Measurements of the elastic wave velocities under the high P-T conditions and estimation of the crustal composition

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The knowledge of rock composition is significant to understand the dynamics of the lithosphere in subduction systems. To estimate rock composition of the lithosphere, it is an effective method to compare the elastic wave velocities measured under the high pressure and temperature condition with the seismic velocities obtained by active source experiment and earthquake observation. Until now, various crustal rocks have been determined by means of high P-T measurements [e.g., Christensen and Mooney, 1995]. However, rock composition of the overriding plate is still poorly understood.
Due to an arc-arc collision in central Hokkaido, middle to lower crust is exposed along the Hidaka Metamorphic Belt (HMB), providing exceptional opportunities to study crust composition of an island arc. We collected rocks at Hidaka Mountains and have tried to simultaneously measure the travel times of the P and S waves through a rock sample under high P-T conditions using a piston-cylinder apparatus at Yokohama National University.
Comparing with the velocity profiles across the HMB (Iwasaki et al., 2004), we estimate that the lower to middle crust consists of amphibolite and tonalite, and the estimated acoustic impedance contrast between them suggests an existence of a clear reflective boundary, which accords well to the obtained seismic reflection profile (Iwasaki et al., 2014). And, we can obtain the same tendency from comparing measured V_p/V_s ratio and V_p/V_s ratio structure model (Matsubara and Obara, 2011).

Keywords: Elastic wave velocity, P wave velocity, S wave velocity, High P-T condition, Hidaka Metamorphic Belt

3D Electromagnetic imaging of the deep structures and North Anatolian Fault in the Marmara Sea

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In this study, we perform 3D modeling of the electromagnetic data to investigate major tectonic structures beneath the Marmara Sea. The Marmara Sea and surrounding region located in northwestern Turkey were formed as a result of closure of the Tethys Ocean and following extension and strike-slip regimes. This region accomodates the northwestern branch of 1600 km long North Anatolian Fault (NAF) that represents the main transform boundary in Turkey. NAF runs parallel to the northern coast of Turkey and reaches to the Marmara Region as three branches. Historical seismicity catalogues suggest a westward migrating pattern of destructive earthquakes along the NAF as well as a seismic gap within the Marmara Sea. Following the last two devastating earthquakes (1999 Izmit and Duzce earthquakes) that occurred at the eastern edge of the Marmara Sea, an increase in seismic energy on the Marmara Sea branches of the NAF have been monitored. Although the NAF and its branches on land are well investigated, their lateral and vertical extension within the Marmara Sea still remains elusive. Our knowledge of the continuation of tectonic structures in the Marmara Sea has a crucial role on understanding stress accumulation and geodynamic evolution after closure of the Tethys Ocean that has not been well uncovered yet. Earlier on- and off-shore magnetotelluric (MT) studies showed that MT method could be very efficient tool for the investigation of electrical resistivity variation that is now considered to be an important parameter to reveal tectonic structure of the Marmara Sea. Thus, we performed the MT method using ocean bottom electromagnetic (OBEM), wide-band and long period MT data set collected within and around the Marmara Sea. Totally at 27 sites continuous electric and magnetic fields were recorded. Phase tensor analysis and induction arrows show complexity of the structure especially at shallow depths and indicate that a 3D analysis of the data is required. They also represent existence of conductive anomalies beneath the Marmara Sea. 3D modeling results indicate high conductive anomalies, which are separated by resistive zones laterally, at crustal and upper mantle depths. Locations of these resistive-conductive boundaries clearly imply the trace of the NAF on land. Conductive and resistive zones can mark the regions with fluid rich and fluid free zones, respectively, and those regions are considered either to triggger easily a large earthquake or accumulate stress in the brittle zone of the crust. Resistivity variations resolved in this 3-D MT modelling study imply a continuation of the tectonic zones underneath the Marmara Sea in a similar fashion as observed from earlier 2-D modelling of land stations in the east.

Keywords: Magnetotelluric, Marmara Sea, North Anatolian Fault, Resistivity, Crust/upper mantle, Tectonic

Seismic velocities and electrical conductivity at upper- and mid-crustal depths - an inferrence from pore structures

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Geophysical observations have been conducted to study the composition, structure and dynamics in the island-arc continental crust. Detailed profiles of seismic velocity and electrical conductivity have suggested that fluids (mostly aqueous fluids) exist pervasively within the crust. Spatial variations in velocity and conductivity are primarily attributed to a spatial variation in the fluid volume fraction. Cracks must be a key component of pores to govern velocity and conductivity at upper- and mid-crustal depths. Based on laboratory experiments, most of cracks have aspect ratios of less than 10^{-3}. The variation in velocity must be caused by that in fluid volume fraction of 0.1%. The spatial variation in conductivity is often up to 4 orders of magnitude. This large conductivity change must occur within a narrow range of the fluid volume fraction. If the connectivity of fluid is identical, the conductivity is proportional to the fluid volume fraction. A small change in the fluid volume fraction cannot make a change of orders of magnitude. The large change in conductivity requires the increase in connectivity of cracks with increasing fluid volume fraction. I will discuss about the connectivity of grain boundary cracks and its implications for seismic velocity and electrical conductivity.

Keywords: seismic velocity, electrical conductivity, pore structure

High resolution color holography of the crustal structures by means of elastic and electromagnetic ACROSS: A perspective view

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ACROSS is an acronym of ‘accurately controlled, routinely operated signal system’, which is being used to detect the subtle temporal variation of the underground structures by elastic wave signal. Whereas seismic ACROSS has been deployed at serval sites, complementary electromagnetic ACROSS has not been payed attention to be implemented. Furthermore, currently operating seismic ACROSS does not appear to exert its high potentiality expected theoretically. Recognizing the substantial potentiality of the simultaneous implementation of both seismic and electromagnetic ACROSS, the present author has kept working with several coworkers towards the better implementation strategy of ACROSS technology.
Recently (2014) we convinced to have found a reasonable way to utilize the potentiality of ACROSS, and started to work with ERI and ELSI (TITECH) to design the detailed tactics and strategy. We have a set of two important factors: (1) designing of implementation technology of ACROSS and (2) development of an ‘operational digital wave theory’ expected to enable us to invert the big data acquired by ACROSS to ‘color holography movie of anisotropy’.
The current state of technology and its prospect are reported in this presentation.
(1) A dense array of both seismic and magnetic sensors combined with a sparse transmitter array of seismic and electromagnetic waves would provide us with such observation data on anisotropy and color (frequency dependence) holography of the crustal structures. As a matter of course, spatial resolution of color and anisotropy depends on the designing of the observation system, frequency range of operation, and also on the time period of data acquisition.
(2) An operational digital wave (ODW) theory developed in this work is quite different from the routine method commonly used on the basis of finite difference approach on wave equation with a weak form. By introducing a hyper-function calculus, differential equations of both elastic and electromagnetic waves are converted to the algebraic equation in wavenumber space in ODW theory. By introducing a sequence of finite discrete coordinates, an efficient iterative innovation strategy is realized for both forwards and inverse computations.
A set of ACROSS technology and ODW theory would promote the transition of the current ‘phenomenological dynamics’ to the qualified dynamics based on the physical properties of material under tectonic stress with sound physics and observation background. A good test field may be the source area of the 2000 Western Tottori Earthquake, where fluid migration dynamics along the subsurface fault zone may be traced through the observation of temporal variation in the anisotropy of conductivity and polarized shear wave velocities. Note that the high quality observation is essential for the modern tectonics studies.

Keywords: ACROSS

Mechanical response of polycrystalline rock during hydration reactions –Experimental investigation of reaction-induced stress and strain in $CaSO_4$-H_2O system–

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Dehydration and hydration reactions deep in the Earth control the water budget in the subduction zone system. Hydration reactions in particular, associate large solid volume changes. Such solid volume changes can induce large stress by the release of Gibbs free energy during the reactions, which can be larger than the strength of rocks and generate fracturing. However, whether the volume change in hydration reactions causes fracturing, enhance fluid flow and promote further hydration reactions, or it fills in the pores, reduces fluid flow and suppresses further hydration, is largely unconstrained. Here we explored mechanical responses of polycrystalline rock through hydration reactions $CaSO_4 + 2\ H_2O \rightarrow CaSO_4 \cdot 2H_2O$.

Although the samples have high porosity (ø = 20–35%), direct measurement of reaction-induced strain under constant load experiments revealed that reaction-induced bulk strain does occur under loadings of 0.01–10 MPa. The increase of loading enhances deformation mechanisms such as pressure-solution creep, and the amount of reaction-induced bulk strain decreases. Constant volume experiments revealed that reaction-induced stress increases linearly with reaction rate. These results suggest that the mechanical behavior during hydration reaction is primary controlled by the competition between the reaction rate and deformation rate.

Keywords: Reaction induced stress, Hydration reaciton, Mechanical behavior

Fluid path in the lower crust

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The Role of geofluids on geodynamics and earthquake generation has long been investigated. It is well known that high pore pressure can reduce the strength of seismogenic faults, and that strain rates increase with high water contents within ductile faults below the seismogenic layer. Furthermore, it is thought that these phenomena are originally related to geofluids upwelling from subducting oceanic plates. The physical and/or chemical processes concerning these phenomena are clear, however, direct evidence about them in the real crust has been rarely obtained until now. In this study, in order to clarify geofluid paths from mantle to seismogenic faults and its role on earthquake generation, we estimated detailed crustal structures mainly by an S-wave reflection analysis using waveforms of natural earthquakes. Since we used the data from the dense seismic network operated by the “manten” project, we estimated relative reflection strengths with a very fine scale of 1.5km in the lower crust.
It is found that near the Moho discontinuity, regions of high reflection strengths are limited at several sites in a region of about 50km x 50km in the central to northern Kinki district in Japan. Further, it is found that low frequency earthquakes (LFE) occur near most of those regions near the Moho discontinuity, and that high reflectivity regions extend from those locations of LFE to the seismogenic fault. These results suggest that fluid paths are limited from mantle to crust and that low frequency earthquakes can be an index of these fluid paths.

Keywords: fluid, lower crust, low frequency earthquake, fault, reflector

Compositional variations of the Arima-type and associated spring waters in the Kinki district, southwest Japan: Implications for origin and upwelling process of deep brine

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Rare earth elements (REEs) of the spring waters upwelling in the non-volcanic fore-arc region of the Kinki district in southwest Japan have been investigated to assess their upwelling processes and deep-seated origins [Nakamura et al., 2014; 2015]. In this study, a principal component analysis of the REE data has identified three principal components (PCs) that cover 89% of the entire sample variance: (1) PC-01, which corresponds to a dilution process by which fluids are introduced at low concentrations, previously represented by major solute binary trends, including $\delta^{18}O$–δD systematics; (2) PC-02, which is a precipitation process of REEs from the brine; and (3) PC-03, which is an incorporation of REEs from country rock by carbonic acidity, although the types of country rocks may also have a significant impact on the spring water compositions. Based on these three PCs, together with the major solute concentrations and hydrogen, oxygen, and helium isotopic compositions determined in previous studies, five distinct types of spring waters in the Arima and Kii areas have been identified: (i) “Tansansen”, (ii) “Kinsen”, (iii) “Ordinary Arima”, (iv) “Ginsen”, and (v) “Eastern Kii”. These five types probably represent (ii) a deep brine, (iii) an evolved deep brine that precipitated REE-bearing minerals, (iv) a mixture of (iii) and meteoric water, (v) a meteoric water carbonated by deep gas derived from (ii), and (i) a spring water similar to (v) with a more significant influence of the country rock constituting the aquifer.
A comparison of the spring waters in the Arima and Kii areas revealed a systematic geographic distribution. The “Ordinary Arima”-type occurs along the Median Tectonic Line, and the “Eastern Kii”-type occurs in the eastern part of the Kii area. The latter seems to upwell in the restricted region where deep low-frequency tremors are observed. We suggest that the geographical distributions are linked to the tectonic setting and/or temporal evolution of fluid upwelling.

Keywords: Arima-type, spring water, slab, tectonic line, geofluid

Fluid flow in the southern termination of the Bolfin fault of the Atacama Fault System, northern Chile

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The NNW-striking subvertical Bofin fault is part of the Atacama Fault System (AFS), which is a large-scale trench-parallel structure developed within mesozoic rocks of the present-day Coastal Cordillera in northern Chile (Cembrano et al., 2005). A well-documented left-lateral activity of the AFS has been interpreted as the result of the SE-ward oblique subduction of the Aluk (Phoenix) oceanic plate between 190 and 110 Ma (e.g., Schuber and González, 1999).
The studied area is in the southern termination of the Bolfin fault, where the fault terminates in a distributed network of low-displacement strike-slip fault zones in a horsetail-type structure (Faulkner et al., 2011). A number of NNW-striking subvertical fractures filled mainly by calcite and quartz are observed in the area. They are 1-20 mm in width and hosted by coarse-grained metadiorite. Some of them cut a thin (~ 10 cm) NW-striking subvertical leucocratic dike with 20-35 mm left-lateral displacements, while the others disappear at the southwestern wall of the dike. A fracture density (number of fractures (> 3 mm in width) per 1.8 m) is 11 in the southwestern host rock of the dike, while only 4 in the northeastern host, indicating NNW-ward propagation of the fracture tips. Faulkner et al. (2011) also concluded that the asymmetry of the damage (alteration) development around the fractures implies northwest propagation if a process zone model is assumed. Green-colored hydrothermal alterations are well developed around the fractures in the southwestern host of the dike, while they are poor in the northeastern host. It is also remarkable that the host metadiorite at the southwestern wall of the dike is strongly altered, while no alteration can be seen at the northeastern wall. Those evidences may suggest that the dike acted as a fluid-barrier during fluid flow through the fractures migrating from the south. Hence, we may conclude that the fluid flow, as well as the fracture propagation, was toward the north, that is, toward the main body of the Bolfine fault.
Although the host metadiorite is highly weathered and altered by hydrothermal fluids percolating through the fractures, it might have consisted mainly of plagioclase and hornblende. On the other hand, chlorite, epidote, calcite and quartz are major in the altered rocks around the fractures. The bulk chemical data obtained by XRF analyses of the rocks indicate that CaO and SiO_2 were added as 2.77 and 4.21 moles, respectively, per a littler of rocks during alteration, while Na_2O, K_2O, Mg_2O and Al_2O_3 were partly removed. Chemical compositions of chlorite in equilibrium with quartz analyzed by EPMA indicate their formation temperatures as around 330°C. On the other hand, microthermometric analyses of fluid inclusions in calcite of the fractures show their homogenization temperatures as about 280°C with a modal salinity of 11.3 wt.% ($CaCl_2$ eq.). Hence, the pressure obtained on an isochore for the brine is 69 MPa. The pressure is consistent with the study of González et al. (2003) in which they noted that the fault has been passively exhumed from depths greater than 3 km.
We simulated the fracture-filling by precipitation of calcite and quartz from the fluids infiltrating through the fractures at the above P-T conditions by MIX99 (Hoshino et al., 2000). The fluids were assumed as equilibrated with calcite, quartz, epidote and chlorite. The compositions of epidote and chlorite were taken as ideal solid solutions of epidote (0.60) - clinozoisite (0.40) and daphnite (0.55) - clinochlore (0.45), respectively, from EPMA data. The result indicates that

86 kg of fluids are needed to fill a litter of space (fracture aperture) with a temperature decrease from 340°C to 330°C. Therefore, a huge amount of fluid might have percolated through the fractures toward the main body of the Bolfin fault.

Keywords: fault, fluid, fracture

Dynamic interaction between mantle convection and water transportation in subduction zones

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The effects of water on subduction dynamics, e.g., plate migration rate, slab geometry, stress field, and back arc spreading, are investigated by using a 2-D self-consistent model for lithosphere subduction and whole mantle convection. We solve water transportation coupled with hydrous mineral phase changes. Mantle flows and water transportation are interactive through constitutive and state equations for hydrous rocks. Our model has successfully reproduced the water distribution in a mantle wedge and along the slab with sufficient resolution comparable to that of previous models that focus on the mantle wedge structure. As a result, low density owing to hydration reduces subduction rates, back arc spreading, and slab stagnation on the phase boundary at 660-km depth, whereas low viscosity owing to hydration enhances rapid subduction, trench migration, and slab stagnation. We attribute these results to mechanisms that cause the hydrous buoyancy of subducting plates to reduce the slab pull force and the accompanying tensile stress on overlying lithosphere. In addition, hydrous weakening diminishes the mechanical coupling of the subducted slab with the wedge mantle and overriding lithosphere. Thus, water is capable of generating two opposite situations in the stress field of the overlying lithosphere and the subduction rate. Water is therefore expected to be an important mechanism for generating broad styles of the subduction structure and kinematics, as observed in actual subduction zones such as Tonga and Mariana, comparable to other tectonic forces such as overlying plate motion. Water in the mantle is thus a key to a better understanding of the whole mantle-scale slab dynamics as well as island arc volcanic processes.

Keywords: water transportation, free convection, subduction dynamics, plate velocity, stagnant slab, trench migration

Evolution of the Median Tectonic Line, Mie Prefecture, south-west Japan and implication for weakening in a large-scale fault zone: a tentative model

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The Median Tectonic Line (hereafter referred to as the MTL) extends from eastern Kyushu to the Kanto mountains, north-west of Tokyo, over 800 km throughout south-western Japan, and the largest scale tectonic line in Japan. Although the structural development of the MTL is complex, the proto-MTL, which was originally formed as a granitic mylonite belt in the Ryoke belt of the inner belt of southwest Japan, was formed when the Sambagawa metamorphic rocks in the outer belt of southwest Japan were exhumed and juxtaposed against the granitic mylonite belt in the Ryoke belt at 63-58 Ma (Ichinokawa phase). Therefore, the MTL was originated as a large-scale normal fault (e.g. Kubota and Takeshita, 2008).
In the eastern part of Mie prefecture, the MTL was not reactivated in the Quaternary period, and hence the proto-MTL is relatively well preserved. We have worked on the MTL in this area to elucidate structural development and weakening processes in a large-scale fault zone since 2014. As a result, we have found some preliminary new facts, which will be presented here. (1) In the study area (Tsukide district, Matsuzaka-city, Mie prefecture), the MTL consists of a few segments each of which trends east-west and dips north at moderate angles, and extends for 0.5 to 1 km. The eastern end of each normal fault segment is stepped to north by c. 70 m (fault jog), and the two fault segments separated by a jog could have been connected by a transfer fault. The upper plate of the MTL consists of cataclasite (i.e. fault core) of c. 70 m thick originated from granitic mylonite, and further overlain by fractured protomylonite (fault damage zone). It should be noted however thin anastomosing cataclasite zones are developed in the protomylonite. (3) Cataclasite was developed into foliated cataclasite with increasing displacement, and the cataclasite developed along the MTL contains clasts of ultramylonite (Jefferies et al., 2006). (4) In the fractured protomylonite, pulverized rocks, which could have been formed by rupture events at the time of earthquakes, have been found. Based on the observation mentioned above, we will discuss the structural development and associated weakening in the MTL fault zone below. The MTL was originally formed as east-west trending many short segments during large-scale normal faulting, which were linked with each other, and further developed into a wide cataclasite zone with increasing displacement. When the MTL was originally formed, the differential stresses were built up to the level expected from rock deformation experiments of intact rocks, generating ultramylonite. However, once cataclasite was formed by seismic faulting, fluids migrated into the MTL fault zone resulting in the formation of mica and clay minerals, which not only facilitated sliding along the MTL by lowering the coefficient of internal friction in rocks, but also operation of pressure solution creep. This series of processes significantly weakened rocks in the MTL fault zone. Textures in foliated cataclasite are very similar to those of weakly metamorphosed rocks (semi-schists), indicating dissolution and precipitation were dominant in these rocks. When the cataclasite zone was weakened, the stress buildup leading to the generation of earthquakes no longer occurred there, which results in the stress concentration in the surrounding rocks, where earthquakes occurred. The hypothesis that this series of processes is repeated in the MTL fault zone, resulting in the increase of thickness of the cataclasite zone can well explain the facts that ultramylonite clasts are contained in the cataclasite zone, and evidences for seismic faulting (i.e. pulverized rocks), which initiated the formation of cataclasite, are observed in the protomylonite in direct proximity to the cataclasite zone.

Keywords: Median Tectonic Line, weakening in a large-scale fault zone, cataclasite, pressure solution, pulverized rocks

Kinematics and K-Ar geochronology of the Median Tectonic Line of western Shikoku, south-west Japan.

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For the long time span of the Paleogene period (66-26 Ma), the fault movement along the MTL (Median Tectonic Line) has not been fully clarified. Kubota and Takeshita (2008) inferred that Paleogene kinematic history of the MTL is divided to 63-58 Ma (Ichinokawa phase) and 45-25 Ma (Pre-Tobe phase). Based on the deformation structure along the MTL of map, outcrop, and section scale, our study indicates that Ichinokawa phase is the large scale normal faulting of MTL(Kubota and Takeshita, 2008), and Pre-Tobe phase is the left lateral slip and top to the south of faults parallel to the trend of the MTL, the Okamura, Kawakami, Shigenobu, and Iyo Fault, and northern part of the MTL in the western Shikoku (Kubota and Takeshita, 2015). Kinematics of the MTL in Paleogene is gradually elucidated, however it is necessary to study more detailed the movement periods. Previous studies, the K-Ar age measurements of fault gouge along the MTL show peaks of ages at ca 60Ma (e.g. Shibata et al. 1989) , but there is little of a measurement showing the multiple movement phase.

The purpose of this study is to date the fault movements, it carried out that the K-Ar age measurements of fault gouge sampled at area avoided overlapping deformation of movement phase divided by the investigation of map, outcrop, and section scale. The measurement object intends for authigenic illite produced by the fault movement. The problem of this measurement method is that it is difficult to separate only authigenic illite from sample, because it consists of detrital illite in samples of fault distributed in wall rocks of sedimentary rock. Therefore, the measurements are the mixed age and become the measurements that are older than the age of the fault movement. We are going to estimate the true age of fault movement by analyzing the polytype. In addition, it intend to analyze the change of ages by the particle size and the polytype quantification based on dating of illite of 3 fraction (0.2-0.4, 0.4-1.0, 1.0-2.0μm) for 1 sample. It shows result of the K-Ar age measurements before the analysis of polytype (Table1). Based on the K-Ar age measurements, it is expected to understand the periods of Ichinokawa phase and Pre-Tobe phase in more detail.

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Keywords: Median Tectonic Line, Paleogene, Kinematic history, K-Ar geochronology

Table 1 Result of K-Ar dating

	Sample No.	Mineral	Grain size (μm)	K content (wt.%)	Rad.^{40}Ar (10^{-8}cc STP/g)	K-Ar age (Ma)	Non-rad.^{40}Ar (%)
Okamura Fault	OK-1-A3	illite	0.2-0.4	5.886 ± 0.118	1054.6 ± 11.3	45.6 ± 1.0	9.0
			0.4-1.0	5.822 ± 0.116	1069.7 ± 11.5	46.7 ± 1.0	8.1
			1.0-2.0	5.562 ± 0.111	1046.2 ± 11.0	47.8 ± 1.1	7.6
	OK-1-A5	illite	0.2-0.4	4.927 ± 0.099	791.7 ± 10.0	40.9 ± 1.0	19.5
			0.4-1.0	4.900 ± 0.098	794.0 ± 9.8	41.3 ± 1.0	18.9
			1.0-2.0	4.871 ± 0.097	802.0 ± 9.8	41.9 ± 1.0	18.5
Shigenobu gawa F.	SG-2-A3	illite	0.2-0.4	5.990 ± 0.120	1410.0 ± 15.3	59.7 ± 1.3	9.5
			0.4-1.0	5.620 ± 0.112	1453.6 ± 15.4	65.5 ± 1.5	8.0
			1.0-2.0	5.149 ± 0.103	1403.9 ± 14.9	68.9 ± 1.5	7.4
Kawa kami F.	YY-1-A4	illite	0.2-0.4	5.917 ± 0.118	1589.7 ± 16.3	67.9 ± 1.5	4.6
			0.4-1.0	5.415 ± 0.108	1592.4 ± 16.3	74.2 ± 1.6	4.8
			1.0-2.0	5.046 ± 0.101	1485.5 ± 15.3	74.3 ± 1.6	5.5
MTL	YA-1-A1	illite	0.2-0.4	6.495 ± 0.130	1288.0 ± 13.4	50.4 ± 1.1	6.3
			0.4-1.0	6.229 ± 0.125	1336.5 ± 13.9	54.5 ± 1.2	6.2
			1.0-2.0	6.080 ± 0.122	1327.5 ± 13.7	55.4 ± 1.2	5.9

K-Ar dating of fault movement in clay rich gouge: an example from the Alpine Fault at Gaunt Creek and Waikukupa River, South Island, New Zealand

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The occurrence of synkinematic and authigenic clay minerals, in particular illite, is a common feature in neotectonic fault gouges. Numerous attempts have been made to date fault gouges [see summary in Zwingmann et al., 2010]. We present new age data for synkinematic illite growth in two fault gouges from surface exposures of the Alpine Fault at Gaunt Creek and Waikukupa River, South Island, New Zealand. The Alpine Fault in the South Island of New Zealand marks the Australian-Pacific plate boundary. An amphibolite-facies mid-crustal ductile shear zone (mylonite series rocks) in the Pacific Plate hanging wall is exhumed along a current brittle fault marked by cataclasite and fault gouge.

Size separation combined with mineral characterization (SEM, TEM, XRD, LPS) enables to identify suitable samples for isotopic dating. Investigations of two <2 micron illite gouge separates from fault gouge samples collected from surface exposures at Gaunt Creek and Waikukupa River yield K-Ar ages of resp. 4.1 ±0.4 and 1.9 ±0.2 Ma, corresponding to the late Pliocene. K-Ar illite ages are consistent with well-defined field constraints and within error similar to c. 1 to 2.5 Ma 40Ar/39Ar ages for micas from hanging wall metapelites and amphibolites and to published K-Ar mica and near-zero apatite fission track ages. The corresponding illite and mica ages suggest that hanging wall rocks were rapidly exhumed and cooled c. 1 –4 Ma ago with coeval exhumation resulting to extensive hydration in the brittle part of the Alpine Fault documented by illite authigenesis. Argon diffusion modeling supports the cooling timeframe. The ages of fault gouge illite provide absolute time constraints on the youngest, retrograde, neotectonic movements on this part of the Australian-Pacific plate boundary. This study highlights the potential of isotopic dating of synkinematic illite to determine upper crustal deformation events.

Zwingmann *et al.* 2010. Geology, v. 38, no 6, 487-490; doi10.1130/G30785.1

Keywords: fault gouge, Illite K-Ar dating, New Zealand

Development of shear zones in the lower crust: Eidsfjord shear zone, northern Norway

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Mode of occurrence and deformation mechanism of shear zones developed in the lower crust are crucial to understand the rheological properties and generation mechanisms of inland earthquakes of the continental crust. We studied the mode of occurrence of shear zones and collected many rock samples, including cataclasite, mylonites and pseudotachylytes in Langøya, Lofoten Islands, northern Norway. According to the previous studies (e.g. Markl 1998, Plattner et al. 2003; Steltenpohl et al. 2011), this area includes a crustal-scale detachment fault (Eidsfjord shear zone) and a zone of many pseudotachylytes (Heier's zone of pseudotachylytes), and then one of the best places for clarifying the deformation process in the lower crust.
In the studied area, coarse-grained anorthosites (Eidsfjord anorthosite) and monzonites are widely exposed (Markl 1998). In these rocks, several centimeters to meters wide coarse- or fine-grained mylonites develop locally as ductile shear zones. The coarse-grained mylonites consist mainly of plagioclase (mean diameter of ~85 μm, up to 350 μm), Cl-rich amphibole, epidote, biotite, muscovite and quartz, with minor kyanite. The fine-grained mylonites are comprised of plagioclase (mean diameter of 42 μm), Cl-rich amphibole, biotite, muscovite, scapolite, garnet and quartz, with minor kyanite and apatite. Plagioclase grains in the coarse-grained mylonites slightly elongated with the aspect ratio of ~2, whereas those in the fine-grained mylonites are polygonal. In the coarse-grained mylonites, fragmented plagioclase porphyroclasts are found. Within the porphyroclasts, there are fracture zones filled with fine-grained plagioclase, suggesting that fracturing and fragmentation is a dominant process for grain-size reduction in these rocks. Anorthite contents of porphyroclastic plagioclase differ from those of matrix grains; the former has higher values than the latter. The fine-grains in the intracrystalline shear zones have the same values in An content with the host porphyroclast. Utilizing the results of the conventional thermobarometers of Kohn and Spear (1990) and Holland and Blundy (1994), pressure-temperature conditions for the formation of the metamorphic minerals during deformation are estimated to be ~700 °C and ~800 MPa. Based on the EBSD analysis, plagioclase aggregates in the matrix of the fine-grained mylonite and in the coarse-grained mylonite do not show any distinct lattice-preferred orientation (LPO), suggesting their deformation mechanism of grain-size-sensitive creep (i.e. diffusion creep or grain-boundary sliding). The results of the study imply that the deformation process to form the mylonites includes (1) fracturing and fragmentation, (2) Influx of Cl-rich fluid, (3) hydration metamorphism, and (4) grain-size-sensitive creep. Furthermore, it suggests that grain-size-sensitive creep may dominate even in relatively coarse-grained plagioclase aggregates with mean grain size of ~80 μm.
References: Holland and Blundy (1994) Contrib Mineral Petrol116:433-447; Kohn and Spear (1990) Am Mineral 75:89-96; Markl (1998) NGU Bull 434:53-75; Plattner et al. (2003) Contrib Mineral Petrol 145:316-338; Steltenpohl et al. (2011) J Struct Geol 33: 1023-1043

Keywords: Rheology of the Lower crust, Gabbroic mylonite, Deformation mechanism

Shear strain concentration mechanism in the lower crust below an intraplate strike slip fault based on rheological laws of rocks

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The existence of the shear zone in the lower crust under an intraplate strike slip faults has been suggested by many studies. To understand the structural characteristics of the shear zone in the lower crust under an intraplate strike slip fault (slip rate of 1mm/yr) and its temporal evolution in a geological time scale, we have been conducting 2-D numerical experiments. In our previous study (Zhang and Sagiya, 2015), stress singularity appears at the bottom of the upper crustal fault where stepwise velocity was assigned as a boundary condition. To avoid the stress singularity, we introduce a yield threshold in the brittle-ductile transition. We also add the fault fictional heating to better evaluate the amount of heat generation due to fault activity.
Calculation with wet anorthite rheology show that the viscosity of the brittle ductile transition is about 10^{22} Pa*s. The brittle-ductile transition is located approximately at 19 km depth, consistent with the cut-off depth of seismicity in the continental crust. On the other hand, for dry anorthite, the depth of the brittle ductile transition exceeds 25km. Therefore water is of importance in making the lower crust weak. Calculated temperature rise for 3Myrs is 15 K for wet anorthite and 22 K for dry anorthite, much smaller than a case of interplate fault (e.g. 30 mm/yr slip rate). Frictional as well as shear heating has very limited effects on shear localization under an intraplate strike slip fault. Grain size is another factor that controls the rheology of the lower crustal rock. While grain size determines the effective viscosity of diffusion creep, grain size varies both in time and space as a result of dynamic recrystallization and dislocation creep. In our calculation, grain size obtained from a stress dependent constitutive law ranges from several micrometers to several millimeters. On the other hand, grain size determined by balancing the shear strain rate of diffusion and dislocation creep ranges from several tens of millimeters to several centimeters. These results provide constraints on the physical mechanism of ductile flow in the lower crust through comparison with the rock sample originated from the lower crust. Our model suggests that for intraplate strike slip fault, lower crustal shear zone is produced by the stress dependent nonlinear rheology and shear and frictional heating has negligible effect on the deformation of the shear zone.

Keywords: Lower crust, shear zone

Contrasting low and high speed exhumation and metasomatic banding in the Sambagawa metamorphic belt

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Contrasting low and high speed exhumation and metasomatic banding in the Sambagawa metamorphic belt
Toriumi, M. (OELE, Jamstec)
The author studied spherical transformation of quartz in albite porphyroblasts in the Sambagawa metamorphic belt in central Shikoku at 1979 and he concluded that the process is controlled simply by boundary diffusion of oxygen of albite and quartz for reducing the interfacial free energy (1). The critical spherical size of quartz inclusion in albite is then estimated by diffusion coefficient and annealing time by their 0.25 power index. Thus the critical spherical size is the potential annealing time under the given temperature.
The author thus, measured the systematic change of the critical sizes of quartz inclusions in albite of metamorphic rocks along the Asemigawa route of central Shikoku, and obtained the general trend of the increasing size by metamorphic temperature. On the other hand, the critical sizes of the highest temperature zone suddenly change the very smaller values than those of the other grade rocks, suggesting the highest grade zone rocks exhumed very rapid rather than surrounding lower grade rocks.
This enigma has not been possibly answered by any model of metamorphic exhumation. However, recent studies of high grade metamorphic terranes revealed that there are abundant dendritic grains of aplitic minerals in so-called felsitic inclusions or nanograinte inclusions in metamorphic garnet (2) (3). Therefore, it is inferred that there are a few blocks or sheets of higher grade metamorphic rocks rapidly intruded into the surrounding metamorphic belt.
The mechanism of these contrasting two exhumation at the same belt is modeled by the viscous drag to friction drag exhumation governed by fluid concentration along on the fluid concentrated faulted narrow zones. Such fluid filled damage zones are evidenced by the large scale abundant metasomatic bands in the boundary zones as described in this paper.
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Keywords: rapid exhumation of metamorphic rocks, annealing time of metamorphic rocks, metamorphic banding

Tectonic stress and fault rock fabrics in the vicinity of the Alpine Fault inferred from DFDP-2 borehole televiewer (BHTV)imagery

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The Alpine Fault is the primary structure accommodating Australia-Pacific plate motion in South Island, New Zealand. Paleoseismic studies have revealed that the fault is late in its seismic cycle. One of the aims of the Alpine Fault, Deep Fault Drilling Project (DFDP) is to reveal the ambient conditions before an earthquake. Stress around the fault is one of the targeted measurements.
Previous stress estimates based on focal mechanism analysis of the principal stress orientations at seismogenic depths reveal a regional axis of maximum horizontal compressive stress trending approximately 115°. However, seismicity adjacent to the Alpine Fault is sparse and does not constrain the stress field close to the fault.
The analysis of planar features revealed in BHTV logs collected during DFDP-2B drilling provides an opportunity to examine stresses in the hanging-wall of the Alpine Fault. 2244 planar features were detected in BHTV logs, and 1680 of them are classified as fractures. Here we present the results of stress analysis utilizing detected fractures.
We compute stress parameters using the Hough transform method, which enables us to make use of faults even if they do not contain slip directions. For this analysis, we assume that all fractures used in the calculation are representing reverse fault motion in response to a single homogeneous stress tensor, and that factures with similar geometries to the Alpine Fault accommodated similar top to the west shear.
The analysis of the dataset as a whole yields orientations (trend/plunge) for the maximum and minimum compressive stress axes S_1 and S_3 of 124/30 and 023/19 (±30°), respectively and a stress ratio of $(S_2-S_3)/(S_1-S_3)$= 0.288. The maximum compressive stress axis, S_1 is slightly different from that estimated by focal mechanism analysis. The orientations are compatible with geologically determined horizontal shortening from analysis of small scale fractures within a few km of the fault trace.
Stress tensors were also determined for groups of fractures within 20 m depth intervals. In most of these groups, the results are similar to the solution for all depths. However, in depth intervals 720-740 m and 780-860 m, the calculated S_1 and S_3 orientations have respectively smaller and larger plunges, and stress ratios are larger.
The thermal profile of DFDP-2B has been measured by Distributed temperature sensing (DTS) using a fiber-optic cable. A thermal gradient changes at ~720 m depth. This depth corresponds to that where results of stress analysis are changed. [N1] Shear and normal stresses for the stress calculated from fractures across the entire depth range were plotted on 3-D Mohr diagram for fractures. In depth intervals 720-740 m and 780-860 m, many fractures oriented such that low shear stresses would be resolved on them.
Slug tests suggest higher fluid pressure in depth interval 780-860 m. It is known that unfavorably oriented faults can slip under high fluid pressure. There is a possibility that high fluid pressure causes the changing of the distribution pattern of fractures which results in the different

solutions of stress tensor inversion and different thermal gradient at the depths deeper than 720 m. To confirm the hypothesis that high Pf facilitates slip on unfavourably oriented faults at depth, we need to acquire complete fault slip data including the orientations of fault planes and slip directions from drill core samples.

Keywords: the Alpine Fault, borehole televiewer imagery, fault rock fabrics, Stress tensor

Paleo temperatures, depths and stresses evaluated using calcite twinning paleopiezometry

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Mechanical twinning along an *e*-plane in calcite occurs if the resolved shear stress along the gliding direction of the *e*-plane exceeds a critical value, τ_c, which is around 10 MPa (Lacombe, 2010). Based on this twinning condition, it is possible to devise inversion schemes to determine non-dimensional deviatoric stress tensors from the orientations of *e*-twin lamellae (e.g., Etchecopar, 1984). The tensor is defined as the deviatoric stress tensor divided by τ_c. However, most of natural calcite aggregates have experienced two or more tectonic phases, which had different stress conditions. Even in such a case the non-dimensional deviatoric stress tensors can be determined from a heterogeneous data set, and the number of the tensors to be detected is evaluated using Bayesian information criterion (Yamaji, this session).
On the other hand, the mechanical twinning results in the simple shear, the amount of which can be evaluated from twin density (e.g., Groshong, 1972). Deformation experiments have demonstrated that the incremental strain increases effective τ_c value. Lacombe (2010) compiled the results of such experiments to show the relationship among temperature, strain and τ_c.
Once the τ_c value is obtained, the depth where the twinning occurred can be estimated from the differential stress determined from the twin data, because the critical differential stress is proportional to depth in the brittle upper crust. Assuming an appropriate geothermal gradient, the depth can be converted to temperature. Based on the relationship by Lacombe (2010) and the deviatoric stress tensors obtained from the data, it is possible to define and solve the simultaneous equations of temperature, depth, deviatoric stress tensor and τ_c.
This method was applied to a calcite vein in a Miocene graben, which was formed during the Japan Sea backarc opening. The preliminary results are introduced in the presentation.

Keywords: geothermics, stress, vertical movements, exhumation

The nature and importance of minor faults developed in the Niigata-Kobe Tectonic Zone

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Recent GPS geodetic observations revealed inhomogeneous strain-rate pattern of the Japan Island (Sagiya et al., 2000, PAGEOPH), even in the back-arc region where the heterogeneously-coupled plate boundary condition may not be affected. The Niigata-Kobe Tectonic Zone (NKTZ), which trends northeast-southwest direction in central Japan, shows dextral movement of ~ 10 mm/y as detected by the dense GPS observations (Ohzono et al., 2011, Geophys. J. Int.). The NKTZ bearing three major active faults; the Ushikubi fault, the Atotsugawa fault, and the Takayama-Oppara fault. If we assume the elastic strain accumulated within the NKTZ is released by the slip along the active faults, short-term strain rate obtained by GPS observation should be equal to the total amount of long-term slip rates of the active faults. However, only about 50 % of the accumulated shear strain is released along the active faults. Here we demonstrate a field occurrence, distribution, mineralogy, and paleostress analysis of minor faults (off-fault damage) distributed in the NKTZ and propose these faults play an important role in the crustal deformation.

Keywords: Niigata-Kobe Tectonic Zone, Atotsugawa fault, C-class active fault, Paleostress analysis, Strain-rate paradox

Effect of crustal partial melting on tectonics of Japan Arc: Case study in the Niigata-Kobe Tectonic Zone (NKTZ)

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Niigata-Kobe Tectonic Zone (NKTZ) is the most conspicuous tectonically active area inside the Japan arc (Sagiya et al., 2000). Large crustal deformation at NKTZ has been interpreted due to the plastic deformation of hydrated lower crust (e.g., Iio et al, 2002). We have reexamined crustal structure of this area based on seismic tomography (Nakajima & Hasegawa, 2007) and reinterpreted the crustal velocity structure based on thermal model and melting phase diagrams on crustal rocks.
In order to interpret observed low velocity in the lower crust by hydration, presence of 1~5 vol% of fluid is necessary in the grain boundary of rocks. This automatically indicates that the lower crust is under “water saturated condition”. Solidus temperatures of rocks at 7-10 kbar under water saturated conditions are: granite: ~600°C, andesite & greywacke: ~650°C, basaltic rock: ~700°C, respectively). Accordingly, lower crust beneath NKTZ should be partially melted if temperature reached more than 700°C in the lower crust.
Lateral variation of the cutoff depth of shallow earthquakes has been compiled beneath the Japan Islands (Omuralieva et al., 2012). Because this depth corresponds with brittle/ductile transition which is sensitive with temperature, the lateral variation should correspond with lateral variation in crustal geotherm. The cutoff depth beneath NKTZ is similar to those beneath volcanic chain in Tohoku Japan where temperature at Moho is estimated to be higher than 800°C (Takahashi, 1978; Nishimoto et al, 2008). Accordingly, we propose that most part of the lower crust beneath NKTZ is partially molten even in the area away from Quaternary volcanoes.
Large effect of partial melting in the lower crust on the tectonics of Japan Arc has been recognized beneath volcanic belt (e.g., Hasegawa et al., 2005). We propose that crustal partial melting is taking place in much broader area than previously thought and they may have large effect on crustal deformation such as in NKTZ. In addition, presence of LF earthquakes in volcanic and non-volcanic area may be explained by the presence of wet partial melt in the lower crust in a coherent manner.

Keywords: crustal partial melting , tectonics, Niigata-Kobe Tectonic Zone

Implications of Persistent Intraplate Deformation in the Niigata-Kobe Tectonic Zone, Central Japan

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We found a persistent localized contraction along the Niigata-Kobe Tectonic Zone (NKTZ) before and after the 2011 Tohoku-oki earthquake through an analysis of GEONET coordinate data (Menese-Gutierrez and Sagiya, 2016). This persistent pattern is identified as short-wavelength components in the strain rate pattern after removing the long-wavelength components. Persistency of deformation pattern under both interseismic and postseismic periods indicates that the localized contraction results from aseismic process driven by the tectonic stress field. Strain rate of this localized contraction is about 0.06 ppm/year, generally consistent with geologically estimated strain rate (Wesnousky et al., 1982, Sato, 1989). The localized pattern can be reproduced by ~10mm/year aseismic slip on a fault cutting the crust up to the depth of a few km. This implies inelastic processes have significant contribution in the crustal deformation of the Japanese island arc. Similar inelastic deformation is expected for other fault zones. However, slip rate of major active faults are smaller and the deeper locking depth makes associated deformation pattern much broader. Thus it is more difficult to detect related signals with a similar approach. The long-wavelength components in the strain rate pattern are considered to be elastic deformation caused by interaction at the plate boundary. Since our precise geodetic observation is limited for the last 20 years, we have not figured out how elastic strain accumulation and release are balanced through an earthquake cycle. Modeling effort of earthquake cycles with realistic lithospheric structure to reproduce the observed deformation pattern is essential to solve the problem.

Keywords: intraplate deformation, inelastic deformation, crustal strain rate

Fold-and-fault structure associated with the Naganoken-hokubu Earthquake in 2014

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We made a geologgical map and geologgical cross sections. We also observed active fault outcrops considered to be related to the Naganoken-hokubu Earthquake in 2014. The Late Miocene to Pliocene strata in this region are separated by NNE-SSW reverse fault (Otari Fault). In the eastern area from the Otari Fault, Late Miocene Yanagisawa Formation is distributed, and subdivided to three members. In the western, Pliocene Hosogai and Iwatoyama Formations are distributed. The Iwatoyama Formation is subdivided to three members. The Hosogai and Iwatoyama Formations consist of syncline (Iwatoyama Syncline), and three members of the Yanagisawa Formation consist of anticline (southern extension of the Hidosawa Anticline) which is cut by the Otari Fault. The hinge lines of the syncline and anticline plunge to the south. The south end of the fold structure is located at the southern margin of the uplift in 2014.

Keywords: Nagano Prefecture, Hakuba Village, Otari Village, Kamishiro fault, active fault, fault rocks

Spatial variation of creep rate on the Philippine fault based on alignment array surveys

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The Philippine fault is a typical arc-parallel strike-slip fault related to oblique subduction of oceanic plate. We identified evidence of surface creep on Leyte Island and estimated creep rate on the basis of offset cultural features. Since 2013, we set up alignment arrays across the surface trace of the Philippine fault to monitor surface creep at 16 locations from southern Luzon Island southward to Masbate, Leyte and Mindanao Islands. Creep rates of 23-29 mm/yr were estimated at two sites on Leyte Island, which are almost the same as a GPS-derived slip rate of the fault. This suggests that the slip on the Philippine fault on Leyte Island is accommodated by aseismic creeping. On Masbate, creep rates of 5-10mm/yr were estimated across the surface rupture of the 2003 Masbate earthquake (M_s 6.2), suggesting that the slip on the fault is accommodated by moderate earthquakes and aseismic creeping.

Recent crustal deformation and comparison among geodetic, seismological, and geological strain rate in the San-in shear zone

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Introduction

We reported that an analysis of the GEONET (GNSS Earth Observation NETwork system) data operated by the Geospatial Information Authority of Japan revealed a strain concentration zone from an eastern part of Shimane Prefecture to Tottori Prefecture in the San-in area (hereafter the San-in shear zone) and that a new dense GNSS array was constructed to clarify a detailed spatial pattern of deformation in the San-in shear zone in the past JpGU meetings. Here, we report recent crustal deformation in the San-in shear zone and comparison of strain rate estimated from geodetic, seismological, and geological data with a different time-scale in and around the shear zone.

Recent crustal deformation in the San-in shear zone

The deformation in the San-in shear zone is characterized by right-lateral strike slip movements in an E-W oriented shear zone along the coast of the Japan Sea. The deformation rate across the shear zone is approximately 4 mm/yr during 2005-2009. The shear zone almost overlaps with the San-in seismic zone. The recent velocity field including the velocities at the new GNSS stations during 2013-2015 suggests that the deformation pattern does not change significantly but that the deformation rate increases to be about 6 mm/yr. The rate increase is possibly caused by postseismic deformation of the Tohoku-oki earthquake. Because not only the broad long-wavelength increase but also that localized in the shear zone is observed, the increase may include a response of the shear zone to the external stress changes due to the postseismic deformation.

Comparison among geodetic, seismological, and geological strain rates

Geodetic strain rate is larger than geological strain rate by an order of magnitude in the Japanese Islands. The Chugoku region including the San'in region is far from subduction zones and has a relatively small strain rate. In order to compare strain rates using different time-scales and methods in such a small strain-rate region, we estimated regional strain rates in the Chugoku region. We divided a region ranging in N34.7°-35.7° and E133.2°-134.8° into 2 by 2 sub-regions and estimated strain rate of each sub-region with geodetic, seismological, and geological methods. The result suggests that the geodetic strain rate is larger than the seismological one by an order of magnitude and is larger than the geological one by two orders of magnitude in all sub-regions except for that including the Yamasaki fault. The strain rates from three methods are in the same order of magnitude in the sub-region including the Yamasaki fault. The difference of the strain rates implies that the present-day strain rate in the San'in region is much faster than the average one in the geological time-scale and that a large part of the geodetic strain rate is inelastic and aseismic deformation.

Keywords: Strain concentration zone, GNSS, San-in region

Distribution of fault system and its characteristics around the aftershock area of the 2000 Western Tottori earthquake

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The 2000 Western Tottori earthquake (Mj7.3) occurred where distinctive active fault and related lineament were not identified. Lager than Mj 1 aftershock still frequently observed in this area. A extreme-density observation with a thousand simplified seismograph around the aftershock area has been projected. The objectives of this study is to clarify the detailed distribution and occurrence of faults which exposed around the aftershock area of the 2000 western Tottori earthquake in the range of 12km×4km by field observation and compare the result with the seismographic observation.
In research area, the Late Cretaceous to Paleogene granitic rock s exposed. Some Miocene (partly Pleistocene) acidic to basic dykes were intruded into the granitic rocks.
About 1000 faults were observed in this study area. Orientation of faults were different for each area: the northwestern area was varied and not concentrated, the central area was concentrated to WNW and NE direction, the southeastern area was concentrated to NNW and NE direction. The fault rocks were composed of some mm to cm thick fault gouge and some cm thick cataclasite. Most of cataclasites were hydrothermally altered. Some NW and NE trending faults shows cross-cutting (conjugate) relationship.
Distribution and orientation of observed fault is approximately corresponding with cracks which estimated from seismographic observation after the 2000 western Tottori earthquake (Yukutake, 2010). This result indicates geometry of the 2000 western Tottori earthquake related faults has interrelationship with orientation of pre-exited geological faults. Hydrothermal alteration of cataclasite suggests that the cataclasite had been formed under the hydrothermal condition in depth and fluid had been affected for fault activity. Several lineament had been recognized after the 2000 western Tottori earthquake by air-photo interpretation. The mapped lineament were mostly less than 10 km and some lineament showed conjugate relationship (Takada et al., 2003). Cross-cutting relationship of NW and NE trending faults observed in this study may indicates segmentation of each faults. Minor and obscure lineaments around aftershock area of the 2000 western Tottori earthquake might be developed as a result of segmentation by the cross-cutting of NW and NE trending faults.

Keywords: 2000 Western Tottori earthquake

Fundamental Structure Model of Island Arcs and Subducted Plates in and around Japan -Trench and Plate Boundary Models -

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The eastern margin of the Asian continent is a well-known subduction zone, where the Pacific (PAC) and Philippine Sea (PHS) plates are being subducted. In this region, several island arcs (Kuril, Northeast Japan, Southwest Japan, Izu-Bonin and Ryukyu arcs) meet one another to form a very complicated tectonic environment. At 2014, we started to construct fundamental structure models for island arcs and subducted plates in and around Japan. Our research is composed of 6 items of (1) topography, (2) plate geometry, (3) fault models, (4) the Moho and brittle-ductile transition zone, (5) the lithosphere-asthenosphere boundary, and (6) petrological/rheological models.
This paper is mainly related with the results of items (1) and (2). The area of our modelling is set 12°-54° N and 118°-164° E to cover almost the entire part of Japanese Islands together with Kuril, Ryukyu and Izu-Bonin trenches. The topography model was constructed from the 500-m mesh data provided from GSJ, JODC, GINA and Alaska University.
Plate geometry models are being constructed for the Pacific and Philippine Sea plates through the two steps. In the first step, we constructed “base” models with very smooth boundaries in our whole model area, providing fundamental geometry of the plates. For 41,892 earthquake data from JMA, USGS and ISC. 7,853 cross sections were taken with several different directions to the trench axes. 2D plate boundaries were defined by fitting to the earthquake distribution forming the Wadati-Benioff zone, from which we obtained equi-depth points for each boundary. These equi-depth points were approximated by spline interpolation technique to make longer wave-length (>75-150 km) qui-depth lines of the plate boundary. The grid data for the individual 3-D “base” plate models were constructed from these equi-depth lines.
As the second step, regional plate configuration including shorter wave-length geometry (<50-100 km) is being constrained in the vicinity of Japan by recent results from seismic tomography, RF analysis and active source experiment. We have collected 44 references, from which plate position data were constructed. These data are used as ‘correction terms’ which are superposed to the “base” plate models described above. Preliminary analysis indicates that the plate boundary of the PAC plate from the controlled source experiments is systematically shallower than that from natural earthquakes in a depth range of 10-30 km, which may arise from the difference between the structural and mechanical boundaries of the subducted plate. These regional data are also very important for modelling the PHS plate, particularly beneath the SW Japan arc with less seismic activity.

Keywords: tectonic strucutre, plate boundary, trench

Deformation rates of island-arc crust estimated from seismic, geodetic, and geomorphic data

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Steady plate subduction brings about steady uplift of the island-arc lithosphere [1]. This process is simply explained as convex upward bending of an elastic plate by the effect of gravity [2]. So, there is no analogy in mechanism between the steady uplift and steady horizontal shortening or stretching of island-arc crust. The island-arc crust is basically elastic, but it includes a number of defects. Brittle fracture and/or plastic flow at these defects, which occur so as to release the overall elastic strain energy produced by mechanical interaction at plate interfaces, cause the horizontal shortening or stretching of island-arc crust [3]. To sum up, the crustal shortening or stretching is a purely inelastic deformation process. In northeast Japan, for example, the evidence of crustal shortening has been reported from seismic, geodetic, and geomorphic data [4, 5]. The point is a discrepancy in its rates. One of the reasons is difference in the length of observation periods. Actually, geodetic observation is too short to cover the entire cycle of large earthquakes. Another, more essential, reason is that different kinds of data provide different information about crustal deformation; that is, seismic and geomorphic data provide information about purely inelastic crustal deformation, whereas geodetic data provide information about total (elastic + inelastic) crustal deformation. So, we cannot directly compare the crustal shortening rates from geodetic data with those from seismic and geomorphic data unless geodetically observed deformation is divided into the elastic and inelastic parts [3].

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Keywords: island arc, deformation rate, inelastic strain, seismic data, geodetic data, geomorphic data

Linkages between tectonics, denudation, and landscape evolution in humid active orogens, revealed by terrestrial cosmogenic nuclides

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This lecture overviews methodology and applications of terrestrial cosmogenic nuclides for quantifying denudation of diverse mountainous landscapes in humid active orogen. We measured cosmogenic ^{10}Be by accelerator mass spectrometry in quartz grains in bedrock and/or fluvial sediment sampled from outlet of watersheds underlain by granite or granodiorite in Japan, to determine the millennial-scale average rate of denudation over the catchment areas. Topography of the study sites spans from low-relief gentle hills to high-relief steep mountainous terrains under diverse tectonic settings. The ^{10}Be-based catchment-averaged denudation rates increase nonlinearly with increasing mean gradient of the watersheds. The watershed denudation rates are comparable to soil production rates in gentle landscapes but exceed it beyond orders in steep areas. This seems concordant with a model simulating process transition from soil creep with shallow landslides to direct bedrock landsliding, thereby forming threshold hillslopes controlled by rock mass strength. Our data also reveal the existence of steep but slowly eroding watersheds over the threshold slope condition, implying the significant role of large-scale deep-seated bedrock landslides in evolution of a high-relief mountainous landscape. The approach using terrestrial cosmogenic nuclides combined with topographic analysis on geographic information systems and long-term tectonics obtained by low-temperature thermochronology reveals relationships between tectonic uplift (base-level lowering), rates and processes of hillslope denudation, and development of mountainous topography in a tectonically active margin under humid temperate climates.

Keywords: terrestrial cosmogenic nuclides, denudation rate, low-temperature thermochronology, geographic information systems, landscape evolution modeling

Deformation processes of island arc during the interseismic period of Tohoku-oki earthquake: Vertical movement and horizontal strains

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This study models the deformation of the crust and upper mantle of the northeastern Japan island arc during the interseismic period of the Tohoku-oki earthquake considering heterogeneous rheological structure. Nishimura (2012) investigated the crustal deformation of northeastern Japan based on geodetic data for the 120-year period preceding the 2011 Tohoku-oki earthquake. The results indicate north-south extension and east-west compression along the central axis of northeastern Japan. Vertical deformation data for a 100-year period indicates uplift in the backarc region but subsidence in the forearc region. Recently, Shibazaki et al. (2014) calculated the effective viscosity of the crust and upper mantle of the Japanese island arc based on the thermal structure obtained by dense geothermal observations using Hi-net boreholes (Matsumoto, 2007) and by Tanaka et al. (2004). They reproduced several elongated low-viscosity regions in the crust and upper mantle of the northeastern Japan arc, striking transverse to the arc, which correspond to hot fingers. We develop a finite element model of the viscoelastic deformation processes during the interseismic period considering heterogeneous viscosity structures. In order to model interseismic coupling, we give back-slip along the subduction plate boundary for 500 years. We investigate several cases by changing back-slip distribution to model interseismic deformation. To reproduce the uplift observed from the volcanic front to the backarc and the subsidence in the forearc, we need to consider back-slips at the deeper subduction plate interface. In this region, the back-slip rate decreases from 8 cm/yr at a depth of 40 km to 0 cm/yr at a depth of 90 km. Compared with the model with only elastic structures, the smaller amount of the deep back-slip is necessary for the model with the heterogeneous viscoelastic structure to reproduce the observed uplift. Strain rates during the interseismic period show east-west compression and north-south extension. Our results indicate that the heterogeneous rheological structure of the crust and upper mantle of the island arc and back-slip at the deeper region are necessary to reproduce the observed interseismic strain distribution and vertical deformation.

Keywords: The Tohoku-oki earthquake, The northeastern Japan arc, Interseismic deformation, Viscoelasticity, Back-slip, Deep coupling

Three dimensional fluid distribution and crustal deformation around the focal area of Iwate-Miyagi Nairiku Earthquake

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The 2008 Iwate-Miyagi Nairiku Earthquake (M 7.2) was an unusually large earthquake, which occurred near the volcanic regions. We used new data at 66 sites in a few kilometer grid intervals and existing data at 44 sites on three profiles. We inverted detailed 3d resistivity structure. In our final resistivity structures, aftershocks are distributed in high resistivity zones and avoiding low resistivity anomalies. We found a pathway of fluids from Mt. Kurikoma to the hypocentral area at 10km depth. The hypocenter is located at the rim of the conductor.
Large coseismic slip zones are located in high resistivity in our model. On the other hand, post-seismic slip zones are located in low resistivity zones and high resistivity zones. Iinuma et al.(2009) showed two different kinds of triggers of post-seismic slips. One comes from fluids and the other comes from the static stress change caused by mainshock. Our results imply the different triggers of post-seismic slips as implying in the previous work. These results would come from the difference of character like ductile or brittle and the existence of fluids.

Keywords: fluids, resistivity, crustal deformation, magnetotellurics

On the causes of across-arc mountain ranges in the back-arc region of Tohoku arc: Importance of north-south compression

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In the back-arc region of the Northeast Japan (Tohoku) arc, we can recognize across-arc (east-west direction) mountain ranges, while the most significant topographic structure, which are the Ou backbone range and the Dewa range, runs in the north-south direction. The across-arc mountain ranges and the Ou and Dewa ranges constitute topographic high of a ladder structure.
It has been widely believed that the ladder structure of the back-arc region of the Northeast Japan arc is caused by the upwelling of hot material due to mantle wedge convection driven by the oceanic plate subduction (hot finger model; Tamura et al., 2002). If we turn our eyes to other subduction zones, however, it is very rare to see such a ladder structure. This suggests that the primary cause of the ladder structure in the Northeast Japan arc should not be the mantle wedge convection, because this can occur in other subduction zones.
In island arcs under a compressional stress regime, topographic high always coincides with the volcanic front. On the other hand, this relationship does not hold true for islands arcs under a tensile stress regime. Therefore, in making across-arc (east-west direction) mountain ranges in the Northeast Japan arc, the north-south compression seems to be important, although the direction of the principal compressional stress (sigma-one) is east-west. Focal mechanisms of earthquakes in this region, which are mostly reverse faults with an east-west compressional stress axis, do not contradict with this hypothesis.

Keywords: Northeast Japan arc, subduction zone, ladder structure

Stress heterogeneity in northeastern Japan and its relationship with induced seismic activities by the 2011 Tohoku-Oki earthquake

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After the 2011 M9 Tohoku-Oki earthquake, a great number of earthquakes are induced even in the inland regions separated by more than several hundred kilometers from the large slip area. Because of the very large size of this earthquake, it is expected that we can investigate detailed characteristics of the induced seismicity, which will help improve our understanding of its generation mechanism. In this study, we investigated the seismicity, focal mechanisms and stress fields in northeastern Japan to understand the causes of the induced seismicity.
On the spatial distribution of the induced seismic activities, they tend to concentrate in several locations as clusters rather than distribute widely. Many of these clusters in northeastern Japan are located in regions where seismicity was inactive before the 2011 earthquake. Stress tensor inversion results before and after the earthquake are significantly different from each other. In addition, the stress orientations after the earthquake are quite similar to those of the static stress change [Yoshida et al., 2012]. This suggests the following two possibilities. a) Stress orientations rotated after the 2011 Tohoku EQ by its static stress change. b) Static stress triggered earthquakes in regions where stress orientations are different from the typical stress orientation in the surrounding areas but is consistent with the static stress change.
To distinguish these two possibilities, we reinvestigated the stress orientations before the Tohoku-Oki earthquake by using data of Tohoku University for the period of 1980-2002 and those by Yoshida et al. (2015a). In the arc and the backarc in northeastern Japan, it has been known that the compressive stress orientations are oriented WNW-ESE homogeneously in space. However, several regions were detected, where stress orientations are different from the regional orientation. Some of the regions have favorable stress orientations for the induced earthquake focal mechanisms there. This supports the possibility (b).
The regions having such anomalous stress orientations seem to be located near the focal regions of the past large earthquakes such as the 1896 Rikuu earthquake, the 1904 Shonai earthquake and the 1913 Akita-Senboku earthquake. Recently, spatially heterogeneous stress orientations were detected in the focal regions of the 2008 Iwate-Miyagi Nairiku earthquake and the 2011 Fukushima-Hamadori earthquake, which were probably caused by the mainshocks. This suggests that the spatially heterogeneous stress states have been formed by the past M~7 earthquakes. This is what is expected if the deviatoric stress magnitude is very small (differential stress < 20 MPa) in northeastern Japan as suggested from the correlation between observed stress regime and surface topography [Yoshida et al., 2015b]. Or, it might be partly caused by the effects of the heteronomous temperatures structure or the sliver motion in the Hokkaido corner.
In contrast, there exist some regions where the static stress change cannot explain increase in seismic activity. The earthquake cluster in the Yamagata-Fukushima border is positioned where the coulomb stress decreased [Terakawa et al., 2013]. It is considered that the reduction of frictional strength by upwelling fluids caused the induced seismicity in this region based on the following three reasons: 1) seismic activation delayed for eight days after the 2011 earthquake, 2) it is located just beneath the Ohtoge caldera, and 3) the seismicity migrates in space. Yoshida & Hasegawa [2015, SSJ] investigated the temporal evolution of the frictional strengths by using the diversity of focal mechanisms. As a result, the temporal increase in frictional strength was found. We can understand this induced seismic activity if this was caused by the pore pressure increased

after the Tohoku-Oki earthquake and diffused with earthquake generations.

Keywords: the 2011 Tohoku-Oki earthquake, induced seismicity, stress, frictional strength

Various fault geometries in the source regions of normal faulting sequences induced by the 2011 M9.0 Tohoku-Oki

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We relocated numerous earthquakes in the source regions of normal faulting sequences induced by the 2011 M9.0 Tohoku-Oki, using seismic waveforms retrieved from a dense seismic network deployed after the Tohoku-Oki earthquake. The seismic network has consisted of around 60 portable stations equipped with short-period sensors. Initially, we detected earthquakes from continuous waveforms from July 2011 to June 2014, by applying an automatic detection algorithm. Then, we calculated differential arrival times obtained by the automatically picked and waveform correlation method. We obtained more accurate differential arrival times that contained 56 million P wave observations and 51 million S wave observations for use in the double difference relocation. Applying a double-difference algorithm to the arrival data-set, we succeeded to relocate ~200000 earthquakes with high accuracy. We found that most earthquakes show planar alignments, and the fault distribution varies along the source region. At the northern part, many tiny fault planes are distributed like a flower structure. In contrast, a sharp fault well develops in the central portion. The thinnest width of the sharp fault is close to only 100 m. At the southern part, there are some conjugate fault systems. These spatial variations of fault geometries in the source region of normal faulting sequence reflect fault evolutions.

Relationship between fault-related folds in the focal area of the Hokkaido Nansei-Oki Earthquake and the aftershock distribution

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Reverse faults formed by E-W compression after the late Pliocene are developed in the eastern margin of the Japan Sea and consist of a contraction deformation zone[6]. Some large earthquakes with magnitudes larger than 7 had been occurred by the fault activities in this zone since 20th century. The 1993 Hokkaido Nansei-Oki Earthquake with magnitude of 7.8 occurred in the sea area around the Okushiri Island located in the central part of eastern margin of the Japan Sea. Many studies for analyses of observed seismic data[e.g.[2],[3]], modeling of earthquake faults[e.g.[1],[4]], and numerical simulations of tsunami[e.g.[5]] for this earthquake event are presented. In contrast, the geological structures including fault geometries at shallow depth in this area are not clear. We therefore conducted structural analyses of seismic reflection profiles obtained in the sea area around the Okushiri Island, which aims to clarify the geological structures of this focal area and their relationships with the seismic faults (observed seismic data) related to the earthquake.
We used profiles obtained by single channel seismic reflection survey conducted by AIST (GSJ) during the GH94 and GH95 cruses—which mainly aim to construct marine geological maps. The study area covers a range of ~170 km (N–S; ~41º 20’–42º50’N) x~130 km (E–W; ~138º 50’–140º 20’E) where the Okushiri Island is located at the central part of this area.
The geological structures are generally correlated to seafloor topography, e.g., remarkable rises of acoustic basements along the steep escarpment at the eastern margin of the Japan Basin and at the western margin of the Okushiri Spur. In addition, fault-related folds, which are generally recognized as one of the main characteristic structures in the eastern margin of the Japan Sea, are well developed also in this study area. Distributions of faults inferred from structures such as fault-related folds and height differences of basements show the developments of the reverse faults roughly trending N-S direction with length more than several tens km. Faults to the south of the Okushiri Island (which we call here as “south fault group”) dominantly dip to the east while those to the north side (“north fault group”) dip to the west. From their distributions, the south fault group is sub-divided into three groups roughly running parallel to each other while the north fault group seems consisting a single fault zone.
Comparisons between the faults recognized in this study and the aftershock earthquakes shown by Aoyagi *et al.* (2000) show a good correlation in their distributions: the aftershock earthquakes are aligned along the fault with eastward dipping developed in the western margin of the Okushiri Spur to the south of the study area and those along the fault with westward dipping developed within the Japan Basin to the north. In addition, the fault geometries inferred from seismic reflection profiles in this study are also correlated to those of the earthquake faults estimated by using the aftershock data, showing consistency between the structures at shallow depth and those at deeper depth.

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Keywords: Hokkaido Nansei-Oki Earthquake, eastern margin of the Japan Sea, contraction deformation zone, focal area, fault-related fold, Okushiri Island

Inelastic strain in the seismogenic zone, Kyushu, Japan inferred from focal mechanism of earthquakes

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Strain in the seismogenic zone of the crust is a key parameter to understand crustal dynamics. GNSS data provide us with great information about deformation rate at the surface, which have been investigated by many researches and modeled kinematic behavior as elastic medium. Generally, strain in the earth's medium consists with elastic and inelastic ones. The two kinds of strain result different effects on the stress field. Therefore, detecting inelastic strain is important to know state of stress in the crust as well as elastic one. Inelastic strain is caused by such as fault creep, viscoelastic response, and earthquakes. Here, we showed the inelastic strain in the seismogenic zone of Kyushu, Japan from seismic moments and focal mechanisms data by counting Kostrov's sum in the spatial bins. Seismic moment tensors about 9000 earthquakes with magnitude greater than 2 for 13.5 years were obtained from seismic network data in Kyushu Island and F-net catalog. Total released moment at every spatial bin with 0.15 x 0.15 degree in latitude and longitude was estimated and then strain rate was calculated from the moment, compliance of the medium, and volume of the bin. The estimated maximum strain rate achieves 10^-7 strain/year. This strain rate is comparable with that from GNSS data. However, the strain rate mainly revealed the different principal direction from the one of GNSS. On the other hand, the directions were similar to the behavior of active faults in Kyushu. The result in this study showed that inelastic strain due to earthquakes is enough large, suggesting that the effect should be considered for modeling crustal dynamics.

Keywords: inelastic strain, seismic moment tensor, Kyushu

Cluster Analysis of the Velocity Field in the Japanese Islands Derived from Dense GEONET Data

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Spatial inhomogeneity of crustal deformations is a key for understanding tectonics of plate convergence zones. The concentration of deformation triggers earthquakes and contributes to forming topography. Therefore, detecting deforming zones from observed data is of great importance. Recently, GNSS observation networks have become significantly denser, so that statistical approaches are effective methods for revealing crustal structure associated with geophysical phenomena. Simpson et al. (2012) and Savage and Simpson (2013) conducted cluster analyses of GNSS velocity fields in the San Francisco Bay Area and Mojave Desert, respectively. They successfully found tectonic boundaries. The application of the clustering approach to regional GNSS velocity field is able to yield objective crustal block segmentations based on quantitative criteria.
In this study, we modified the method and applied it to the GNSS velocity field of Japan. The obtained results are compared with geological features to assess the effectiveness of the method.
We performed a cluster analysis of horizontal components of the GNSS velocity field with the Hierarchical Agglomerative Clustering algorithm (HAC). The HAC algorithm organizes data according to their successive geometrical distance. First, we set N-samples (hereafter data) as initial individual clusters. Then we search for the nearest pair of clusters and create a new data at their average position. We merge the nearest pair of clusters in a solution tree (tree space) and replace the clusters with single data in the velocity space. We repeating this procedure successively until a single data remains in the velocity space. At each step, pairs of clusters with minimum geometrical distances in the velocity space are merged.
There is an ambiguity in determining the optimum number of clusters. Previous studies used a statistical method called “Gap Statistics”. The method provides an optimum number of clusters by comparing a random data set and the organized results. However, the sampling zone must be designated manually and may affect the evaluation procedure. For example, if we take a wider area, then a smaller number of clusters will be preferred.
To avoid such a disadvantage, we introduced a new simple cluster evaluation function based on the ratio of the standard deviations for the within-cluster distances and the between-cluster distances. If we divide the much smaller inter-station distances by the larger cluster distances, the cluster size will slowly decrease. Then we select the point where the curvature of the ratio changes, as an optimum number of clusters. This method successively identified larger features in the velocity space which reflect major crustal structures.
The obtained results were well organized in geographic space even though no geographical constraints were applied. Also, obtained cluster boundaries coincided with major known active faults, which suggests that we could make unbiased identification of crustal blocks from GNSS data. In addition, we easily obtained relative motions between the identified clusters, providing an intuitive understanding of the regional deformation. Furthermore, the optimum ratio may reflect the degree of internal deformation in the analyzed area.
We present some results for specific areas. In the central Kyushu region, we identified a stress field which indicates north-south extension and east-west compression. In the Kinki district, the Hanaori fault and the Biwako Seigan fault were suggested as boundaries where strain partitioning is occurs.

Keywords: GNSS, Crustal Deformation, Statistics

Aseismic strike slip associated with the 2005-2010 Afar rifting event

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Himematsu and Furuya (2015) have reported that the 2007 dike intrusion episode in Tanzania accompanied with significant aseismic strike slip along the subsidence of the graben. To our knowledge, no previous studies have considered such strike slip components associated with dike intrusion events. Although seismic swarms during rifting events are often attributed to the magma intrusion, there is a hypothesis that aseismic slip may be responsible for the generation of seismic swarm (e.g., Lohman & McGuire, 2007). It is thus possible that similar aseismic strike slip could have been universally occurring during any rifting events.
We re-examine the crustal deformation signals during the 2005-2010 Afar rifting episode using ALOS/PALSAR (L-band) images. The seismic swarm and the dike intrusion intermittently occurred from September 2005 to May 2010. Some previous studies have already reported the 3D displacements for the September 2005 rifting event (e.g., Wright et al., 2006). While two ~Mw5.5 right-lateral slip earthquakes were reported around the focal region, their results showed no remarkable horizontal displacements around the subsiding zone of the graben. However, we argue that the insignificant horizontal displacements along the intruded dike would be due to the lack of coherent signals near the subsiding zone.
We applied an offset tracking technique to the ascending-track data sets (12 June 2007 –5 Aug. 2010) to acquire the robust crustal deformation signals. Both the azimuth offset and the multiple aperture interferometry (MAI) data are sensitive to the displacement along the satellite track (~N350°E). The results showed clearly the NNW horizontal displacements at the subsiding zone. At the subsiding zone, the range offset and azimuth offset data depict the maximum changes of about 225 cm and 110cm, respectively. Because focal mechanisms of the earthquakes reported by previous studies and Global CMT catalogue during the rifting indicate alomost no strike components, we propose that the horizontal displacements may be caused by aseismic strike-slip. We will discuss the mechanism of the aseismic strike slip relating with the seismic swarm.

Keywords: Dike intrusion episode, Synthetic Aparture Radar, Aseismic slip, Divergent plate boundary, Earthquake swarm, ALOS/PALSAR

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

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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

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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

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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

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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

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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

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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.

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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

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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

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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

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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)

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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

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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

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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

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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

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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

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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.

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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

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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

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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

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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

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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

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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-

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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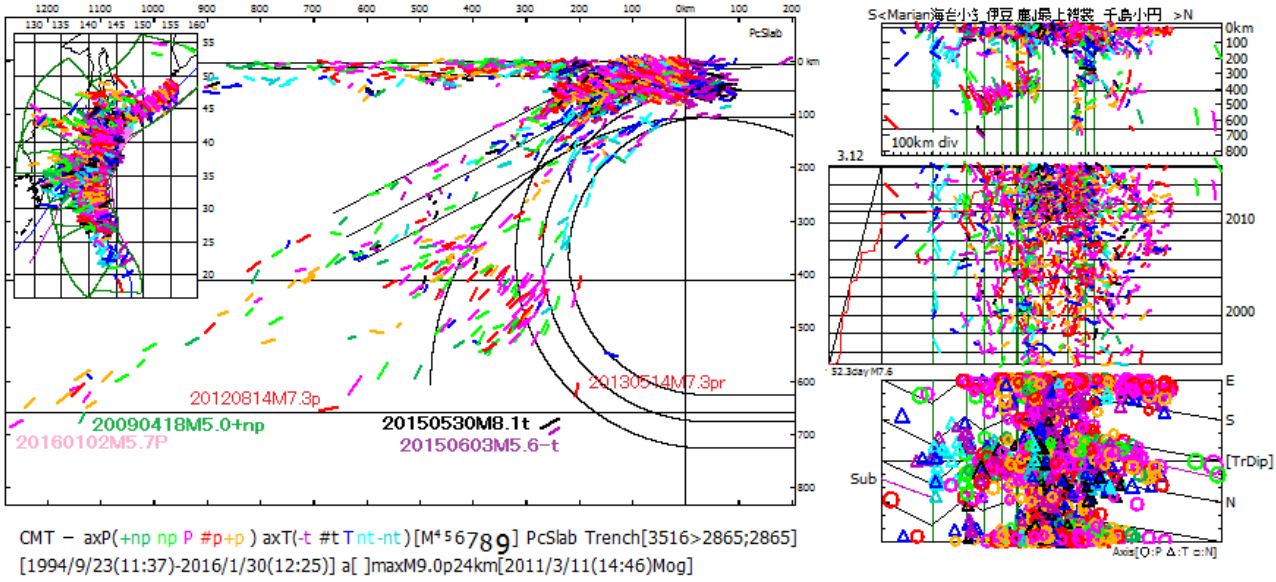
Pacific slab has been crossed over the upper boundary of lower mantle and started of collapse into lower mantle are discussed in this presentation.
M8.1 Earthquake with the depth of 682km happened off Ogasawara Islands in May 30 of 2015, which quaked all over the Japanese Islands with stronger than 1 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

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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

