Simultaneous measurements of elastic wave velocity and conductivity in a brine-saturated sandstone under confining pressures

*Minako Nambu[1], Tohru Watanabe[1]

1.Graduate School of Science and Engineering, University of Toyama

Pore-fluid pressure is a critical parameter that governs geodynamic processes including seismic activities. Its evaluation through geophysical observations provides us insights into these processes. The quantitative evaluation requires a thorough understanding of the influence of pore-fluid pressure on geophysical parameters, such as seismic velocity and electrical conductivity. We have studied elastic wave velocities and electrical conductivity in a brine-saturated sandstone under different confining and pore-fluid pressures.

Berea sandstone (OH, USA) was selected as a rock sample for its high porosity (~20%) and permeability (~10^{-13} m^2). It is mainly composed of subangular quartz grains, with small amounts of feldspar grains. Microstructural examinations showed that clay minerals (e.g., kaolinite) and carbonates (e.g., calcite) fill many gaps between grains. The grain size is 100-200 micrometers. Cylindrical samples (D=26 mm, L=30 mm) were saturated with 0.1 M KCl aqueous solution. Measurements have been made using a 200 MPa hydrostatic pressure vessel, in which confining and pore-fluid pressures can be separately controlled. An aqueous pore-fluid is electrically insulated from the metal work by using plastic devices. Elastic wave velocity was measured with the pulse transmission technique (PZT transducers, f=2 MHz), and electrical conductivity the two-electrode method (f=40 - 100 kHz).

Confining and pore-fluid pressures work in opposite ways. Increasing confining pressure closes pores, while increasing pore-fluid pressure opens them. For a given pore-fluid pressure, both compressional and shear velocities increase with increasing confining pressure, while electrical conductivity decreases. When confining pressure is fixed, velocity decreases with increasing pore-fluid pressure while conductivity increases. The closure and opening of pores can explain observed changes of velocity and conductivity. For a given differential pressure, velocities show no significant change with increasing confining pressure, while conductivity decreases. The decrease in conductivity might be caused by irreversible compaction of clays under confining pressures.

Keywords: Seismic Velocity, Electrical Conductivity, Fluid, Pore Fluid Pressure

Pressure dependence of elastic wave velocity and electrical conductivity in a brine-saturated granitic rock

*miho makimura[1], Tohru Watanabe[1]

1.Graduate School of Science and Engineering, University of Toyama

Geophysical mapping of fluids is critical for understanding crustal dynamics. A unified model of a fluid-bearing rock for velocity and conductivity is essential for quantitative inference on the fluid distribution. We have measured elastic wave velocities and electrical conductivity in a brine-saturated granitic rock under hydrostatic pressures and observed pore structures by X-ray CT and BIB-SEM. Based on observation of pores, we have constructed a phenomenological model to explain the observed pressure dependence of velocity and conductivity.
Measurements were made on a fine grained biotite granite saturated with 0.1 mol/L KCl solution. Both compressional and shear wave velocities increased with increasing confining pressure and electrical conductivity decreased. The velocities approached to those of solid phase at high pressure, while the conductivity was still much higher than that of the solid phase. These changes must reflect the closure of pores under pressure.
X-ray CT examinations showed that a lot of grain boundaries were open and that they formed connected conduction paths. Few intragrain cracks were observed. BIB-SEM observations on open grain boundaries showed that the aperture varied along a grain boundary. Grain boundary segments with large apertures must be connected to form connected conduction paths under high pressure.
“Bed of nails” model (Gangi, 1978) was employed to model an open grain boundary with varying aperture. The model assumed a power law distribution of aperture. Compressional wave velocity was calculated following the formulation of Carlson and Gangi (1985). “Bed of nails” model was combined with the effective medium theory (Kirkpatrick, 1973) to calculate electrical conductivity. The observed pressure dependence of compressional wave velocity was well reproduced, while that of conductivity poorly reproduced. The calculated conductivity tends to be lower than the measured value at high pressures. The model should take into account the connectivity of pores. The spatial distribution of aperture should be investigated.

Keywords: seismic velocity, electrical conductivity, fluid, resistivity

Electrical conductivity change in a brine-saturated granitic rock under uni-axial compression

*Ryo Sawaki[2], Misaki Morimoto[2], Tohru Watanabe[1]

1.Gradudate School of Science and Engineering, University of Toyama, 2.Faculty of Science, University of Toyama

Geophysical observations have shown that fluids exist pervasively within the crust. Fluids fill intergrain cracks (open grain boundaries) and intra-grain cracks at the upper and middle crust conditions. Since the opening of cracks strongly depends on the stress state, electrical conductivity should be anisotropic under a stress state. We have conducted uni-axial compression tests on brine-saturated granitic rocks and studied the change in electrical conductivity in the directions parallel and perpendicular to the compression.

The loading system is composed of a hand press (Maximum load: 20 kN), a load cell and stainless steel end-pieces. A fine grained (100-500 mm) biotite granite (Aji, Kagawa Pref., Japan) was selected as a rock sample for its small grain size and textural uniformity. A cube sample with the edge length of 25 mm was filled with 0.1 M KCl aqueous solution and loaded up to 20 MPa. Electrical impedance was continuously monitored during a compression test with two-electrode method (Ag-AgCl electrodes).

Electrical conductivity decreased with increasing axial stress in the directions parallel and perpendicular to the compression. When the axial stress was increased from 0 MPa to 5 MPa, the magnitude of decrease in conductivity was 2% and 4% in the direction parallel and perpendicular to the compression, respectively. The decrease in conductivity was much smaller than that observed in hydrostatic compression tests (e.g., Watanabe and Higuchi, 2015). The decrease in conductivity must be caused by the closure of cracks, which were perpendicular or subperpendicular to the compression.

Keywords: electrical conductivity, stress, anisotropy

Elastic wave velocities and electrical conductivity in a brine-saturated chert

*Youhei Kaiwa[2], Tohru Watanabe[1]

1.Gradudate School of Science and Engineering, University of Toyama, 2.Faculty of Science, University of Toyama

Geophysical mapping of fluids is critical for understanding crustal processes. Seismic velocity and electrical resistivity structures have been revealed to study the fluid distribution. However, the fluid distribution has been still poorly constrained. Observed velocity and resistivity should be combined to make a quantitative inference on fluid distribution. The combined interpretation requires a thorough understanding of velocity and resistivity in fluid-saturated rocks. We have studied elastic wave velocities and electrical conductivity in a brine-saturated chert to understand the connectivity of pores at low porosity.

A fine grained chert (Kyoto Pref., Japan) was selected as a rock sample for its low porosity. The rock sample was mostly composed of quartz. Circular disks (D=10 mm, L=3 mm) were cut from the rock sample, and the compressional and shear wave velocities were measured to estimate the crack density. Disc samples were filled with 0.1 M KCl aqueous solution, and the electrical conductivity was measured at ambient conditions with the two-electrode method. The relation between the crack density and electrical conductivity will be presented in our poster.

Keywords: elastic wave velocity, electrical conductivity, fluid

Sintering of fine-grained polycrystalline clinopyroxene

*Yumiko Tsubokawa[1], Masahiro Ishikawa[1]

1.Graduate School of Environment and Information Sciences, Yohokohama National University

The rheology of lower crust and upper mantle has been determined by deformation experiments of polycrystalline samples of rock-forming minerals. In these experiments, the samples were often synthesized to obtain fine-grained polycrystalline. In this study, we investigates a method for preparing the fine-grained polycrystalline clinopyroxene from nano-sized natural powders of clinopyroxene.
The starting materials for the experiment were prepared from two types of diopside single crystals (Di97Hed3:$Ca_{0.99}Na_{0.01}Mg_{0.97}Fe_{0.03}Si_2O_6$, Di99Hed1:$Ca_{0.97}Na_{0.02}Mg_{0.86}Fe_{0.13}Si_2O_6$) and a salite single crystal (Di87Hed13:$Ca_{0.97}Na_{0.02}Mg_{0.86}Fe_{0.13}Al_{0.02}Si_2O_6$) . They were crushed and milled into nano-sized powders. The milled powders were uniaxially pressed and sintered at 1230 - 1280 ℃ in atmospheres of argon or vacuum for 2-6h. After the sintering, sample surfaces were polished and thermally etched to expose grain boundaries. Grain size and porosity were determined from the microstructure of scanning electron microscope (SEM) .
After sintering at 1230℃, the relative density increased with increasing sintering time and reached the value of 98.0% and 93.5% of the theoretical density for Di97Hed3 and Di99Hed1 samples respecrively. The grain size of the each sample remains about <2μm. On the other hand, only 94.1% and 90.5 vol% of theoretical density were obtained from samples sintered at 1280℃ and the grain size increased to 5μm. Abnormally large grains and large porosities were found in Di87Hed13 sample. We found that the sintering temperature of 1230℃ is more suitable for densification and grain growth of polycrystalline clinopyroxene than 1280℃.

Keywords: sintering, clinopyroxene

Lower limit of Shimanto belt: constraints from elastic wave velocities of rocks from the Kanto Mountains and the Tanzawa Mountains

*Masahiro Ishikawa[1], Satoko Honda[1]

1.Graduate School of Environment and Information Sciences Yokohama National University

The lithological interpretation of crust beneath the Kanto area is important for understanding the crustal dynamics of the Knato area. The oceanic island arc (Izu-Bonin-Mariana arc) is developed along the eastern margin of the Philippine Sea Plate. The forearc part is subducting as the Philippine Sea slab beneath the Kanto area, whereas the Izu peninsular is colliding with the Honshu arc. In recent geophysical studies (Arai et al., 2009, 2013, 2014), seismic structure models have been constructed by refraction/wide-angle reflection seismic profiling across the Izu collision zone and the Kanto Mountains. The Kanto Mountains is located at the northern side of the Tanzawa Mountains Izu collision zone, and mainly composed of the accretionary complex represented by the Chichibu belt and the Shimanto belt.
In this study, we collected sandstone and mudstone samples from the Shimanto and Chichibu belts and greenstones from the Tanzawa group, and then measured compressional wave velocities (Vp) and shear (Vs) wave velocities. Ultrasonic measurements on these rock samples were conducted up to 1.0 GPa at 25℃ in a piston cylinder apparatus. At pressure up to 0.35GPa, Vp and Vs of the sandstone and mudstone samples from the Shimanto and Chichibu belts are 5.9-6.0km/s and 3.6-3.7km/s, respectively. The low Vp/Vs ratio (1.6-1.65) reflects the high content of quartz in the sandstone and mudstone samples. In contrast, Vp/Vs ratio of the greenstone sample from the Tanzawa group shows higher value. We then compared the rock velocities with the seismic velocity profiles (Arai et al., 2009, 2013, 2014), and inferred that the Shimanto and Chichibu belts are not distributed at depths deeper than 10km.

Keywords: Izu collision zone, Shimanto Belt, Kanto Mountains, Tanzania Mountains

Elastic wave velocities of sandstones and mudstones from the Southern Chichibu and Shimanto belts in the Kanto Mountains and greenstone from the Tanzawa group at high pressure.

*Satoko Honda[1], Masahiro Ishikawa[1]

1.Graduate School of Environment and Information Sciences, Yokohama National University

The lithological interpretation of crust and mantle beneath the Japan islands is important to understand the crustal evolution of the Honshu arc.
The Izu-Bonin arc is developed along the eastern margin of the Philippine Sea Plate. In the Kanto area, the forearc of the Izu-Bonin arc is subducting as the Philippine Sea slab under the Honshu arc, whereas the Izu peninsular have been collided with the Honshu arc (Taira et al., 1998). In recent geophysical studies (Arai et al., 2009, 2013, 2014), seismic velocity models have been constructed by refraction/wide-angle reflection seismic profiling across the Izu collision zone and the Kanto Mountains.
The Kanto Mountains is located at the northern side of the Tanzawa Mountains Izu collision zone, and mainly composed of the Paleozoic to Mesozoic accretionary complex represented by the Sambagawa metamorphic belt, the Chichibu belt and the Shimanto belt.
We collected sandstone and mudstone samples from the Shimanto and Chichibu belts and greenstones from the Tanzawa group and measured compressional wave velocities (Vp) and shear (Vs) wave velocities. Ultrasonic measurements on these rock samples were conducted up to 1.0 GPa at 25℃ in a piston cylinder apparatus. At pressure up to 0.35GPa, Vp and Vs of the sandstone and mudstone samples from the Shimanto and Chichibu belts are 5.9-6.0km/s and 3.6-3.7km/s, respectively. The low Vp/Vs ratio (1.61-1.65) reflects the high content of quartz in the sandstone and mudstone samples. In contrast, Vp/Vs ratio of the greenstone sample from the Tanzawa group shows higher value. We then compared the rock velocities with the seismic velocity profiles (Arai et al., 2009, 2013, 2014), and inferred that the Shimanto and Chichibu belts are not distributed at depths deeper than 10km.

Keywords: elastic wave velocity, Shimanto belt, Izu collision zone

Ultrasonic measurements of P-wave velocity and S-wave velocity under high pressure and high temperature conditions in Oki-Dogo xenoliths, southwestern Japan

*Hirokazu Takahashi[1], Masahiro Ishikawa[1]

1.Yokohama National Univercity

Imaging the lithology of the deep crust of Japan arc provides a critical constraint for understanding its crustal evolution. Oki-Dogo Island is one of the most important xenolith localities because it is located in the most inner zone of the South-west Japan arc. Ultramafic (e.g. pyroxenite and dunite) and mafic (e.g. granulite and gabbro) xenoliths are abundant in the Oki-Dogo alkaline basalts whereas spinel lherzolite is a minor component (e.g. Abe et al., 2003). Takahashi (1978) proposed a deep crustal-mantle lithological model beneath the Oki-Dogo Island on the basis of petrologic studies on the mafic and ultramafic xenoliths. These xenoliths thus provide an excellent opportunity to investigate the deep crustal and mantle lithology beneath the most inner zone of the South-west Japan arc. In this study, P-wave velocity (Vp), S-wave velocity (Vs) and Vp/Vs have been measured in the laboratory for pyroxenitic xenoliths from Oki-Dogo Islnad, southwest Japan. Most of pyroxenitic xenoliths comprise orthopyroxene-abundant websterite, and olivine websterite. Simultaneous measurements of Vp, Vs and Vp/Vs were carried out at pressures up to 1.0 GPa and temperatures up to 600°C. Vp of websteritic rocks vary from 7.2-7.4 km/s at 1.0 GPa which corresponds to representative depth for lowermost crust or the uppermost mantle in Japan arc. In the light of rock velocity data, we discuss seismic structure and lithological imaging of the Japan arc. Sub-Moho Vp is intermediate (7.3–7.7 km/s) in places beneath Japan arc, and this study suggests that some intermediate Vp of Sub-Moho can be explained by websteritic pyroxenites.

Keywords: Elastic wave velocity, xenoliths, high pressure experiment

Three-Dimensional Geofluid Distribution of a Seismogenic Region, Northern Miyagi

*Zenshiro Saito[1], Yasuo Ogawa[2], Masahiro Ichiki[3], Atsushi Suzuki[1], yusuke kinoshita[1], Puwis Amatyakul[4]

1.Department of Earth and Planetary Sciences, Graduate School of Science and Engineering, Tokyo Institute of Technology, 2.Volcanic Fluid Research Center Tokyo Institute of Technology, 3.Graduate School of Science, Tohoku University, 4.Department of Physics, Faculty of Science, Mahidol University

Northern Miyagi is located in one of the strain concentration zones in NE Japan (Miura et al., 2004). This area is known to have high seismicity and experienced two large earthquakes, the 1962 Northern Miyagi Earthquake (M6.5) and the 2003 Northern Miyagi Earthquake (M6.2). The 2003 earthquake was well studied and its focal mechanism and aftershock distribution support that the earthquake was a high angle reversed fault, which is a reactivation of an originally normal fault, created in the Miocene during the Japan opening. The surface extension of the fault is recognized as a flexure. Geologically, the area is mostly simply covered with thick sediment and is surrounded by granitic rocks of Kitakami Mountains to the east and to the north. A high magnetic anomaly under the Izu-Numa area may represent the existence of relatively deep sediment. The objective of this study is to image the geofluid in three dimensions and relate them to earthquake activities in the region. The previous studies were by 2D modelings. We used MT data at 52 sites in total: 24 sites are new and are arranged in an approximately 2 km grid whereas two older dataset were along profiles, one NEE-SWW profile with 18 sites (Mitsuhata et al., 2001), and one NNE-SSW profile with 12 sites (Nagao, 1997). We inverted the data using WS3dMTINV (Siripunvaraporn and Egbert, 2009) The preliminary model showed that shallow (less than 5km depth) and deep (deeper than 5km) conductors exist: Shallow conductors represent sedimentary layers. One of them runs along the edge of the Kitakami Mountains. Deep conductors may imply an anomalous body containing saline fluids originating from slab fluids. Two deep conductors are significant. One is located at south of Izu-numa with flexure, which is consistent with the previous result of Mitsuhata et al. (2001). Another deep conductor exists to the south toward the hypocentral region of the 2003 Northern Miyagi earthquake. We noticed that seismic activity is high around the deep conductors covered by high-resistivity. The may imply the episodic migration of fluid from the fluid reservoir to the upper brittle crust triggers high seismicity.

Keywords: geofluid, MT

Resistivity structure of Beppu-Haneyama fault zone

*Koki Aizawa[1], Takao Koyama[2], Azusa Shito[1], Asuma Wakabayashi[4], Masahiro Miyazaki[3], Kazunari Uchida[1], Yuko Tsukashima[1], Kaori Tsukamoto[4], Kanade Takashima[1], Kentaro Kondo[1], Hiroki Kawamoto[4], Shiori Fujita[1], Yuto Yamamoto[4], Miki Ogata[4], Makoto Uyeshima[2]

1.Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University, 2.Earthquake Research Institute, University of Tokyo, 3.Disaster Prevention Institute, kyoto university, 4.Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University

By using the broad-band magnetotelluric (MT) data acquisition system (Metronix ADU-07 system) and the recently developed telluric loggers (NT System Design ELOG1K), we measured electromagnetic fields in the eastern part of the Beppu-Haneyama fault zone, Kyushu island, Japan. At 53 telluric measurement sites, the MT impedances were calculated by using the magnetic fields recorded at other sites. Total number of Broad-band (200~0.0003 Hz) MT and telluric sites amounted up 73. Preliminary 3-D inversion shows the following features of the resistivity structure; (1) sub-vertical conductors are imaged at a shallow level beneath the faults; (2) the deep resistivity structure is approximately trending NE-SW direction that is not consistent with the EW-trending directions of the fault zone. The studied area is known not only as the faults but also as geothermal activities with famous hot-springs (Beppu and Yufuin) and three active volcanoes (Tsurumi, Garan, and Yufu). Therefore, it is likely that the geothermal fluids supplied beneath the volcanoes flows along NE trending faults, then discharges out in hot springs. However, the preliminary result shows that the deep trend of the resistivity structure is not consistent with the surface trace of faults, which may imply the faults are not extended to the deep level. It should be noticed that the hypocenters of earthquake swarms around Beppu City in 2007 (Maeda et al., 2010) are distributed NE-SW horizontally, which is consistent with the trend of deep resistivity structure. This may suggest that the fluids movement was not guided by the faults but by the deep resistivity structure, subsequently triggered the earthquake swarms in around Beppu City.

Acknowledgment
We are greatly indebted to the land owners for their permission for field campaigns. The MT data were partly obtained using the ADU07 system from Earthquake Research Institute, University of Tokyo (Kyodo-Riyo Code 2015-F2-04). The geomagnetic data used for the remote-reference processing were provided by the Kakioka Geomagnetic Observatory of JMA. Our gratitude goes to Y. Ogawa and W. Siripunvaraporn for supplying his 2-D and 3-D inversion code. We used the computer systems at the Earthquake Information Center of the Earthquake Research Institute, University of Tokyo, for 3-D inversion of the resistivity structure. This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

Keywords: Magnetotellurics, Resistivity structure, Earthquake swarm

Preliminary report on wide-band MT survey across southern part of Tohoku (on Agano-Samegawa line)

*Makoto Uyeshima[1], Masahiro Ichiki[2], Shin'ya Sakanaka[3], Makoto Tamura[4]

1.Earthquake Research Institute, The University of Tokyo, 2.Graduate School of Science, Tohoku University, 3.Department of Earth Science and Technology, Graduate school of Engineering and Resource Science, Akita University, 4.Geological Survey of Hokkaido, Hokkaido Research Organization

In order to elucidate dynamics of the intense crustal activities induced by the 2011 great Tohoku earthquake in Tohoku area, several field surveys have been promoted under the Earthquake and Volcano Hazards Observation and Research Program by the MEXT. Among these field surveys, this research tries to obtain a 3-D image of electrical resistivity distribution beneath the southern part of Tohoku arc, where intense induced earthquake activities took place in the fore-arc area of Iwaki and North Ibaraki, and intense strain rate accumulation was observed in the back-arc area along the Niigata-Kobe tectonic line. Electrical resistivity is especially sensitive to existence of conductive interstitial fluids and their connectivity. By combining the resistivity structure with structures of seismic wave velocity or attenuation, spatial distribution of the seismic foci and spatial distribution of the crustal deformation obtained from the GNSS survey, we try to elucidate subsurface physical properties and mechanism of those induced activities. Thus seismic and GNSS surveys have been also performed along the same observation line as ours.
In FY 2015, we did a wide-band MT survey along the Agano-Samegawa observation line from Nov. to Dec., 2015. We installed 15 wideband MT instruments along the 150km line and obtained 32Hz and 1024Hz 5-channel EM data (of two horizontal electric field and three magnetic field components). We also used two component horizontal magnetic field data as remote references, which were obtained at Okura, Yamagata Pref. by GERD Corp. and N-Iwoyama, Miyazaki Pref. by Dr. K. Aizawa, Kyushu University. In this presentation, we will introduce spatial characteristics and period dependence of the obtained MT and GDS responses together with inter-station horizontal magnetic field transfer functions. We will also show primary interpretation on subsurface structure beneath the area from those response functions.

Keywords: Magnetotelluric Survey, Southern Part of Tohoku District, crustal activities induced by the 2011 Great Tohoku Earthquake, electrical resistivity, crustal fluids

Exchangeable cation composition of the smectite-rich plate boundary fault at the Japan Trench

*Jun Kameda[1], Chisaki Inaoi[1], Marianne Conin[2]

1.Earth and Planetary System Science Department of Natural History Sciences, Graduate School of Science, Hokkaido University, 2.Université de Lorraine CNRS, CREGU

The source fault of the 2011 Tohoku-oki earthquake (M_w9.0) and accompanying tsunami is extremely enriched in pelagic smectite. To better understand physico-chemical processes in such a smectite-rich fault zone, we examined exchangeable cation composition of core samples recovered by the Integrated Ocean Drilling Program (IODP) Expedition 343 The Japan Trench Fast Drilling Project (JFAST).

The exchangeable cation compositions (Na^+, Ca^{2+}, K^+ and Mg^{2+}) for the bulk samples were determined by two methods. Four samples including two slip zone samples were analyzed by extracting cations in ammonium acetate solution (Schollenberger method), and the concentrations of extracted cations in the solution were measured using an atomic absorption photometer (Z-2000; Hitachi). Other samples were analyzed by extracting cations with cobaltihexamine [Orsini and Remy, 1976], following standard NF X31-130 at the INRA (Institut National de Recherche Agronomique) soil analysis laboratory in Arras, France.

Our chemical analyses revealed that the fractional concentrations of exchangeable Ca^{2+} and Mg^{2+} are higher in the slip zone than in surrounding host rocks, while Na^+ is depleted in the slip zone. K^+ shows a complicated depth profile, and this is probably due to strong interaction of K^+ with smectite interlayer such as K-fixation. Based on pore fluid chemistry data, we estimated apparent selectivity coefficient of exchange reactions in ternary system of Ca^{2+}-Mg^{2+}-Na^+. Comparison of the coefficients suggests that Na^+ to Mg^{2+} exchange reaction on smectite might have progressed markedly in the slip zone. One explanation for this feature is local progress of the reaction triggered by a recent thermogenic event, that was probably related with frictional coseimic slip during the earthquake. Considering that frictional property of smectite gouge is dependent on the exchangeable cation composition, chemical processes as observed in this study are intimately linked to physical aspect of smectite-bearing faults.

Keywords: Tohoku-oki earthquake, cation exchange reaction, pelagic smectite

Generation of pseudotachylyte and interseismic plastic deformation under granulite facies conditions at Tonagh Island in the Napier Complex, East Antarctica

*Tsuyoshi Toyoshima[1], Yasuhito Osanai[2], Masaaki Owada[3], Toshiaki Tsunogae[4], Tomokazu Hokada[5], Norio Shigematsu[6]

1.Department of Geology, Faculty of Science, Niigata University, 2.Division of Evolution of Earth Environments, Kyushu University, 3.Department of Earth Sciences, Yamaguchi University, 4.Faculty of Life and Environmental Sciences, 5.National Institute of Polar Research, 6.National Institute of Advanced Industrial Science and Technology

Seismic faulting (pseudotachylytes-producing faulting) and plastic deformation (formation of ultramylonite) alternated under lower continental crustal conditions in Tonagh Island (Toyoshima et al., 1999). We illustrate interseismic plastic deformations related to the Tonagh pseudotachylytes as examples of ancient seismogenic zones in lower crust.
There are many granulite-facies mylonite zones in Tonagh Island, the Napier Complex, East Antarctica. In some of them, cataclastic zones occur. Cataclastic zones are composed of alternation of thin ultramylonites and pseudotachylytes formed under granulite-facies conditions. Cataclastic zones are pseudotachylyte-producing fault zones. Granulite-facies ultramylonites occur also abundant outside cataclastic zones. There are evidences for multiple generations of pseudotachylytes and ultramylonites under granulite facies conditions.
There are two different types of granulite-facies ultramylonites in microstructures of recrystallized plagioclase grains: type 1 and 2. Type 1 ultramylonites have polygonal medium grains, with abundant triplejunctions, of plagioclase with smooth grain boundaries and very weakly undulose extinction. Recrystallized quart grains of type 1 ultramylonites have polygonal shapes, accompanied by fine recrystallized quartz grains. Type 2 ultramylonites include very fine grains and elongated fine grains of plagioclase with strongly undulose extinction and irregular grain boundaries with bulges. Plagioclase grains were fractured and became cataclasites before formation of type 2mylonites. Quart of type 2 ultramylonites is strongly elongated quartz porphyroclasts with bulges and fine recrystallized grains. Quartz ribbons are also abundant in type 2 ultramylonites. Type 2 ultramylonites occur only in cataclastic zones (granulite-facies pseudotachylytes-generating fault zones) and have been cut by fault veins of pseudotachylyte. Type 2 ultramylonites include porphyroclasts of plagioclase aggregates of type 1 ultramylonites. Pseudotachylytes include fragments of plagioclase aggregates of both type 1 and type 2 ultramylonites. Some of the granulite-facies pseudotachylytes were mylonitized and became type 2 ultramylonites, which have also been cut by other granulite-facies pseudotachylytes. The microstructures of quartz of type 2 ultramylonites appear occasionally to have become polygons, which observed in type 1 ultramylonites. Many of pseudotachylytes were subjected to type 2 mylonitization and show a mylonitic foliation.
We clarified generation of pseudotachylytes occurred under high-temperature, lower crustal conditions in the Tonagh Island. We also recognized the following two interseismic plastic deformations under lower crustal, high-temperature conditions.
(1) Low strain rate or low differential stress plastic deformation
(2) High strain rate or high differential stress plastic deformation
The microstructural and petrological features of lower crustal shear zones point to locally and temporally, high strain rate or high differential stress at the cataclasitic zones immediately before and after seismic faulting. These features also suggest continuous low strain rate or low differential stress plastic deformation punctuated by episodes of high strain rate or high

differential stress plastic deformation, leading of following to seismic events.
This is imaged acceleration of strain rate or stress relaxation before or after seismic events, respectively.

Keywords: pseudotachylyte, mylonite, interseismic plastic deformation, lower crust

Overview and summary of operations of DFDP-2

*Norio Shigematsu[1], Rupert Sutherland[2], John Townend [3], Virginia Toy [4], Naoki Kato[5], yusuke kometani[6], Weiren Lin[7], Osamu Nishikawa[8], Hiroshi Mori[1], DFDP-2 Science Team

1.Research Institute of Earthquake and Volcano Geology, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, 2.GNS Science New Zealand, 3.Victoria University of Wellington, 4.The University of Otago, 5.Oosaka University, 6.Yamaguchi University, 7.Japan Agency for Marine-Earth Science and Technology, 8.Akita University

The Alpine Fault is the dextral transpressive fault forming the Australia-Pacific plate boundary in the South Island of New Zealand. New Zealand's Alpine Fault is a site of international scientific importance for the study of active geological faults. The Alpine Fault provides an opportunity to study a major fault late in the cycle of stress accumulation ahead of a future earthquake, to search for precursors to large earthquakes. The hangingwall uplift rate is very rapid ranging between 9-10mm/yr, resulting in the exhumation of mylonitic rocks that was formed in the deep portion of the Alpine Fault. The hangingwall of the Alpine Fault is, therefore, a young proxy for deformation currently occurring at mid crustal depth.
The goal of the Alpine Fault, Deep Fault Drilling Project (DFDP) is to go beneath the surface, to sample and make observations of the fault rocks and physical conditions at a range of depths, and monitor these over coming decades. To date, no active fault drilling experiment has targeted the mid-crustal roots of a long-lived active fault, or addressed fault zone evolution throughout the seismogenic zone and towards the brittle-ductile transition.
DFDP-2A drilling started in August 2014 and DFDP-2B was completed in January 2015, having reached a maximum depth of 893 m (measured depth). Technical problems, most notably the loss (and recovery) of the bottom-hole assembly on two occasions, caused delays in the drilling schedule, and the failure of a casing string ultimately caused drilling to be terminated at a shallower depth than planned and before the fault had been intersected.
A very extensive data set was collected including geological, geophysical, geochemical and hydraulic measurements extending the length of the DFDP-2B borehole. Samples of rocks and fluids were collected, and a long-term observatory installed. Of particular significance are the observations that the geothermal gradient is extremely high, exceeding 140°C/km in the upper part of the borehole, and that the hangingwall is overpressured, as predicted prior to drilling.
This poster documents the technical planning and execution of DFDP-2 drilling, summarizes the scientific methods and types of data collected, and describes the observatory constructed.

Keywords: The Alipine Fault, DFDP-2, Fault zone drilling, Fault Mechanics, Geophsical wireline logging, earthquakes

Frictional Characteristics of Cleaved Mica Surfaces and Theoretical Considerations of the Frictional Mechanism

*Hiroshi Sakuma[1], Kenji Kawai[2], Ikuo Katayama[3]

1.National Institute for Materials Science, 2.University of Tokyo, 3.Hiroshima University

Friction among rocks and minerals is critical for understanding fault slip and landslide. The maximum and steady-state friction coefficients of common minerals of mica and clay minerals have lower friction coefficients relative to common rocks and minerals. The friction coefficients were reduced under the presence of adsorbed water.
Interlayer bonding energy (ILBE) of these layered minerals has been believed to have a linear relationship with the friction coefficients [1]. However, this linear relationship was not confirmed by recent shear experiments [2,3]. Reliable ILBEs derived by the first-principles electronic state calculations [4] revealed that the linear relationship is unclear for both experimental friction coefficients [1,2]. In this study, we tried to understand a factor controlling the friction of mica and clay minerals instead of the ILBE.
Double shear test of cleaved mica surfaces was conducted as a function of normal stress ranging from 5 to 60 MPa. The friction coefficient decreased with increasing normal stress. This behavior has been observed for the powder of mica and clay minerals [2], however, the mechanism is unclear. In this talk, we discuss the mechanism by comparing our results with previous powder experiments and by using the first-principles electronic state calculations.
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Keywords: Dependence of normal stress, Double shear test, Layered minerals, Water, First-principles calculations

Characteristics of dependency of frictional properties on after-slip propagation speed

*Keisuke Ariyoshi[1], Toru Matsuzawa[2], Akira Hasegawa[2], Ryota Hino[2], Takane Hori[1]

1.Research and Development Center for Earthquake and Tsunami, Earthquake and Tsunami Forecasting System Research Group, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2.Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University

We have investigated relations between the after-slip process, effective normal stress, and friction parameters for a rate- and state-dependent friction (RSF) law from the view of theoretical analysis. For Nagata-law of RSF, the results show that the after-slip propagation speed (APS) increases exponentially with the higher value of A(=aσ), where ‘a’ is a frictional parameter of RSF and σis the effective normal stress. APS is approximately positive and negative proportional to the value of b and dc, respectively, where ‘b’ and ‘dc’ is also frictional parameter of RSF. We also check the dependency of frictional parameter ‘c’ of Nagata’s RSF law.

Keywords: rate- and state-dependent friction, effective normal stress, numerical modeling

Study of fault evolution based on texture and chemical analyses of fault gouge: Case study of the Byobuyama fault, Gifu prefecture, central Japan.

*Takuma Katori[1], Kenta Kobayashi[2], Masakazu Niwa[3], Mayuko Shimizu[3], Tetsuya Komatsu[3], Ken-ichi Yasue[3], Yasuharu Horiuchi[3]

1.Graduate School of Science & Technology, Niigata University, 2.Department of Geology, Faculty of Science, Niigata University, 3.Japan Atomic Energy Agency

The Chubu region is one of the most concentrated area of active faults, which forms the complicated fault geometry system. Such active structures affect the formation of riverine and mountain system. It can be said that active structures are important factors to consider the landform development. Although studies of active faults are multi-faceted, geological view is critical in order to consider a certain amount of time scale. In this study, we performed structural and chemical analyses of fault rocks of the Byobuyama fault, as a case study for improving research technique to reveal the history of active faults.

Studied outcrop is located in Rontochi area in Mizunami city, Gifu prefecture. Wide brittle zone along the boundary of the Toki Sand and Gravel Formation (Pliocene) and Inagawa Granite (Cretaceous) is identified in this outcrop. This brittle zone consists of cataclasite zone shows sinistral sense and fault gouge zone shows dextral sense (Katori et al., 2015). In the fault gouge zone, multiple subzones were observed as a difference of their color and deformation texture, and they show different sense of shear between each others (Katori and Kobayashi, 2015). Based on these features, the fault gouge zone observed in this outcrop preserves the several stages of fault activity at shallow depth. To reconstruct the history of the fault activity at shallow depth, we collected samples for structural and chemical analyses from this outcrop. As a chemical analysis, we performed XRD, XGT and EPMA analyses.

Based on these structural and chemical analyses, the following results were obtained.

1. There are zones undergoing significant flow deformation in the fault gouge internal where a porphyroclast showing dextral sense is observed.
2. In the most part of the zone, the matrix of the fault gouge is composed mainly of smectite. In contrast, illite is abundant in the zone observed flow deformation.
3. In the tail (pressure shadow) of the porphyroclast, quartz, K-feldspar and biotite show fragmentation by fracturing, while albite shows eluviation structure of Na.

From the above results, fault gouge zone along the Byobuyama fault has experienced activities of several stages under different stress, and significant differences in the deformation and alteration mechanism exist between these stages. Especially, the flow deformation of the fault gouge indicates that a large amount of fluid was present during the deformation. Abundance of illite infers that such fault gouge was formed by relatively high temperature fluid. In addition, eluviation structure of albite may indicate a deformation under environment such as to promote reaction solution. In this presentation, we discuss the vicissitudes of deformation and alteration mechanism in the fault gouge along the Byobuyama fault.

This study was carried out under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

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Keywords: Fault evolution, Fault gouge, Active fault, Clay mineral, Byobuyama fault

Size distribution of sandstone blocks in block-in-matrix fabrics of the Shimanto Belt, southwest Japan

*Yu Tabuchi[1], Satoshi Tonai[2]

1.Graduate School of Integrated Arts and Science, Kochi University, 2.Department of Applied Science, Faculty of Science, Kochi University

Block-in-matrix fabrics in accretionary complex are formed by slope failure, tectonic compaction, or injection, and are a key structure to solve material recycling and tectonic deformation. We need quantitative criterion because discussion of origin is difficult to unclear the whole structure. We focus on size distribution of block. For example, the size distribution of fraction such as intrafault materials by brittle failure is power law (e.g., Shimamoto and Nagahama, 1992). But, there is no study example that intend size range few cm to 10 m. We investigate to difference of size distribution that is measured researched block-in-matrix fabrics, and discussion these factors.
Object regions are five areas in the Shimanto Belt. Geologic body of three areas (the Neogene Sarashikubi Formation, the Paleogene Muroto Formation, the Cretaceous Ukibuchi Formation) is thought slope failure deposits, and that of two areas (the Cretaceous Mugi Mélange, the Cretaceous Nonokawa Formation) is thought deformed by tectonic compaction. Sandstone block is surrounded by mudrock matrix in these areas. These areas are suitable for the measurement because around bedding dip slant high angle. Measurement used by photographic image taken at various heights (1.5–50 m). We checked cumulative size distribution from 400–4000 block-size data, in addition inputted data is over 20 pixels.
The result of size distribution shows different trend according to origin. We approximate size distribution by power law, and calculated determination coefficient (R^2). R^2 values of failure deposits (the Sarashikubi Formation, the Muroto Formation, the Ukibuchi Formation) are 0.993, 0.984 and 0.997, respectively. On the other hand, R^2 values of boudinaged body (the Mugi Mélange and the Nonokawa Formation) is 0.980 and 0.897, and lower than one of failure deposits.
Size distributions of failure deposits are judged power law distribution by R^2 values. Size distribution in the Ukibuchi Formation is power law in the range of 10^{-3} to 10 m from other heights data. Block of failure or sedimentary deposits is sorting by transportation. The failure deposits measured by this study keeps size distribution when slope failure because transport-distance is short. On the other hand, R^2 values of boudinaged body are relatively lower than those of failure deposits, because ratios of thickness and viscosity of strata make specific size blocks.
In conclusion, size distributions of failure deposits and boudinaged body are different trend. Then, determination coefficient may be effective as index for judged origin in mappable scale.

Keywords: size distribution, block-in-matrix fabric, accretionary complex, Shimanto Belt, mélange

Structural development in cataclasite zones associated with faulting: an example of the Median Tectonic Line

*Shun Arai[1], Toru Takeshita[1], Ayumi S. Okamoto[1]

1.Department of Natural History Sciences, Graduate School of Science, Hokkaido University

The Median Tectonic Line (MTL) is extended more than 800 km in the East-West direction in Southwest Japan, and it is the largest fault, which defines the boundary between the Sambagawa and the Ryoke belts. It is very important to observe exhumed faults, which were active in the past for understanding the development of fractures along faults. In this study, we described the geological map around the MTL, which is distributed in Tsukide, Iitaka-town, Matsusaka-city, Mie-prefecture, and microstructures in deformed rocks and inferred their genesis. Then, we showed brittle fracturing along the MTL, and the development of geological structures related to the faulting.In this study, we mapped lithology along eight valleys, which extend ~300 m in N-S direction, in the area spanning 2 km in E-W direction, including the MTL. As a result of field study, we showed that around the MTL the rocks are structurally overlain in the ascending order of the Sambagawa pelitic schist (>50 m) and pelitic schist derived from chert-laminite (~90m), and cataclasite (~80m) and fractured protomylonite derived from the Ryoke Granitoids (>15m). Furthermore, we classified protomylonite and cataclasite distributed in this region by two kinds of microstructures; crack density (/cm) and the ratio of matrix and clast (%). As a result of crack density measurement, we classified deformed granitic rocks into four groups: non-, weakly, moderately, and strongly fractured rocks. In this classification, we showed that the rocks are strongly fractured near the MTL, and are moderately fractured far from the MTL. On the other hand, with respect to fragments caused by fracturing, we distinguished clasts from the fine-grained matrix, which is defined by fine-grained aggregates consisting of crushed particles with size <50 μm. From the preliminary results, we divided the ratio of matrix in protomylonite and cataclasite samples into three classes; (A) ~20%, (B) 40~50%, (C) ~100%. Furthermore, based on the comparison of two different classification results and microstructural observation with scanning electron microscope (SEM), class (A) and (C) samples were further divided into two classes by the degree of development of cracks and by the presence of strongly foliated structure, respectively. Further, we can show that it seems that the crack density is related to the ratio of clast and matrix between non- to weakly fractured and class (A) rocks, while between moderately to strongly fractured and class (B) to (C) rocks, these two microstructure indices are not correlated.Based on the results described above, we classified protomylonite and cataclasite in this region into 5 classes (the rocks which have the least ratio of matrix and crack density are defines as class 1). Further, we showed that in the structural development of cataclasite three stages may exist; increase of crack density (1 to 2), reduction in grain size (2 to 4), and foliation formation (4 to 5).In the stage of reduction in grain size, it seems that the cracks which are initially created gradually grow and widen, and the area of matrix increases. In the stage of foliation formation, the ratio of quartz and clay minerals and their preferred orientations resulting from pressure solution and precipitation could be responsible for the formation. Based on the spatial distribution of different classes of protomylonite and cataclasite in the geological map, it has been found that in the protomylonite zone rocks of class 1 and 2 exist, while in direct proximity to the MTL rocks of class 5 exist, though between those classes of rocks cataclasites of class 3, 4 and 5 are distributed heterogeneously. This heterogeneity of fracture development in the cataclasite zone and the growth of cracks which results in the increase of the area of matrix can be discussed in relation to the existing models of development of fault zone (Fusseis *et al.,* 2006, Schrank *et al.,* 2008).

Keywords: Median Tectonic Line, cataclasite, pressure solution, fault zone

Brittle and ductile textures within Kashio mylonites along the Median Tectonic Line, Urakawa area, Shizuoka, Japan

*Hiroto Endo[1], Katsuyoshi Michibayashi[2]

1.Graduate School of Science, Shizuoka University, 2.Institute of Geosciences, Shizuoka University

In this study, we considered microstructural development of Kashio mylonites in the Urakawa area, Sakuma-cho, Shizuoka, central Japan. Median Tectonic Line (MTL) is the largest fault in Japan, and is the geological boundary between Inner zone and Outer zone. Kashio mylonites occur in Inner zone along the MTL. We collected the Kashio mylonites outcropped in Ohchise-gawa and Shippei-sawa and made thin sections in XZ-plane. These thin sections were observed by optical microscopes and were subsequently analyzed crystallographic orientations by a SEM-EBSD system. Several samples were analyzed to identify mineral phases by XRD. Kashio mylonites showed typical sheared textures consisting of fine-grained matrix and coarse-grained porphyroclasts and were classified into protomylonites, mylonites and ultramylonites. The protomylonites have fine-grained quartz matrix with larger feldspar and amphibole porphyroclasts. Intragranular microfractures locally occur in feldspar porphyroclasts in the fine-grained matrix. The mylonites consisted of dynamically recrystallized fine-grained quartz and feldspar matrix (about 20 micron). Intragranular sheared microfractures occur feldspar porphyroclasts in the fine-grained matrix. One ultramylonite sample consists of very fine-grained matrix of quartz and feldspar with a few large porphyroclasts and is subsequently overprinted by cataclasitic textures. On the other hand, one cataclasite sample consists of mylonite clasts in fine-grained fragments with chlorite infills. Calcite veins occur in all samples, whereas laumontite veins occur in the protomylonites and the cataclasite. The crystallographic orientation analyses show that quartz c-axis fabrics in Kashio mylonites show Y-maxima patterns. It suggests that prism slip promoted in the medium temperature (amphibolite facies) was dominant. Some of the mylonites have quartz c-axis fabrics of weak single and cross girdle patterns in addition to Y-maxima patterns. There quartz c-axis fabrics could result from transition of slip systems from prism to rhomb as well as basal slip promoted in lower temperature (greenschist facies). As a consequence, it suggests that Kashio mylonites in Urakawa area have been developed under the conditions ranging from plastic to brittle regime. This microstructural development in Kashio mylonites during progressive retrogression may be associated with the development of MTL.

Keywords: Median Tectonic Line, Kashio mylonite, Brittle texture, Quartz c-axis fabric

Localized chemical changes of the fault gouges at the Awano-Tabiki outcrop of the Median Tectonic Line in Matsusaka-city, Mie Prefecture

Yuta Yamada[1], Chisaki Inaoi[2], *Tomoyuki Ohtani[1], Jun Kameda[2], Norio Shigematsu[3], Satoru Kojima[1]

1.Gifu University, 2.Hokkaido University, 3.National Institute of Advanced Industrial Science and Technology

The Median Tectonic Line (MTL) is the longest onshore fault in Japan, and it is accompanied by long deformation history and large fault zones. As the MTL has long history, the records of faultings at variable depth of the crust are expected to be well preserved. In this study, we analyzed the chemical and mineral compositions at a large outcrop exposed at Tabiki-Awano, Matsusaka-city, Mie Prefecture to understand the chemical change of the fault in the crust using the X-ray fluorescence analysis (XRF) and the powder X-ray diffraction analysis (XRD). For the XRD, the mineral assemblage analysis was performed by RockJock (Eberl, 2003).
At the Awano-Tabiki outcrop, the MTL juxtaposes the Sambagawa metamorphic rocks to the south (the footwall) against sedimentary rocks corresponding to the Izumi Group to the north (the hanging wall). The Sambagawa metamorphic rocks are variably damaged to the south by faulting with the dextral sense of shear for the distance about 20 m from the lithological boundary (Shigematsu *et al.*, 2015). Two slip zones comprising fault gouges distribute along the lithological boundary and a few meters beneath the boundary in the footwall. As the latter exhibits sharp distribution, this would be the principal slip zone. The principal slip zone consists of the foliated black gouge, gray gouge and unfoliated black gouge. As the gray gouge exhibits sharp boundaries and continuous distribution, this is expected to be the latest slip zone.
The results of the XRF show the increases of CaO, MgO, Fe_2O_3, Ignition Loss and the decrease of SiO_2 in the gray gouge. The contents of Na_2O, Al_2O_3, CaO, MnO, MgO, Fe_2O_3 are different between the both sides of the principal slip zone. No remarkable change of chemical composition is detected except the principal slip zone and rock fragments. The results of RockJock show the difference of the clay mineral contents between the both side of the principal slip zone and the distinct increases of smectite and dolomite in the principal slip zone. No remarkable change of the mineral assemblage is detected except the principal slip zone and rock fragments.
To discuss the chemical change in the principal slip zone, we examine the possibility that the decrease of SiO_2 is a relative change due to the increases of the CaO, MgO and Fe_2O_3 as carbonate minerals. The increases of Ca, Mg and Fe from the host rock are defined as three different variables. The relative decrease of SiO_2 is calculated from these variables, and they are calculated by the least square method. The result of the calculation shows that the chemical change of the principal slip zone is explained by the addition of carbonate minerals to the adjacent fault rock in the footwall side.
Although the thickness of the fault zone is large, the distinct changes of chemical compositions and mineral assemblages concentrate only in the principal slip zone. Oohashi et al. (2015) reported that the frictional coefficient is drastically decreased in the slip zone with > 30 wt% of smectite. The principal slip zone is estimated to be very weak due to the formation of smectite.

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Keywords: localized chemical changes, fault gouges, Median Tectonic Line

Fault Properties of the Shionohira Fault and its Southern Extension in Fukushima and Ibaraki Prefectures, Japan

*Masao Kametaka[1], Toru Sakai[1], Yumiko Tanaka[1], Kazuhiro Aoki[2], Yoshihiro Tanaka[2], Kazuyoshi Seshimo[2], Masakazu Niwa[2], Yuki Masuda[2]

1.Dia Consultants, 2.Japan Atomic Energy Agency

Co-seismic surface ruptures from Tabiuto-Nameishi to northeastern Ishizumi-Tsunaki in the Tabito-cho of Iwaki City, Fukushima Prefecture, caused by the Apr 11, 2011 Fukushima-ken Hamadori Earthquake (Mj7.0), were named the Shionohira Fault by Ishiyama et al. (2011) (hereinafter referred to as "the active segment of the 4.11 Earthquake") .
In previous studies of the 4.11 Earthquake, the Itozawa Fault consisting of some lineaments suspected as active faults was depicted (The Research Group for Active Faults of Japan, 2011). The Shionohira Fault nearly overlaps this lineament, but further extends southward from the southern end of the surface rupture. Moreover, it continues south to connect to a geological fault named the Kuruma Fault (Sugai et al., 1957) (hereinafter referred to as "the non-active segment of the 4.11 Earthquake").
The authors investigated these faults, focusing on the differences between active and non-active segments of the 4.11 Earthquake. This paper shows the results of boring surveys and properties of fault zones in boring core samples taken from both the active and non-active segments.
The study area is composed of a schist of Gozaisyo metamorphic rocks and overlaying Paleogene-Neogene sedimentary rocks, cut by the Shionohira Fault. In the active segment, studies of the fault outcrops and oriented boring surveys were carried out at Shionohira and Betto areas of Tabito-cho in Iwaki City. Vertical boring and inclined boring were conducted at Shionohira. The fault surface (N20W/75W) was found to have a 20-30 cm thick dark green gouge near the boundary between conglomerate and green schist in both core samples. Fault breccias were well developed around the fault gouge, especially thick in green schist at the footwall. An inclined boring was performed at Betto. The fault surface (N7W/80W) was found to have about 25 cm thick brown gouge in the fracture zone of the schist.
In the non-active segment, oriented boring surveys were carried out at Minakami-kita area (Fujigaoka, Sekimoto-cho, Kita-Ibaraki City). The lithology of the core sample was identified as top soil, Paleogene sedimentary rocks (mainly conglomerate), green schist and psammitic-pelitic schist, in descending order. Green schist was unconformably overlain by the conglomerate; however, the boundary was indistinct because of a fault shear. A fault surface (N4E/74W; core-depth 20.86m) with 2 cm thick blackish green gouge, and a fault surface (N1E/86W; core-depth 20.86m) with 11 cm thick grayish green and gray gouges were found. The former was in fault breccia of green schist, and the latter on the boundary between fault breccia of green schist and fault breccia of psammitic-pelitic schist. A thick fault breccia continued below the fault gouge in the footwall and partly contained cataclasite-like rocks.
The scale and properties of fault zones indicated that the Shionohira Fault and its southern extension possibly had moved before the deposition of Paleogene sedimentary rocks.
XRD analyses showed the fault gouge samples from the outcrops of Shionohira and Betto of the active segment to contain smectite with a small or non-detectable amount of chlorite. On the other hand, fault gouge samples from Minakami-kita contained chlorite with a small amount of illite and smectite. Thus, significant differences were recognized in clay minerals of fault gouge between active and non-active segments.
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Keywords: Shionohira Fault, Kuruma Fault, property of fault zone, fault gouge, fault activity

Frictional Properties of Shionohira Fault Gouge (Part 2)
-A Comparison with Kuruma Fault Gouge at the Southern Extension of Shionohira Fault-

*Kazuhiro Aoki[1], Kazuyoshi Seshimo[1], Yoshihiro Tanaka[1], Masakazu Niwa[1], Yuki Masuda[1], Masao Kametaka[2], Toru Sakai[2], Toshihiko Shimamoto[3]

1.Japan Atomic Energy Agency, 2.Dia Consultants, 3.Institute of Geology, China Earthquake Administration

The April 11, 2011 Fukushima-ken Hamadori Earthquake (the largest aftershock of the 2011 off the Pacific coast of Tohoku Earthquake) formed co-seismic surface ruptures trending in the NNW-SSE direction in Iwaki City, Fukushima Prefecture situated in southeast Tohoku, Japan. Ishiyama et al. (2011) named the fault Shionohira (hereafter called the “active segment”). A N-S trending geological fault with lineaments (named Kuruma Fault) exists along the southern extension of the active segment, although surface ruptures did not appear in this area (hereafter called the “non-active segment”). The authors have been elucidating the differences of active and non-active segments resulting from the 4.11 earthquake, and have reported on the low to high velocity friction experiments for the fault gouges sampled from the surface outcrops of only the active segment at the 2015 JpGU. The current report discusses results for both the active and non-active segments by conducting low to high-velocity friction experiments on the gouge collected from shallow borehole cores of both segments.
All experiments were conducted using a rotary-shear low to high-velocity frictional testing apparatus at the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration. The apparatus is capable of producing slip rates of 0.2 microns/s to 2 m/s under dry and wet condition, at room temperature and at normal stresses of mostly 1MPa by using a TiAlCr alloy piston as a host specimen which exhibits similar behavior to those of rock specimens. Experiments were performed under drained condition because gouges were sealed by teflon sleeves. Gouge samples were taken from shallow borehole cores at depths of 20.90~20.95m of the Minakami-kita outcrop for the non-active segment, and at depths of 12.82~12.87m of the Shionohira outcrop and 5.96~6.00m of the Betto outcrop for the active segment.
As for the slip behavior of the fault gouge, three velocity regimes were recognized based on the velocity dependence of steady-state friction coefficient: low velocity-regime of below 10 to 100 microns/s showing almost no velocity dependence; intermediate velocity-regime of 100 microns/s to 1 mm/s showing clear velocity strengthening, and high velocity-regime of above 1 to 10 mm/s showing significant velocity weakening. Steady-state friction coefficients of dry gouges were 0.6 to 1.0 at low to intermediate slip velocity, whereas their values were low at about 0.1 at high slip velocity. On the contrary, wet gouges of both outcrop samples of Betto and Shionohira and borehole core sample of Betto measured below 0.2 at low slip velocity although core samples of Shionohira and Minakami-kita varied between a wide range of friction coefficient from 0.4 to 1.0. Gouges of Shionohira and Kuruma faults showed heterogeneous friction characteristics under wet conditions. Results of experiment using a new sample cell which can control water content will be discussed in the poster to illustrate how friction strength can change greatly depending on water content.

Keywords: frictional properties, fault gouge, Shionohira fault, low to high velocity friction experiment, Fukushima-ken Hamadori earthquake

Distribution of fault system around the epicenter area of the 2000 Western Tottori earthquake

*Hideto Uchida[1], Hideki Mukoyoshi[1], Kenta Kobayashi[2], Tetsuro Hirono[3]

1.Department of Geoscience Interdisciplinary Graduate School of Science and Engineering, Shimane University, 2.Department of Geology, Faculty of Science, Niigata University, 3.Department of Earth and Space Science, Graduate School of Science, Osaka University

The 2000 Western Tottori earthquake (*M*:7.3, maximum seismic intensity: 6 upper) occurred in a place where no active fault was identified. The estimation of fault shape and crack distribution based on very high-density seismic observation of seismograph in 1000 point has been planned in this seismic aftershock area as one the Crustal Dynamics project. Comparison of this seismic observation with surface distribution and characters of fault rocks around aftershock area based on the field observation is also planned. This study is one of the field surveys. The objective of this study is to reveal the distribution and characters of fault rocks around the epicenter area of the 2000 Western Tottori earthquake.

The late Cretaceous to Paleogene granitic rocks which is called the Neu Granitic Pulton is widely exposed in the survey area. The granitic rocks mainly consist of coarse-grained biotite granites. Basalt-andesite dikes, rhyolite dikes, and aplite is intruded into the granitic rocks.

Fault planes in the survey area is generally N60°W and N60°E strike with high-angle dip. Orientation of dykes in the survey area is generally N60°W strike, high-angle dip, while joints in granites is N70°W strike, high-angle dip and N50°E strike, vertical dip. This orientation shows similar trend with faults. Cross cutting relationship of NW and NE trending faults were observed at several outcrop.

By thin section observation, cataclasites were recognized from 12 fault rocks. Previous study reported that cataclasites distributed in only aftershock area. However, cataclasites were recognized not only aftershock area but also outer aftershock area in this survey. The cataclasites in this survey are cataclasites with random fabrics and foliated cataclasites which includes highly plastically deformed biotite. Pulverized rock which is thought to be fractured rock by seismic shock wave was recognized in thin section observation of granite sample of near fault gouge of about 40 centimeter thick.

Cross cutting relationship of lineament of partially developed fault makes difficult to recognize. Fault system in this survey area had cut relation each other, and the relation makes the lineament with poor topographic manifest. Orientation of N60°W strike, high-angle dip of fault system which observed in the survey area is considered as the Riedel shear planes of N38ºW, 90ºmain seismic source fault (Horikawa et al.,2001). Occurrence of cataclastic fault rock indicates repetitive fault activity before this earthquake and the faults developed selectively along dikes than joints as weak planes. Fault activity has been continued after dike intrusion because dike is also fractured. Pulverized rocks observed in this survey area suggests fault activity with big seismic shock wave in shallow depth with low confining pressure.

Keywords: The 2000 Western Tottori earthquake, Cataclasite, Pulverized rock, Active fault

Statistical mixture model for separating deviatoric stress tensors from heterogeneous calcite twin data

*Atsushi Yamaji[1]

1.Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University

Mechanical twinning results in the simple shear of a crystal grain. The twinning in calcite occurs if the resolved shear stress, τ, along the gliding direction of an *e*-plane is greater than a critical value, τ_c, which is known to be around 10 MPa (Lacombe, 2010).
The twinning condition, $\tau > \tau_c$, has a geometrical interpretation. That is, a data point on a unit sphere in 5D space corresponds to a twin datum, which consists of the orientation of a twin lamella and its gliding direction; whereas a spherical cap on the sphere represents a deviatoric stress tensor. The twinning condition is equivalent with the condition that a data point exists on the spherical cap that represents the deviatoric stress tensor responsible for the twinning (Yamaji, 2015a). Accordingly, the stress inversion of the orientations of twin lamellae comes down to the search problem to determine the spherical cap that best fits data points on the sphere (Yamaji, 2015b). However, natural data are usually heterogeneous, meaning that twin lamellae that were formed under different stress conditions coexist in a calcite aggregate. In that case, the data points make clusters on the sphere; and the deviatoric stress tensors can be determined by fitting spherical caps to the data points (Yamaji, 2015b).
A computer program was made in the present work to materialize this idea. That is, a probability density function was defined to describe the twinning condition on the sphere. Second, the mixture model of the functions was fitted to data points through genetic algorithm with assuming the number of stresses to be detected was 1, 2, 3, etc. This number was determined using Bayesian information criterion. The program determines the non-dimensional deviatoric stress tensor, which is equal to the deviatoric stress tensor divided by τ_c. The method to determine τ_c is shown in the poster of the author in this session.
Mechanical twinning results in strain hardening, which can be regarded as the gradual increase of τ_c. A preliminary test using a natural data set did not show this effect.

Keywords: mixed distribution, information criterion, ductile deformation, tectonic stress

Trishear inverse modeling by using fault-slip data from meso-scale faults

*Akihiro Kokado[1], Atsushi Yamaji[1], Katsushi Sato[1]

1.Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University

In this study, we improved the method of the trishear inverse modeling (e.g., Allmendinger, 1998; Cardozo, 2005), which is a method to infer subsurface geological structures quantitatively. The trishear model (e.g., Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998) is a kinematic model of fault-propagation folds. In the conventional trishear inverse modeling, observed bedding data (positions of key beds and bedding dips) have been used to constrain the trishear model. However, observed bedding data are usually so limited in number and location that the inverse modeling usually gives several trishear models which have similar goodness of fit for the bedding data and nevertheless represent different geological structures (Cardozo et al., 2011). To deal with this problem, we incorporated fault-slip data of meso-scale faults as a constraint condition. In the new method, the trishear models concordant with the fault-slip data are selected from ones obtained by the modeling using bedding data. The goodness of fit of a model for a fault-slip datum is defined by the angular difference between the observed slip direction and the direction of the maximum shear strain on the fault plane calculated from the model. This new method was tested by the artificial trishear model prepared as an answer of the inverse modeling (answer model) and artificial bedding and fault-slip data simulated from the answer model. As the result of the test, it was found that the trishear models close to the answer model can be selected by using fault-slip data of meso-scale faults. In addition, we applied the trishear inverse modeling to the Matto Anticline in the central part of Niigata Prefecture, NE Japan. The anticline has been regarded as a fault-propagation fold which was formed by a concealed fault. There is a controversy in the dip direction of the concealed fault (Yamada et al., 1992; National Research Institute for Earth Science and Disaster Prevention, 2012). To infer the dip direction, we collected bedding data and fault-slip data from outcrops and carried out the inverse modeling by them. As a result, the east-dipping fault was found to be more concordant with the observed data than west-dipping one.

Keywords: Trishear, Fault-propagation fold, Fault-slip data, Inverse modeling, Uonuma Formation

Automatic detection of solutions of stress tensor inversion by fitting mixture probability distribution

*Katsushi Sato[1]

1.Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University

Stress tensor inversion from orientations of faults is a key technique to elucidate modern and ancient state of stress in the upper crust. In studies of structural geology, we need to detect multiple stress tensors responsible for multiple tectonic events in the geologic time. However, the detection of solutions of stress tensor inversion techniques has not been fully automated and there remains subjectivity in the result. This study aims at automating the detection of stress tensors. The input data for stress tensor inversion is called fault-slip data which carries fault plane orientations and slip directions. A reduced stress tensor, which is the unknown parameter with four degree of freedom to be determined in the inversion analysis, corresponds to a point on five-dimensional (5-D) unit sphere (Fry, 1999; Sato and Yamaji, 2006). Assuming that a fault slips along the shear stress acting on the fault plane, a fault-slip datum constrains stress tensor to the corresponding points on a great semicircle on the 5-D unit sphere. The Hough-transform-based stress tensor inversion method (Yamaji et al., 2006), hereafter HIM, superimposes the semicircles specified by observed faults to obtain the distribution of objective function to be maximized. The peaks of the distribution give optimal reduced stress tensors. The HIM requires us to set a threshold to detect the peaks or to visually recognize the peaks on stereograms. This study proposes to fit a mixture probability distribution to the distribution of objective function. The 5-D Kent distribution is employed as the component distribution in order to express the anisotropy caused by the shape of the great semicircle. The number of peaks is determined according to the Bayesian information criterion.
The new method was tested by the analysis of a synthetic fault-slip dataset, which consists of two groups of faults originated from different stress tensors. As the result, two given stress tensors are successfully detected. The new method was applied to meso-scale fault-slip data gathered from the Pleistocene Sekinan Group, Oita Prefecture, southwest Japan. Two stress tensors were detected with NNE-SSW and NNW-SSE horizontal tension axes, suggesting a temporal change of stress state.
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Keywords: stress tensor inversion, fault-slip analysis, mixture probability distribution

Development of a method to estimate spatial stress pattern from P-wave first motion data: a preliminary numerical simulation

*Takaki Iwata[1]

1.Tokiwa University

A method of estimating spatial stress pattern from a centroid moment tensor (CMT) dataset has been developed by Terakawa and Matsu'ura [2008, GJI, 172, 674-685]. However, often the number of available CMT solutions is limited if our interest is the estimation for a small area. For such a case, it is difficult to apply this method because of the insufficiency of data. To meet this difficulty, this study proposes a method to estimate from P-wave first motion data, instead of CMT data. We assume that the direction of a pre-existing fault plane is random and that the direction of a seismic slip is parallel to that of the tangential component of the stress vector. Under these assumptions, we can compute the probability of the polarity (up/down) of a P-wave first motion if stress field at an hypocenter and the geometry between the hypocenter and seismic stations are given. Thus, on the basis of a likelihood function constructed from the computed probability and a prior distribution corresponding to a spatial smoothness constraint on the stress field, we can estimate the spatial stress pattern through a Bayesian approach.
The development of this method is currently at preliminary stage, and thus only a numerical simulation has been done. For the simplicity of the simulation, a case where hypocenters and seismic stations are located in a two-dimensional space (i.e., plane) is considered; one is horizontal and the other is vertical. Also, the direction of the intermediate principal stress (sigma2) and that of a fault plane of each earthquake are supposed to be vertical to the considered plane. The spatial variation of the plunge of the direction of the maximum principle stress (sigma1) is assumed to be follow a particular pattern (and consequently, the direction of the minimum principle stress sigma3 is also determined). Under these conditions and assumptions about the directions of a fault plane and seismic slip as described above, datasets of P-wave first motions are generated. Then, the proposed Bayesian approach is applied to these datasets. As a result, the estimated spatial pattern almost agrees with the one assumed in the generation of the simulation datasets, which suggests the validity of developing this Bayesian approach.

Keywords: stress field, spatial pattern, P-wave first motion, Bayesian estimation

(U-Th)/He thermochronometric mapping in NE Japan Arc: Insights into understanding long-term crustal deformation

*Shigeru Sueoka[1], Takahiro Tagami[2], Barry P. Kohn[3], Shoma Fukuda[2]

1.Japan Atomic Energy Agency, 2.Department of Geology and Mineralogy, Kyoto University, 3.School of Earth Sciences, University of Melbourne

A paradox of deformation in NE Japan Arc is that the short-term deformation observed by geodetic techniques and the long-term deformation estimated from geomorphic and geologic evidence is different in rate and/or direction (e.g., Ikeda, 1996, Active Fault Res.). Deformation observed by geodetic research consists of elastic deformation canceled by earthquake cycles and inelastic deformation expended in developing landforms. To separate the two components, using geomorphic/geologic techniques is a practical approach to estimate inelastic deformation (Ikeda et al., 2012, J Geol Soc Jpn). We performed apatite and zircon (U-Th)/He (AHe and ZHe) thermochronometric analyses from Cretaceous or early Paleogene granitic rocks along two profiles across NE Japan Arc for estimating its long-term vertical deformation rates. The northern profile (N-profile) ranges across the Kitakami Mountains, Ou Backbone Range (OBR), and Taihe-Shirakami Mountains, while the southern profile (S-profile) includes the Abukuma Mountains, OBR, and Iide-Asahi Mountains. So far, AHe and ZHe ages of the S-profile and AHe ages of the N-profile have been obtained. AHe ages on the fore-arc side, i.e., Kitakami and Abukuma Mountains, are older than about 50 Ma, implying a stable tectonic/geologic setting over the Cenozoic. On the other hand, young AHe ages of <10 Ma are obtained in OBR and the back-arc side, namely Taihe-Shirakami and Iide-Asahi Mountains; the youngest ages are ~1 Ma in OBR. These AHe ages can be grouped into three populations of ~10 Ma, ~5 Ma, and <3 Ma, which are consistent with uplift stages of the mountains estimated from provenance analyses of the adjacent basins (e.g., Nakajima et al., 2006, PPP; Moriya et al., 2008, J Geol Soc Jpn). In addition, the sample localities are generally at some distance from high geothermal gradient zones around volcanic centers. Therefore, the AHe ages obtained are interpreted as reflecting a record of uplift and denudation over the last ten million years. On the back-arc side, AHe ages are generally estimated at ~10 Ma in the Iide-Asahi Mountains to the south, but at ~5 Ma in the Taihe-Shirakami Mountains to the north. Taking into account that Moriya et al. (2008) proposed that uplift of the Asahi Mountains is older than that of the Dewa Hills to the north at ~5 Ma, the AHe ages around 10 Ma may indicate the initiation of uplift of the Iide-Asahi Mountains. Both the AHe and ZHe ages tend to yield younger ages from mountain bases to ridges in OBR and the back-arc side. This observation is in contrast with the case of the Kiso Range (Sueoka et al., 2012, AIR) and northern Akaishi Range (Sueoka et al., 2011, J Geogr), reverse fault block mountains in SW Japan Arc, where thermochronometric ages young from ridges to the marginal faults. The difference might arise from the existence of the volcanic arc, i.e., horizontal heterogeneity of the thermal structure and/or domal isostatic uplift derived from magmatic intrusions, but this is still debatable. For more detailed constraints on the thermal histories, we are planning to apply other thermochronometers, such as the apatite/zircon fission-track and zircon U-Pb methods, and to conduct additional AHe and ZHe age determinations.

Keywords: NE Japan Arc, (U-Th)/He thermochronometry, long-term crustal deformation

Compilation of low-temperature thermochronometric data in NE Japan Arc:A preliminary report of apatite fission-track ages

*Syoma Fukuda[1], Shigeru Sueoka[2], Takahiro Tagami[1]

1.Graduate School of Science, Kyoto University , 2.Japan Atomic Energy Agency

We are trying the estimation of vertical deformation on geologic time scale in NE Japan Arc based on low-temperature thermometric methods, as a part of “Crustal Dynamics –Unified understanding of intra-island deformation after the great Tohoku-oki earthquake-”project. All of the 30 samples were collected from Cretaceous or early Paleogene granitic rocks across two profiles; the northern profile (N-profile) ranges the Kitakami Mountains, Ou Backbone Range (OBR), and Shirakami Mountains, while the southern profile (S-profile) ranges Abukuma Mountains, OBR, and Iide Mountains. So far, apatite and zircon (U-Th)/He (AHe and ZHe) ages on the S-profile, and AHe ages on the N-proile are obtained. The previous apatite Fisson-Track (AFT) ages of Cretaceous on the Pacific side of NE Japan were obtained from granitic rocks of Kitakami and Abukuma Mountains (Goto 2001, Ohtani et al., 2004), which imply the total amount of denudation is estimated at about ~3 km from late Cretaceous to present. On the other hand, young AFT ages of Miocene or Pliocene were reported in Iide and Echigo Mountains on the Japan Sea side(Goto 2001, Sueoka unpublished data), which may reflect rapid uplift and denudation since Neogene. AHe and ZHe ages of S-profile indicate about 50 Ma in Abukuma Mountains, whereas AHe ages of both profiles are estimated at younger than 10 Ma on all the based on sampling localities to the west of Fukusima Basin. These young ages reflect the thermal histories since the opening of the Japan Sea (25-15 Ma), and they are consistent with the initiation of the uplift of Dewa Hills and Asahi Mountains (Moriya et al., 2008). In addition, the compression field in NE Japan Arc initiated since the end of middle Miocene, and the mountains started to be uplifted since the end of Miocene or Pliocene (Ota et al., 2010). The young AHe ages are attributable to cooling and denudation accompanied with the mountain uplifting. Thermal reset due to volcanism is less possible considering the distance from the Quaternary volcanoes and adjacent high-geothermal gradient regions (Tanaka et al., 2004) and Neogene caldera (Yoshida et al., 2013).
In this presentation, we report the new AFT ages of S-profile at which He ages were previously obtained, and discuss uplift and denudation history of NE Japan Arc by combining with the previously reported FT and He ages. AFT ages were measured by following procedures of Hasebe et al. (2004) in which uranium contents are estimated by using LA-ICP-MS. For more detailed constraints of the thermal histories, we are planning to apply U-Pb and zircon FT methods, and to conduct additional measurements of AFT ages.

Keywords: thermochronology, (U-Th)/He age, fission track age, NE Japan Arc

Spatial variation in coda Q in the northeastern Niigata-Kobe Tectonic Zone

*Masanobu Doujou[1], Yoshihiro Hiramatsu[1]

1.Graduate school of Natural Science and Technology, Kanazawa University

We focus on a high strain rate zone called Niigata-Kobe Tectonic Zone (Sagiya et al., 2000) to understand a stress accumulation process of source fault. Jin and Aki (2005) showed that low coda Q for 1-2 Hz and 2-4 Hz frequency bands corresponded spatially to the high strain rate zone. Hiramatsu et al. (2013) and Tsuji and Hiramatsu (2014) suggested that the cause of the high strain rate zone was attributed to the high deformation rate below the brittle-ductile transition zone in the crust along the Atotsugawa fault zone and around the Nobi fault zone. This study investigates details of the spatial distribution of coda Q in the northeastern Niigata-Kobe Tectonic Zone and discusses a relationship to the high strain rate zone.

We analyze 1196 events during the period January 2012–October 2014 in the northeastern Niigata-Kobe Tectonic Zone. Those magnitudes are greater than 2.0 and the depths shallower than 30 km. We use seismic waveforms recorded at stations of three national universities, Japan Meteorological Agency, and Hi-net data. For each station, we select events of which epicentral distances are within 30 km for the analysis of coda Q.

We recognize three different patterns of the spatial distribution of coda Q. To compare the spatial distribution of coda Q with that of differential strain rate in the same period, middle frequency bands (4-8 Hz and 8-16 Hz) shows more significant negative correlation than low frequency bands (1-2 Hz, 2-4 Hz).[YH1] Positive correlations are found between the perturbation of the S-wave velocity (Nakajima and Hasegawa, 2007) at 25 km depth and coda Q at low frequency bands, and between the perturbation of the S-wave velocity at 10 km depth and coda Q at middle frequency bands.

In the northeastern Niigata-Kobe Tectonic Zone, these facts imply that the spatial distribution of coda Q at low frequency bands reflects mainly the heterogeneity of the lower crust and that at middle frequency bands mainly the heterogeneity of the upper crust. The spatial distribution of coda Q at middle frequency bands is related dominantly to the concentrated high strain rate. Therefore, in the northeastern Niigata-Kobe Tectonic Zone, it is because Niigata plane is sedimentary basin that the deformation rate in the upper crust is high, so that we observe high strain rate. However, the 2011 Touhoku earthquake have provided a large change in strain rate in this study area. We need to investigate the spatial distribution of coda Q before the earthquake.

Keywords: Niigata-Kobe Tectonic Zone, coda Q, differential strain rate, S-wave velocity

Slip pattern along the northern Sumatran fault, Indonesia revealed by geodetic and geomorphic observations

*Takao Tabei[1], Takeo Ito[2], Hiroyuki Tsutsumi[3], Fumiaki Kimata[4], Yusaku Ohta[5], Airi Watanabe[1], Taku Ozawa[6], Makoto Okubo[1], Tadashi Yamashina[1], Yoshio Soeda[7], Endra Gunawan[8], Nazli Ismail[9], Irwandi Nurdin[9], Didik Sugiyanto[9]

1.Kochi Univ., 2.Nagoya Univ., 3.Kyoto Univ., 4.Tono Res. Inst. Earthquake Sci., 5.Tohoku Univ., 6.NIED, 7.West Japan Eng. Cons. Inc., 8.Bandung Inst. Technology, 9.Syiah Kuala Univ.

We have conducted geodetic and geomorphic observations in Aceh province, northern Sumatra, Indonesia to clarify slip history and current strain accumulation along the northernmost segments of the Sumatran fault. Evaluation of the earthquake generation potential in Aceh province is highly urgent because of the largest slip rate along the 1900-km long Sumatran fault, absence of major earthquakes for more than 120 years, and local Coulomb stress increase due to two recent interplate megathrust events at the Sunda Trench, the 2004 Sumatra-Andaman (Mw 9.2) and 2005 Simeulue-Nias (Mw 8.7) earthquakes.
We have deployed continuous and campaign GPS network since 2005 called AGNeSS (Aceh GPS Network for the Sumatran Fault System). Using horizontal and vertical displacements spanning over five years with different relaxation times, we have proposed multiple physical mechanisms (afterslip and viscoelastic relaxation) that control postseismic deformation (Gunawan et al., 2014). Moreover we have inferred shallow creep/locking distribution along the Aceh segment of the Sumatran fault (Ito et al., 2012). The result shows the segment is capable of producing a M 7 event in the future. In 2013 two M 6.1 earthquakes occurred successively in the network and we detected clear coseismic displacements.
Tectonic geomorphic features are also investigated to reveal long-term slip history of the fault. We used high-resolution stereo-paired ALOS/PRISM satellite images to map the surface trace and conducted field observations to ensure it. The trace is well-defined by fault scarps, pressure ridges, linear troughs and deflected streams. In addition, we set up alignment arrays at four locations to directly determine surface creep rates by repeated geodetic surveys. In 2015 we revealed the evidence of at least three slip events from one paleoseismic trenching site. We will conduct carbon dating of samples to estimate the timing of the most recent event and a recurrence interval.
InSAR analysis of ALOS/PALSAR images has supplemented limited coverage of GPS stations and geomorphic observation sites. Stacked images spanning approximately three years from 2007 to 2009 shows a clear contrast of LOS (line-of-sight) contraction in one side of the fault and extension in another side. Profile of the LOS change across the fault is characterized by a step-like offset of about 10-15 mm/yr at the location of the surface fault trace. The pattern of the LOS change is consistent to the right-lateral slip motion of the Sumatran fault though the offset seems too large compared with the expected slip rate of the fault. We will develop the interpretation of the LOS change including GPS displacement rates and geomorphic information.

Keywords: Sumatran fault, GPS, SAR, Geomorphology

Source fault model of the 1703 Genroku earthquake with the constraints of average stress drop

*Junki Komori[1], Ryosuke Ando[1], Masanobu Shishikura[2]

1.Graduate School of Science, University of Tokyo, 2.National Institute of Advanced Industrial Science and Technology, GSJ

Crustal deformations, such as uplifts or subsidence, accompanied with fault dislocations are often observed after large earthquakes. From these distributions of crustal deformations, rupture areas and slip amounts of source faults can be derived by inversion analysis. While we can evaluate the source faults precisely if detailed data of crustal deformations or waveform are abundant, it is quite difficult to estimate the parameters of faults of paleoearthquakes because only sparse data is available for remaining geomorphological evidences. In this study, with focus on the 1703, Genroku Kanto earthquake, I attempted to add a new constraint to the method for estimating the source faults of paleoearthquakes based on the physical properties of the fault, which is the stress drop. The geomorphological evidence obscurely determines the source model size of the Genroku earthquake, while a large fault area extending to southeast off the Boso peninsula is estimated only from historical records of tsunami (Matsuda et al., 1978; Namegaya et al., 2011). This limitation raises problems in the reconstruction of the history of paleoearthquake and the long-term earthquake forecasting in this region.
Kanamori and Anderson (1975) revealed that nearly all of huge earthquakes exhibited an almost constant stress drop between 1 to 10 MPa. Although there exists an important characteristics of fault parameters called the scaling law, which determines the relationship between fault sizes and slip amount through the stress drop, previous paleoseismological studies barely take them into account.
The coseismic crustal deformation accompanied with the Genroku earthquake was estimated from uplifted shoreline (Shishikura, 2003) together with GEONET data to determine the steady deformation rates. We assumed several rectangular subfaults, and grid-searched the optimal source size, location and slip to describe the data. .
As a result of this study, it was revealed that the fault extending to the offshore is necessary to explain the distribution of crustal movement of Genroku earthquake when the constraint of stress drop is introduced to the model. This is understandable if we consider the large uplift in the Boso peninsula cannot be accommodated by the fault slip on the fault areas beneath the Boso peninsula and Tokyo bay, needed the extension of the source area to the southwest off shore. This result may provide a new insight to the studies of paleoseismology through the physical properties concerned to the parameters of earthquakes.
We also mention how this physically based source modeling is used to interpret the newly revealed gap in the emergence date of the marine terraces in Chikura low land, southern Boso peninsula (see presentation by Komori et al., 2016, this meeting).

Keywords: 1703 Genroku Earthquake, Slip inversion, paleo-seismology

Accelerated vertical crustal movements in the Tohoku region prior to the 2011 Tohoku-oki earthquake: discussion of GPS and tide gauge data

*Takeshi Sagiya[1,2], Yuri Kurokawa[2]

1.Disaster Mitigation Research Center, Nagoya University, 2.Graduate School of Environmental Studies, Nagoya University

It has been reported that horizontal crustal movements in southern Tohoku was accelerated toward the Japan Trench before the 2011 Tohoku-oki earthquake [*Mavrommatis et al,* (2014)]. They consider the aseismic slip acceleration on the plate interface as a possible trenchward accelerations source. If this slip acceleration occur on the plate interface, similar acceleration is expected in the vertical component. However, the previous study did not discuss the vertical crustal deformation in this region and when this acceleration start. Therefore we analyze vertical components of daily GPS coordinate data and tidal records in the Tohoku region. In regard to GPS data, we estimate the best-fit linear trend for the period 1996 to 2003 and 2003 to 2011 by using the least squares method. Then we compare the temporal change of those vertical displacement rates for each period to discuss the possible acceleration. About tidal records, we long term sea level change rates at 23 gauges obtained after removing oceanographic signals using Kato and Tsumura's method (1979). If we refer to the F3 solution in the absolute sense, the velocity changes between 2 periods appear to show systematic accelerated uplift (+2.8 mm/yr on average) in the western Tohoku region. We also find that similar systematic accelerated uplift in order part of Japan such as Kinki and Chugoku regions. However, we do not find that similar velocity changes in tidal records. Such an accelerated changes cannot be attributed to the plate subduction at the Japan Trench and we suspect these changes are related to the reference frame in the F3 solution. Thus we removed common-mode errors estimated from stations around the western Tohoku region. As a result, the vertical GPS velocity is consistent with the tide gauge data and we find accelerated subsidence along the pacific coast of Tohoku region. In particular, rapid subsidence acceleration (-3.0 mm/yr on average) occurred in the north of Oshika Peninsula. These accelerated subsidence is consistent with a deep seismic slip proposed by *Mavrommatis et al.* (2015) to interpret the horizontal acceleration. The estimated aseismic slip area appears to occur surrounding the coseismic slip area of the 2011 Tohoku-oki earthquake. This result suggest unfastening of coupling occur around the future coseismic slip area before Megathrust earthquake. Furthermore we estimate the vertical velocity for the period 1970 to 2011 using tide gauge data. As a result, we find significant accelerations from 1996 to 2011 as well as subsidence acceleration in GPS data. On the other hand, tidal records from 1970 to 1996 do not show significant accelerations. Consequently, the subsidence accelerations in GPS data are more likely to occur after the late 1990s.

Keywords: the 2011 Tohoku-oki earthquake, vertical crustal movement, accelerated deformation

Characteristics on Postseismic Deformation following the 2003 Tokachi-oki Earthquake and Estimation of the Viscoelastic Structure in Hokkaido, Northern Japan

*Yuji ITOH[1], Takuya NISHIMURA[2]

1.Graduate School of Science, Kyoto University, 2.Disaster Prevention Research Institute, Kyoto University

1. Introduction
The 2003 Tokachi-oki earthquake is an interplate earthquake along the Kurile trench and is followed by postseismic deformation. Postseismic deformation is mainly caused by afterslip and viscoelastic relaxation. Previous studies estimated the afterslip in the 1st year but didn't consider viscoelastic relaxation. The viscoelastic structure has never estimated in the region. Estimation of spatiotemporal afterslip distribution is a key to reveal the healing process of the fault strength, however, estimated afterslip can include a systematic error if viscoelastic relaxation is ignored. In this study, we evaluate the both effect in postseismic deformation during the 2nd-7th year and estimate parameters of viscoelastic structure.
2. Data analysis
We use the data observed at 81 stations of the GEONET in Hokkaido and don’t use stations in southwest Hokkaido because the signals of postseismic deformation of the 1993 Hokkaido-Nansei-oki earthquake and volcanic activity of Mt. Usu were observed. First, we eliminate linear component and significant displacement due to several earthquakes, such as the 2004 Kushiro-oki, the 2006 Central Kurile, and the 2007, 2008, 2009 Tokachi-oki earthquakes. We estimate the horizontal and vertical velocity by piecewise linear approximation every year and every 2 years, respectively, with considering annual and semi-annual variations.
3. Modeling and Estimation
Displacement $U(x,t)$ at the station x and the time t due to afterslip is modeled by the following equation (1),
$U(x,t)=Au(x)\ln(1+t/B)$ (1)
where $u(x)$ is the calculated displacement at x from the afterslip model for the first 4 months, which we estimate with the inversion method of Nishimura [2009]. We assume that spatial distribution of afterslip doesn’t change temporally. Because $u(x)$ is calculated from the 4-month model, A and B is constrained by the following equation (2) and B is estimated.
$A\ln(1+1/3B)=1$ (2)
We model viscoelastic relaxation due to the 2003 Tokachi-oki and the 2004 Kushiro-oki earthquakes. We use the Fortran code PSGRN/PSCMP [Wang et al., 2006] to calculate. We use the coseismic model of GSI [2003] and Nishimura [2009], respectively, and assume the 2 layers model, which consists of an elastic layer with thickness H overlying a viscoelastic half-space with viscosity η.
We estimate B, H, $\eta$and translation components of the whole network by grid search.
4. Results and Discussion
The estimated values of B, H and $\eta$are 0.115 year, 50 km and 2.0×10^{19} Pa s, respectively. The estimated viscoelastic structure is consistent with that in the Tohoku region, northern Japan (e.g. Diao et al., 2014).
Our model explains the horizontal velocity roughly but systematic misfits are distributed locally in all the periods, which is due to afterslip of the 2004 Kushiro-oki, the 2008 and 2009 Tokachi-oki earthquakes. Our model explains the uplift in the Pacific coastal region qualitatively but not quantitatively and large systematic misfits are broadly distributed mainly in the Tokachi Plain area. These misfits suggest that the 4-month distribution of afterslip changes and that

afterslip velocity is faster than that calculated from the logarithmic model in the down-dip side of the coseismic source area.
Our study suggests that afterslip plays the dominant role at most stations in the 2nd year and is still sustained near the coseismic source area in the 7th year, and that viscoelastic relaxation is large enough to be detected in the northern area in the 7th year. Deformation due to viscoelastic relaxation of the 2004 Kushiro-oki earthquakes is much smaller than that of the 2003 Tokachi-oki earthquake.
Acknowledgement: We used the GEONET F3 solution provided by the GSI.

Keywords: The 2003 Tokachi-oki earthquake, Viscoelastic relaxation, Afterslip, Postseismic deformation, GNSS

Two-dimensional analysis of post-seismic deformation of the 2011 Tohoku-Oki earthquake by subduction zone thermal-flow model

*Jun Muto[1], Shun-suke Horiuchi[2], Hikaru Iwamori[2], Takeshi Iinuma[2], Bunichiro Shibazaki[3]

1.Department of Earth Science, Tohoku University, 2.Japan Agency for Marine-Earth Science and Technology, 3.International Institute of Seismology and Earthquake Engineering, Building Research Institute

Post-seismic deformation of the 2011 Tohoku-Oki earthquake observed in the world densest geodetic network may provide a robust constraint to the rheological properties over the NE Japan island arc-trench system. Various geophysical observations and petrological models also have given strong constraints for the thermal-flow structure of the NE Japan. Horiuchi and Iwamori (2016) have recently created a numerical model on thermal-flow structure of a subduction zone with plate coupling and chemical reaction. The consistent model takes account of the fluid distribution incorporating slab-dehydration, mantle hydration (such as serpentinization) and melting reactions in the mantle wedge. Using this model with a range in viscosity of serpentinites, the model successfully reproduces the various observations; surface heat flow distribution, alignment of Quaternary volcanoes, and seismic velocity structures of the NE Japan arc. The viscosity distribution calculated in the model includes the temperature- and water content-dependent law for olivine, and can be incorporated into FEM to test various parameters and assumptions of the model with respect to the post-seismic deformation. We used a two-dimensional FEM model incorporating the geometry of subducting slab and viscosity distribution estimated by the thermal-flow model (Horiuchi and Iwamori, 2016). Viscosity structure in the thermal-flow model is mapped to a two-dimensional FEM model as a steady-state value to calculate viscoelastic relaxation. The coseismic slip distribution was calculated according to Iinuma et al. (2012). Preliminary results show that the observed post-seismic vertical deformation of inland area can be reproduced by the thermal-flow model with a certain parameter range. In the presentation, we will show numerical results with various parameter spaces (such as viscosities of serpentinites, water contents and so on) and compare them with those based on our previous rheological model.

Keywords: post-seismic deformation, Tohoku-oki earthquake, rheology, subduction zone, viscoelastic relaxation

Subsurface density structure and serpentinized rate of the mantle wedge beneath southwest Japan estimated from gravity anomaly

Yuji Iwaki[1], Akihiro Sawada[1], *Yoshihiro Hiramatsu[1], Tomoyuki Mizukami[1]

1. Kanazawa Univ.

In Shikoku region, metamorphic belts are distributed parallel to the trench axis of the Nankai trough and deep low-frequency tremors and slow slips occur on the transitional region of the subducting Philippine Sea plate. The tremor and short-term slow slip event (SSE) are distributed to the high Vp/Vs regions, suggesting that those occur at a boundary section of serpentinized mantle wedge and Philippine Sea slab (Matsubara et al., 2009). In this study, we estimate the subsurface density structure beneath southwest Japan (Shikoku and Chugoku regions) and discuss a serpentinized rate of the mantle wedge based on gravity anomaly analysis.
The gravity data we analyzed here are measured by Kabazawa University and other institutes (Sawada et al., 2009; Yamamoto et al., 2011; Geospatial Information Authority of Japan, 2006; Geological Survey of Japan, 2004: Gravity Research Group in Southwest Japan, 2001). We adopt the density of 2,670 kg/m^3 for Bouguer correction and terrain correction. We calculate the terrain correction using the method of Honda and Kono (2005). We also use the configuration data of the basement depth (National Research Institute for Earth Science and Disaster Prevention), Conrad and continental Moho (Katsumata, 2010) and oceanic Moho of Philippine Sea slab (Shiomi et al., 2008).
We set 7 profiles in the east-west direction and 5 ones in the north-south direction on the land area from Shikoku to Chugoku regions for the density structure analysis. The inital density structure model is constructed from the configuration data mentioned above. We modify the depths of Conrad and continental Moho to explain the observed gravity anomaly by applying sequential iteration with the two-dimensional Talwani's method. In the modification, changes of the depths are constrained within the two times of the error of Conrad and continental Moho reported by Katsumata (2010).
First, we estimate the density structure with no serpentinized region. For the profiles of north-south direction, we obtain the structure, which reproduce well the observed gravity anomaly except for the difference between the observed and synthetic gravity anomalies caused by the effect of the surface structure and the shallower slab except for the profile in the central part of southwest Japan. For the profiles of east-west direction, the difference is large in the eastern part of Shikoku region. This difference may be caused by intricate configuration of the Philippine Sea slab, which implies inadequacy of the two-dimensional analysis beneath the eastern part of Shikoku.
Second, to examine a serpentinized rate in the mantle wedge, we assume following three cases of serpentinized region: (i) on the surface of the slab, (ii) in the high Vp/Vs region, (iii) combination of (i) and (ii). Here we judge that an estimated density structure is possible if the misfit, which is defined by the sum of the square of residual, is less than that of the case of no serpentinized region. For the case (i), a possible serpentinized rate is up to 100 % in the serpentinized region with ~3 km of thickness on the surface of slab. For the case (ii), 20 % is the upper limit of serpentinized rate in the eastern part of Shikoku, whereas 40 % is maximum in the other parts. For the type (iii), 20 % and 40 % are the upper limit of serpentinized rate in the eastern and the western parts of Shikoku region, respectively. As a result, the serpentinized rate in the eastern part is lower than that in the western part for the type (ii) and (iii).
We suggest that the difference in the serpentinized rate between the eastern and the western parts is caused by the difference in the thermal structure and the degree of dehydration due to the

variation of the configuration of the subducting PHS slab. The number of the tremors decreasing from the west to the east is possible to be linked with the serpentinized rate in the mantle wedge beneath Shikoku region.

Keywords: Serpentinization, Mantle wedge, Gravity anomaly

Has the collapse of Pacifc slab been started into Lower Mantle

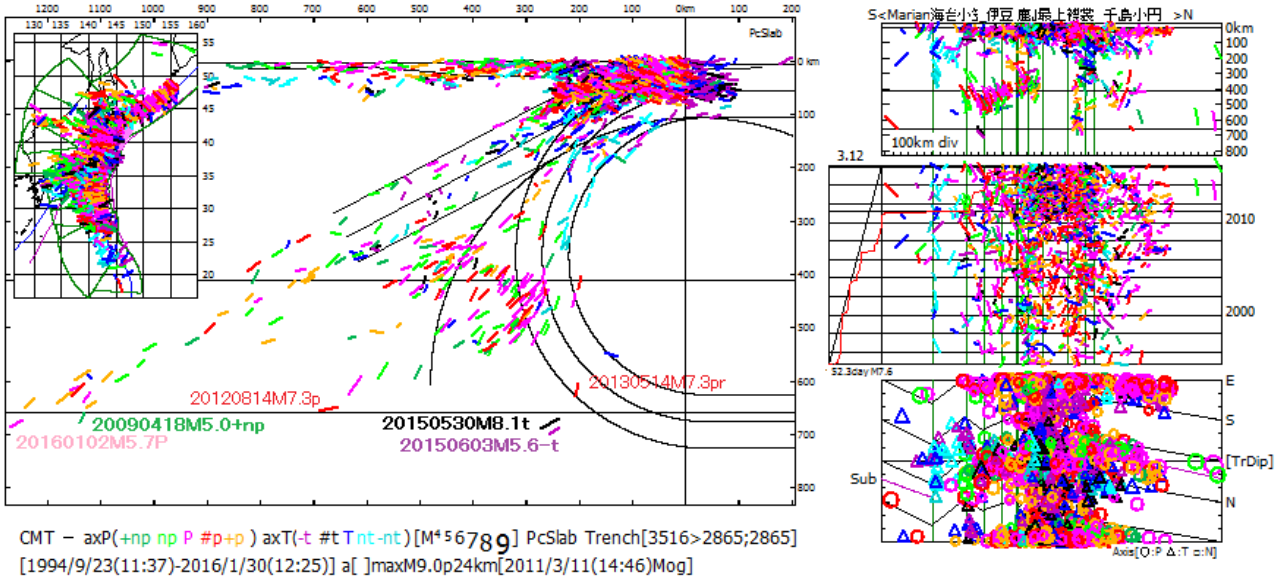
*Nobuaki Niitsuma[1]

1.Institute of Geosciences,Shizuoka University

Pacific slab has been crossed over the upper boundary of lower mantle and started of collapse into lower mantle are discussed in this presentation.
M8.1 Earthquake with the depth of 682km happened off Ogasawara Islands in May 30 of 2015, which quaked all over the Japanese Islands with stronger than 1 of Japanese seismic scale, and indicated Pacific slab continue to the focus and the slab crossed the upper boundary of lower mantle with depth of 660km. Three days later, June 3 M5.6 in the same area with depth of 695km clearly showed Pacifc slab reached into lower mantle. Focal mechanisms of the earthquakes were similar normal fault type.
The focal area was characterized with changes in the focal mechanism after East Japan Mega Earthquke 2011.3.11, and volcanic reruption at Nishinoshima Island. Hypocenter of Earthquake M7.3 of May14, 2013 in the south of this area with depth of 619km indicated Mariana Slab of Pacific plate is overturning above the lower mantle boundary, continuing to concentric bending along trench. Izu slab subducts along Izu trench in the north of this area, with concentric bending and unbending into plane. The declination of planar slab increases southward, and lower mantle earthquakes occurred at the southern margin of Izu slab.
The lower mantle earthquakes have the deepest title superior the last title holder of April 18, 2009 M5.0 of 671km in Vladivostock area, of which depth was also below the depth 660km of lower mantle boundary. The upper mantle principal mineral of olivine leads to phase transition to perovskite of lower mantle under the pressure and temperature of the 660km depth in the Earth. Because the pressure for the transition is higher in the lower temperature, slab with lower temperature cannot transit and stagnate above the lower mantle boundary. Earthquakes within the stagnant slab occurred in Vladivostock area and the earthquakes have reverse fault type focal mechanism, however, the last title holder has strike-slip fault type focal mechanism. The difference in focal mechanism and the hypocenter in the deepest side with the warmest portion of the stagnant slab suggest that the last title holder was also lower mantle earthquake. If the stagnant slab has started to fall into lower mantle, the leading part of the transited slab to lower mantle should lose the buoyancy and pull the following stagnant slab. The pressures for the pulled following slab might inclease and lead to transition, which could make chain reaction and induce collapse of the stagnant slab. The collapse scenario used for the explanation in the movie “Sinking Japan”. If the collapse of stagnant slab has already started in 2009, East Japan Mega Earthquake could be explained as the result.
In this year, January 2, 2016, earthquake M5.7 with 681km of depth occurred in Vladiostock area. The depth 681km is determined with initial motion, however the depth with CMT was 641km and the focal mechanism was reverse fault type, common in stagnant slab above the lower mantle boundary. In the case of April 2009, the depths with initial motion and CMT ware equal to 671km and in the Ogasawara 682/688km and 695/695km. Because the depth of January 2016 uder 660km of initial motion indicates for the starting position of fracture and of CMT above 660km for the main portion of fracture, the earthquake occurred in the stagnant slab above the lower mantle boundary but started from pulled under the boundary by leading wedge of lower part of the slab for April 2009.
Chishima Slab has already earthquake M7.3 in August 14, 2012 with the depth of 654km just above lower mantle boundary. If Chisima slab is going to get into lower mantle, Pacific Plate would collapse with Chishima slab, Vladivo slab and Izu slab. Japanese Islands have been experienced

sinking of the area of present ebackbone range under the sea level in 10 Ma. We need to make up new earth science based on the geologic experienses of sinking.

Keywords: Pacific slab, stagnant,, , , stagnant slab, lower mantle, phase transition, focal mechanism, sinking Japan



Fracture zone outcrop exposed in the 2000 Western Tottori Earthquake aftershock region

*Shun Suzuki[1], Kenta Kobayashi[2], Takuma Katori[2], Keita Takahashi[1], Yumeki Hoshika[1], Kenji Ohashi[1], Shohei Naito[1], Tomoyo Huzinami[1], Moeko Kanno[1], Madoka Minami[1], Maya Kaneko[1], Akari Imura[1], Hideki Mukoyoshi[3], Hideto Uchida[3]

1.Department of Geology, Faculty of Science, Niigata University, 2.Graduate School of Science & Technology, Niigata University, 3.Interdisciplinary Faculty of Science and Engineering, Shimane University

2000 Western Tottori Earthquake(Mw6.6) had occurred in Nanbu city, Tottori prefecture. And epicenter was in seismic gap area. We think it is very important to study structural analysis on micro scale(outcrop scale). On the other hand, Crust Dynamics project(new academic) is in progress at this area. And ultra-high density observation of aftershocks has been measured. In this study, we aimed to reveal developing process of earthquake source fault in macro scale, and focused on the following three themes.

(Ⅰ)Structural and chemical analysis in the fracture zone outcrop

At west of the Ryokusui lake(Saihaku-gun, Nanbu city), we found out large fracture zone(about 15m length, 2m width) after the outcrop cleaning. In this outcrop, brittle fracture zone along the boundary of the Neu granitic rocks(Cretaceous) and rhyolitic intrusive rocks(Neogene, Miocene) is identified. And we can observe basaltic intrusive rocks in the area. Fault gouge and cataclasite are identified inside of the fracture zone. At this outcrop, we performed the description of the detailed sketch and structural elements, and collected fault rocks to do structural and chemical analysis.

The result of the analysis, it was clear that fracture zone was formed by left-sense because of the developed Y-P-R1 fabric. We can observe calcite vein or fragment. Kaolinite, vermiculite, and chlorite are included well, and illite contains small amount. Tendency of smectite rich was confirmed in the gouge zone.

(Ⅱ)Occurrence of intrusive rocks in the vicinity of ryokusui lake

We tried to grasp the relationship between the distribution of rhyolite dikes, deformation structures and fracture zone in contact with the northern margine of the fracture zone.

Rhyolite has developed a flow structure. We concluded that the rhyolite from the asymmetric structure in the flow structure was approximately intrusion from the east direction to the west direction. Newly we discovered basalt dikes in contact with the northern margine of the rhyolite. In the observation under the microscope, organization of basalt fragments included the fault rocks is very similar to this dikes organization. In addition, we discovered the fracture zone extension in the swamp and slope in the west of the outcrop. As a result, the distribution of fracture zone with the dike is likely to be extended more than 10m to the west.

(Ⅲ) Volcaniclastic rocks around Mt.Yogai

A study of around Mt.Yogai, purpose of relationship of (Ⅰ) Fault and small fault of Hossh-ji F., and intrusion time of the intrusive rock of (Ⅱ).

Lithology of Hossh-ji F. is composed of a lapilli tuff phase and welded tuff phase. Thickness and distribution of this formations are not known. In addition,there is a gravel of fine basalt like the intrusive rocks of (Ⅱ) from a small outcrop of Mt.Yogai northwest.

Lapilli tuff phase, there is a small fault of a few mm ~ number of cm. Then, which is a conjugate relationship.

Considering host rock of fault rocks, texture and array of intrusive rocks, we presume the rhyolitic dikes intrusion event after the basaltic dikes intrusion event around this outcrop.

Fracture zone is developed at the boundary of granite and dikes, which had been already shown in the large number point(Aizawa et al, 2000 ; Manaka et al, 2012). In this study, theme (Ⅰ) and (Ⅱ) are proved it. This outcrop is located in the after shock area, and it is presumed to be located about 10m north side of the surface earthquake fault(Aizawa et al, 2000). Since shear sense are both left-lateral strike slip, they may have a common geometry. During the activities of the fracture zone, they might have experienced the movement of fluids involved in the generation of clay mineral and calcite vein. It is concluded that activity time is after the intrusion of the basalt and rhyolite, deposition of the pyroclastic rocks(Miocene), and continuing until now.

Keywords: Western Tottori Earthquake, immature active fault, fault rock, fracture zone, clay mineral, intrusive rock

