformed mylonites.

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Keywords: Quartz, Cathodoluminescence, Mylonite

Raman spectra of carbonaceous materials within the black fault rocks in Kodiak accretionary complex

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Estimation of frictional heat generated in the principal slip zone (PSZ) of a fault is a key to understand fault mechanics. Recently, analyses on carbonaceous material (CM) such as vitrinite reflectance and Raman spectroscopy, which were widely used as geothermometer, have been applied to fault rocks and products of friction experiments (e.g Sakaguchi et al., 2011; Kitamura et al., 2012; Furuichi et al., 2015; Kaneki et al., 2016; Kouketsu et al., 2017). Raman spectroscopy of CM has an advantage in 2-dimentional mapping, and therefore useful for quantifying high temperature zone along PSZ generated by thermal diffusion of frictional heat. However, distribution of Raman spectra of CM within a PSZ has not considered well. In this presentation, we show the result of Raman spectra of CM within the PSZ of the Pasagshak Point Thrust in the Kodiak accretionary prism. The thrust is characterized by ultrafine-grained black fault rocks (BFR) including weakly molten pseudotachylyte formed during seismic slips (Rowe et al., 2005; Meneghini et al., 2010; Yamaguchi et al., 2014).
Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (ISTO-BRGM; Orléans) with 514 nm laser. The laser beam power at sample surface was set to ~0.5 mW. Analysis was performed to traverse internal textures of the BFR. Spectra was decomposed into five peaks, center positions around 1350 cm^{-1} (D1, D3 and D4) and graphite bands centered around 1580-1600 cm^{-1} (D2 and G). Microstructures of the BFR were observed under cathodoluminescence microscope.
Although D1-band develops within the crystalline microlayers of aphanitic BFR, which is thought to be melt-origin pseudotachylyte (Meneghini et al., 2010), development of G-band was not detected even in the crystalline microlayers. This observation suggest that Raman spectra of CM do not reach the equilibrium in the case of short-time heating, as pointed out by Nakamura et al. (2017). An alternative possibility is that Kodiak BFR has formed temperatures of <400 degrees C, without frictional melt.

Frictional Properties and Microstructures of Main Fault Gouge of Mont Terri Rock Laboratory, Switzerland

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Friction experiment was conducted on samples of main fault of Mont Terri Rock Laboratory, Switzerland and then microstructures of experimented fragments were observed by a JCM-6000. Samples were taken at the depths of 47.2m and 37.3m of borehole BSF-1, and at 36.7m, 37.1m, 41.4m and 44.6m of borehole BSF-2, which were drilled from the drift floor at the depth of 260m from the surface. Friction experiment was conducted on above 6 samples using a rotary shear low to high-velocity friction apparatus at Institute of Geology, China Earthquake Administration in Beijing at a normal stress of 3.95 to 4.0 MPa and at slip rates ranging 0.2 microns/s to 2.1mm/s. Cylindrical specimens of Ti-Al-V alloy with 40 mm in diameter were used as rotary and stationary pistons and the alloy pistons exhibit similar behaviors as host rock specimens. A Teflon sleeve was used around the piston to confine the sample during a test.

Main experimental results are summarized as follows.
1) Mud rocks in Mont Terri drill holes (BFS-1, BFS-2) have the following ranges of steady-state or nearly steady-state friction coefficient μ_{ss}: μ_{ss} *(wet)*: mostly 0.1˜0.3, μ_{ss} *(dry)*: mostly 0.5˜0.7
Dry gouges have about twice as large friction coefficients than wet gouges.
2) However, fault rock (37.3 m, BFS-1) with scary fabric has: μ_{ss} *(wet)*: 0.50˜0.77, μ_{ss} *(dry)*: 0.45˜0.78 (no difference between the two) This is probably because the clay contents of this rock is less (˜ 33 %) than those in other rocks (67˜73 %).
3) Initial peak friction coefficient μ_p is more or less on the same order of magnitudes as μ_{ss} although μ_p can increase with increasing contact time and cementation in natural environments.
4) Deformed gouges are characterized by well-developed slip zones adjacent to the rotary and stationary pistons, accompanied by slickenside surfaces with clear striations. Those slickenside surfaces are similar to those developed in the drill core samples used in our experiments.
5) Slip zones are unclear in deformed fault rock from 37.3 m (BFS-1), and probably slickenside surfaces form easily in clayey mudrocks.

Keywords: friction experiment, Mont Terri Rock Laboratory, friction coefficient, back scattered electron image

Determination of the deformation conditions of the Shajigami Shear Zone developed in Fukushima Prefecture, northeast Japan, based on deformation microstructures of mylonites

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The Shajigami Shear Zone (Yamamoto et al., 1989) extends NE–SW in the South Kitakami Belt, eastern margin of Abukuma Mountains, northeast Japan. Hisada and Takagi (1992) reported that the granodiorite mylonite indicate a sinistral shear whereas the granodiorite cataclasite and the limestone mylonite indicate a dextral shear. In this presentation, the deformation condition is estimated based on the lattice preferred orientation (LPO) and the grain size distribution of recrystallized quartz of the granodiorite mylonite and calcite of the limestone mylonite are measured using SEM–EBSD.
The granodiorite mylonite is distributed along the Shajigami Fault and mostly overprinted cataclasis. The mylonites show quartz LPO patterns suggesting activity of rhomb <*a*> and/or prism <*a*> system. The microstructures and LPO patterns suggest dislocation creep took place at about 400 °C (Takeshita, 1996; Passchier and Trouw, 2005). The mean grain size of recrystallized quartz ranges 13.8–21.1 μm.
The grain size (mean: 16.9–46.9 μm) of recrystallized calcite in the limestone mylonite is minimum along the fault. Asymmetric deformation microstructures indicate a dextral shear, but some calcite porphyroclast preserve a microstructure of former sinistral shear. The LPO is characterized by a maximum of the *c*–axes in the Z direction rotating clockwise (10–20°). The *a*–axes are distributed within a girdle in the XY plane. The twin geometry of calcite grains indicates the plastic deformation above 200 °C (Burkhard, 1993). Hisada and Takagi (1992) estimated the granodiorite cataclasites are formed up to 90 Ma.
In conclusion, the granodiorite mylonites are deformed at about 400 °C after 105 Ma (hornblende K–Ar ages; Agency for Natural Resources and Energy, 1990). After the strike–slip inversion, the limestone mylonites and granodiorite cataclasites were formed at 200–300 °C up to 90 Ma.

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Keywords: Shajigami Shear Zone, Mylonite, Lattice preferred orientation

Distribution and characteristics of fractures in the vicinity of spray fault branching off from out of sequence thrust: a case of the Sengen fault, Miura Peninsula

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Pore fluid on fault plane influences fault movement. Therefore estimation of fluid behavior of in the vicinity of a fault is important to understand deeply occurrence mechanism of earthquakes. At subduction zones, out of sequence thrusts (OST) often branch off from a decollement zone associated with making accretionary prism. OST is known to be an effective fluid flow path in accretionary prism. Fluid is expressed from deposition by lateral compression associated with making accretionary prism, and may cause high pore fluid pressure. The high pore pressure fluid may flow into cracks in the vicinity fault which are created associated with fault activity. As an evidence of the fluid migration, mineral veins such as calcite have been observed at outcrops along faults. Therefore, to research distribution and characteristics of fractures along OST is important to evaluation of fluid behavior in the vicinity OST. This study reports distribution and characteristics of fractures in the Sengen fault, which is a spray fault branching off from the Jogashima thrust, OST in south Miura peninsula. Paleo-stress conditions and pore pressure were also estimated by applying a paleo-stress analyses method of Yamaji [1] to data of calcite veins orientations in the vicinity fault.
The Sengen Fault is a reverse fault (N 84°W, 70°N) A fault core and the vicinity of the Sengen fault is composed of three distinct parts: a black gouge zone of about 1 centimeters thick as main slip surface, a breccia zone of about 20 meters thick on the hanging wall side, and a shear band zone on the footwall side. The gouge zone shows mineral alignment parallel to the fault plane, and the breccia zone exhibits weak mineral alignment in the orientation oblique to the fault plane in microscope scale. Fracture density decreases as a distance from the main slip surface, and when the distance is larger than approximately 100 m, the density is nearly constant. An orientation of a strike of fractures within approximately 100 m from the main slip surface is different from that of fractures which are more than 100 m away from the main slip surface in the hanging wall side, and the orientation of strike of the former is closer to the strike of the Sengen fault. Therefore, a width of damage zone, in which the fault-related fractures are distributed,) was estimated as approximately 100 m. Yamamoto et al. [2] indicated that calcite veins are commonly recognized on the hanging wall side of the fault. Calcite veins were recognized from 80-200 m from the main flip surface on the hanging wall side. A orientations of strikes seems weakly to concentrate around N 50~80°E. Paleo-stress analyses estimated the stress field of reverse fault (the maximum principal stress: NNW - SSE) and normal fault (the minimum principal stress: NNE - SSW) in the vicinity of the Sengen fault. Estimated pore pressure ratio for stress field of reverse fault is higher than that for stress field of normal fault

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Keywords: out-of-sequence-thrust, damage zone, Paleostress analyses, pore pressure

Structural, mineralogical, and geochemical characteristics of an ancient megasplay fault in the Hidakagawa Formation, Kii Peninsula

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To understand the slip behavior of large earthquakes along subduction zone, a great deal of effort has been made on the accretionary complex such as the Shimanto Belt. Although extensive investigation along the trench is important, no studies have ever tried to analyze fault rocks in accretionary complex of west coast of Kii Peninsula. Here we focus on mélange unit in the Hidakagawa Formation, outcropped in the Mio region, Wakayama Prefecture. We revealed geological setting and mineralogical and geochemical characteristic by performing the structural description, Raman spectroscopic analysis, mineral composition analysis, and geochemical analyses of major- and trace-element concentrations of the fault rocks and its surrounding rocks.
The burial depth in this region was estimated 3-4 km, also indicating large cumulative displacement along the fault. Granuation of mineral grains and shear foliation were well developed in the slip zone, and high temperature (>350 ˚C) by fluid-rock interaction was estimated along the slip zone. These features were well coincided to those in the megasplay fault. Furthermore, we discuss the slip behavior and the slip parameters.

Keywords: accretionary prism, trace-element, fluid-rock interaction, megasplay fault, Shimanto belt

Prescribed factor of major and trace elements composition presumed by the borehole core sample of Nobeoka thrust

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Megasplay faults branching from plate boundaries at subduction zones are thought to be important sources of earthquakes generating tsunamis. The Nobeoka Thrust is the low-angle thrust which subdivides the Shimanto Belt in Kyushu into the northern (Cretaceous and Paleogene) and the southern (Paleogene to Neogene) subbelts, and is an exhumed analogue of an ancient megasplay fault. The hanging wall and the footwall of the Nobeoka Thrust show difference in lithology and metamorphic grade, and their maximum burial temperatures estimated from vitrinite reflectance analysis are 320~330°C and 250~270°C, respectively. Assuming this temperature gap was made by fault displacement, the total displacement is estimated to be approximately 10 km (Kondo et al., 2005).
Borehole core samples penetrating through the Nobeoka Thrust were collected by the Nobeoka Thrust drilling project (NOBELL) in 2011. Since then, various studies using the borehole core have been performed. In this research, we performed major and trace element composition analysis for each depth of the borehole core collected by the NOBELL, and aim to clarify the nature of fluid-rock interaction along the fault core of the Nobeoka Thrust.
Major and trace element compositions across the principal slip zone (PSZ) of the Nobeoka Thrust were analyzed 38 samples by XRF (Rigaku ZSX) and ICP-MS (Agilent 7700x ICP-MS) respectively, installed at Kochi Core Center (Kochi University/JAMSTEC). As a result of principal component analysis (PCA) on the results of the major element compositions, a decrease in Si and Na with an increase in K is found in the PSZ. This suggests the possibility of hydrothermal alteration reaction (albite to illite) during the faulting process. Fukuchi et al. (2014) showed that the illite crystallinity nearby the PSZ of the Nobeoka Thrust could be affected by hydrothermal alterations in addition to mechanical comminution. We also carried out XRD analysis by using samples for chemical composition analysis. Although quantitative change in abundance of illite was not confirmed, disappearance of albite was detected in the PSZ.
Almost all the elements fluctuated largely just above the PSZ. This observation can be ascribed to high-temperature fluid-rock interaction occurred just above the PSZ, because some of the trace elements sensitively react with high-temperature water. However, more carefully, large abundance of elements characteristic in carbonate minerals (Ca, Mg, Fe, Mn and Sr) occurred at the upper part of the PSZ, while positive anomaly of Cs peak was observed 3 cm below the carbonate-enriched depth. Such discordance in depths of anomalies in each element suggest the existence of more complicated reactions occurred within the PSZ.
Through this study, several effects of fluid-rock interaction during faulting process have been clarified. To strengthen the scope of the findings in this study, it would be beneficial to perform a cross-section analysis of the borehole sample. This will enable us to understand the detailed changes of the element and mineral composition that occurs during faulting.

