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

