

## Proper estimation of stress fields in the source region of the 2011 Off the Pacific Coast of Tohoku earthquake

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A various observation data revealed that coseismic slip of the 2011 Off the Pacific Coast of Tohoku earthquake exceeded a few tens of meters near the Japan Trench. This suggests that a prominent spatial variation in stress fields may be found there. In this study, we report that the spatial variation in stress fields can be identified on the basis of proper data-set selection in the stress tensor inversion.

A single earthquake as well as a set of nearly identical focal mechanisms cannot constrain the stress tensor, so that we need an adequately diverse set of focal mechanisms in the stress tensor inversion. Using synthetic focal mechanism dataset, Hardebeck and Hauksson (2001) showed that when the mechanism diversity is low, the stress tensor inversion returns an incorrect solution in which a direction of the maximum principal stress ( $S_1$ ) is about 45 degree from the strike of the reference fault. The same situation may occur in the present study area, because most of earthquakes are low-angle reverse-faulting types occurring along the plate interface.

In order to overcome the problem, we try to divide the dataset into earthquakes along the plate boundary (On-fault earthquake) and other events (Off-fault earthquake). Here we defined the on-fault earthquake that satisfies all the following three criteria: (1) Thrust mechanism categorized in the triangle diagrams of Frohlich (1992), (2) Kagan's angle (Kagan, 1991) relative to a reference mechanism (strike=195, dip=15, rake=90) is less than 35 degree, (3) focal depth is within  $\pm 10$  km of the inferred plate interface. We applied these criteria to F-net moment tensor solutions during the period from February 1997 to the occurrence of the 2011 Tohoku-oki earthquake. The strike and dip angles of on-fault earthquakes are consistent with the geometry of subducted Pacific slab, suggesting that the above criteria work well. Off-fault earthquakes show a diversity of focal mechanisms.

We divided the study region into several small subareas and applied the stress tensor inversion method (Michael, 1984) using off-fault earthquakes. The inversion results show that the plunge of  $S_1$  is subhorizontal within a subarea where a large coseismic slip occurred. Considering the 95% confidence regions, the angle between  $S_1$  axis and the plate interface ( $A$ ) is about 10-40 degree. In contrast, the dip angle of  $S_1$  becomes higher in other subareas and the angle  $A$  in Ibaraki-oki is nearly perpendicular. This suggests that the shear stress was relatively high around the large coseismic slip area, while those in other areas were very low.

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Keywords: stress tensor inversion, 2011 Off the Pacific Coast of Tohoku earthquake, data-set selection criteria

## Stress field of normal-faulting seismic sequences in Ibaraki and Fukushima Prefectures triggered by the Mw9.0 Tohoku-oki

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The 2011 M9.0 Tohoku-Oki Earthquake triggered widespread seismicity throughout the Japanese island arc including Hokkaido and Kyushu regions. In particular, a significant increase in the shallow seismicity was observed in the minutes following the main-shock along the Pacific coast of NE Japan, notably the northern part of Ibaraki Prefecture and the southern part of Fukushima Prefecture. The most striking feature of the induced seismicity is that the focal mechanisms reveal normal faulting with a T-axis orientated in a roughly E-W direction. Several large magnitude events including the maximum 7.0 earthquake have occurred during the sequence. It is very important to understand the stress field of driving such intensive seismic swarm activities.

We have, therefore, conducted a series of temporary seismic observations through a dense deployment of about 60 portable stations after outbreak of the intensive seismic swarm. We manually picked polarity of first motion of P-wave observed at each seismic station. Then, we have determined focal mechanism of earthquakes applying the method developed by Hardebeck and Shearer [2002] to the first motion data.

Most of the determined focal mechanisms at depths shallower than 10 km show normal faulting with a vertical P-axis. It is interesting that the orientation of T-axis shows spatial variation. The T-axis at the northern part of the Ibaraki is roughly oriented ENE-WSW. The T-axis at the southeast part of the Fukushima is roughly oriented NEN-SWS. In contrast, focal mechanisms at depths greater than 15 km are complex. They consist of normal-, reverse- and strike-slip faulting.

## Temporal change in stress field in the northern part of Tohoku district associated with the 2011 Tohoku-oki Earthquake

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We have investigated the stress field in the northern part of Tohoku district for the both periods before and after the 2011 off the Pacific coast of Tohoku (Tohoku-oki) Earthquake. We determined focal mechanisms using data of P-wave first motion, then estimated stress field by a stress tensor inversion method. After the Tohoku-oki earthquake, the seismicity is quite high in Akita prefecture, forming newly activated three major clusters and many minor ones. The location of major clusters is complementary for the periods before the Tohoku-oki earthquake. Seismicity in some clusters started almost immediately after the Tohoku-oki earthquake, however, beginning was delayed even for months in some clusters, and the duration of activity is highly variable among the clusters. Focal mechanisms of earthquakes in the new clusters show predominantly strike-slip or oblique-slip solutions with consistently NW-SE trending T-axis. The stress tensor inversion using focal mechanism data indicates clear temporal change in the stress field due to the Tohoku-oki earthquake, from reverse-faulting regime to strike-slip regime. Thus the new stress field brought the quiescence of seismicity in the former clusters with predominantly reverse faulting, which is consistent with the Coulomb stress calculation. This change is explained qualitatively by the static stress change due to the slip of megathrust of Tohoku-oki earthquake; compressional stress in WNW-ESE direction was reduced by the slip. However, the spatiotemporal variation in seismicity and focal mechanisms suggest the need of additional factors to bring temporal change. Possible factors are, for example, fluid migration in the crust following the static stress change, delayed response of crustal materials, and viscoelastic response in the lower crust and uppermost mantle.

### Acknowledgments

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Keywords: Off the Pacific coast of Tohoku Earthquake, induced seismicity, focal mechanisms, stress field, temporal variation

## Introduction of neotectonics and crustal extension in the Wasatch active fault zone, Utah: Review

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The Basin and Range province (BRP) in the western USA extends north-south, occupying between the Coastal Range and Colorado Plateau, and is characterized by a wide range of east-west extension since the Miocene. The total tectonics from the Colorado Plateau to BRP is similar to Japan as the Cretaceous horizontal shortening and Miocene to the present stretching. The easternmost part of BRP is consistent with the Wasatch Mountains, where the Wasatch active fault zone demarcates in its western margin, eventually in the eastern boundary of the Salt Lake and Utah Valleys as well. The ten segments of the fault zone, each 30 to 70 km long, have 1200 to 1500 years recurrence time within the respective segments, and on average one segment moves at least once every 300 years. Because the last motion > M7.0 moved in 17th century, this fault zone is one of the most dangerous seismic hazardous areas in the U.S. The GPS displacement velocity averages 2-3 mm/yr, relative to the easterly stable continent, suggesting the zone coincides with the strain concentration. The cause and effect between such stretching have been discussed either as the plume first or extension first, but there are no common understandings. The basis of the tectonics is the same of the origin of core complex, and the stretching stress and strain history, tectonics, after Cretaceous-Paleogene convergent tectonics for BRP has not yet reached the definite conclusion. One of the interesting figures is that the magma intrusion is complementary with the active fault movement as the area of intrusion has scarce active faulting, suggesting the strain of stretching is diverted by magma intrusion. There are at least four mechanisms for the stretching that likely all contribute at amounts that are debated. These consist of gravitational collapse of the Laramide orogenic plateau, roll back due to subduction of the Farallon-Pacific spreading ridge, hot spot weakening and doming and plate boundary reorganization associated with NW slip of the Pacific Plate along the San Andreas Fault.

Keywords: Wasatch active fault system, Utah, stretching tectonics, strain concentration, core complex, magma intrusion

## Latest methods for inferring stress conditions from dikes and mineral veins

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Paleostress analysis using parallel dike swarms has been popular since the 1970s. Methodological development has been made since the 1980s for the analysis. Now, stress conditions can be determined not only from the attitudes of parallel dikes but also from those of the dikes whose poles make a girdle. The stress axes and stress ratio optimal for a group of dikes can be determined with 95% confidence limits (Yamaji et al., 2010). And, if there are dikes formed by different stress conditions, the statistical inverse method of Yamaji and Sato (2011) distinguishes and infers the conditions, and evaluates the probability that a dike was formed under each of the conditions. The methodological development is reviewed in this paper.

Keywords: tectonic stress, magma pressure, clustering

## Water level and temperature change of geothermal spring as a good indicator of a vectorial change of the local stress

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Water level and its temperature are changed at some geothermal wells located in Yamagata, southern Fukushima and northern Ibaraki Prefectures just after the 2011 off the Pacific coast of Tohoku Earthquake. Most of them are beared in fractures.

Such change of level and temperature of geothermal wells beared in fractures by a large earthquake is well known at previous large earthquakes as the Southern Hyogo Prefecture Earthquake in 1995 and the Niigata Chuetsu Earthquake in 2004, etc.

Water level and its temperature increase when the secondary local stress by a deformation of the surficial crust by the quake effects compressionally to the water-bearing fractures, and they decrease when the secondary local stress effects relatively tensionally to the fractures.

Thus the change of water level and its temperature of the geothermal wells beared in the fractures is a good indicator of a vectorial change of the local stress field.

Keywords: Water level and temperature change of geothermal spring, vectorial change of local stress field

## Crustal stress around Shikoku and Kii region derived from the construction of integrated groundwater observation network

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GSJ/AIST has been constructing the integrated groundwater observation network around Shikoku and Kii region for forecasting the Tonankai and Nankai earthquakes since 2006FY, and fourteen stations have already been completed. Three observation wells with different depths, usually 30, 200 and 600m, were drilled at each station. Various information about shallow crustal stress was derived by experiments using these boreholes and the drilled cores.

Hydraulic fracturing stress measurements were conducted in the 600m borehole of five stations, where granitic rock was drilled. Flow rate and water pressure were monitored just above the measurement interval to measure the reopening pressure precisely. The measurements were succeeded over a wide range of depths at the station in Toyota, Aichi prefecture, and a reverse fault type stress field with E-W to NE-SW maximum horizontal stress direction was obtained.

Borehole breakout (BB) and/or drilling induced hydraulic fracturing (DIHF) were found at eleven stations on the borehole wall images produced using borehole televiewer/camera. The direction of maximum horizontal stress derived from BB and DIHF as well as the hydraulic fracturing stress measurements ranges between E-W and NE-SW for almost all the stations. This stress direction is perpendicular or largely oblique to the relative convergence direction of Philippine Sea plate to Amour plate. Our results are roughly consistent with the previous stress measurements as well as the focal mechanisms of shallow crustal earthquakes in this region. We are examining the orientation distribution of fractures and its relation to the stress orientations reported here.

Keywords: Shikoku and Kii region, Shallow crustal stress

## Estimation of crustal stress orientations from long-term trends of borehole strainmeters around Kii and Shikoku regions

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Long-term trends measured by borehole strainmeters can be interpreted as the relaxation process of stress disturbance caused by a borehole drilled in stressed rock mass. On the base of this model, the differences of long-term deformations in different orientations are due to an anisotropic stress field so that a borehole is compressed in the direction of maximum horizontal stress. Geological Survey of Japan, AIST has been constructing 14 integrated borehole observation stations in and around the Kii Peninsula and the Shikoku Island since 2006. Crustal strains are being observed with 4-component borehole strainmeters deployed at each station. In this study, we examine the long-term strain measured at each station from a view point of the model of the relaxation process due to stress disturbance by boreholes, and try to estimate the orientation of the maximum horizontal compressive stress by applying this model to strain data.

Firstly we use the strain data of about 700 - 1600 days up to September 2011 since instrument installations at 13 stations, where the strainmeter data were calibrated by comparing actual and theoretical tidal strains with a method of Matsumoto et al. (2011). Secondly, an average strain of 4-component data is extracted from original data to analyze only the anisotropic stress field. Thirdly we calculate the azimuthal distribution of relative change in radial 4 components during 90 days. As radial strain varies with  $\cos 2x$  as shown by this model, we fit a curve of  $\cos 2x$  to the relative change of strain and determine the orientation of maximum compression from the direction of minor axis of a fitted curve, where  $x$  is the angle between maximum horizontal stress and strain gauge. Finally time-varying stress orientations are obtained throughout the entire observed period by moving a time window of 90 days by each one day. The obtained stress orientations are nearly constant in time within a standard deviation of 2 degrees for 9 stations, while the orientations obtained at the other stations show large fluctuations. The stress orientations estimated at the 9 stations are not definite but rather dispersed, being distributed from northeast to southeast. We will compare the stress orientations estimated from this method with other results by hydraulic fracturing, stress-induced wellbore failure and anelastic strain recovery at each station to examine a validity of the proposed method in the next step. Further we will test a viscoelastic model or a poroelastic one to understand a mechanism of the long-term trend of the borehole strain data.

Keywords: crustal stress orientation, borehole strainmeter, long-term trend, Kii Peninsula, Shikoku Island



## Analysis Stress Field Heterogeneity by Using Logging Data

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In general, it is considered that underground stress field is almost homogeneous. Thus stress state, which is measured locally, is identified as representative stress in whole area. However, it can be predicted that stress state is complicated around discontinuities like fault. So I tried to analyze how stress state is fluctuated around fault by logging data at Nankai Trough. I estimated principle stress direction and range of that magnitude from borehole failures.

I found that principle stress direction is rotated around fault. Maximum stress direction is rotated to parallel with surface of fault outside of fault zone, where is softer than around rock, and rotated to normal to the surface inside. And magnitude of stress is increasing outside of fault zone, and decrease inside. And it can be considered that such fluctuation of stress state is caused by difference of rock properties between outside and inside of fault.

Keywords: Stress, logging, Nankai Trough, LWD, borehole breakout

## Transitional patterns of crustal stress field between Honshu arc and Ryukyu arc in Japan

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Deformation and stress state in active island arcs are important for understanding the dynamics. We analyzed crust stress state in the connective region between Honshu and Ryukyu arc to understand the transitional stress between with and without backarc opening of the arcs around southwestern Japan arc. In this study, we apply the multiple inverse method (Otsubo et al., 2008) into the focal mechanism solutions (best double couple components of regional moment tensors derived by F-net, NIED, Japan) in the area. The data were obtained from about ~400 shallow earthquakes (< 20 km) since January 1st, 1997 to December 31st, 2010. All local magnitudes were greater than 3.0. As a result, the multiple inverse method shows different stress province from one found by P-/T- axes. In perspective view, Shmax and Shmin directions rotate gradually from Honshu to Ryukyu. This result constrains patterns of the fan shaped stress trajectory between compressive Honshu arc and extensional Ryukyu arc, which is important issue to the understand geodynamics of subduction zone island arc. In addition, the multiple stress solutions and these stress ratio variations indicate locally heterogeneous stress states between Honshu arc and Ryukyu arc.

### Acknowledgements:

Thanks are also due to the National Research Institute for Earth Science and Disaster Prevention (NIED) for making available the focal mechanism data in the study area.

### Reference:

Otsubo, M., Yamaji, A. and Kubo, A. (2008) Determination of stresses from heterogeneous focal mechanism data: An adaptation of the multiple inverse method. *Tectonophysics*, 457, 150-160.

Keywords: Focal mechanism, Stress, Subduction, Stress tensor inversion, Earthquake, Kyushu

## Parametric and non-parametric methods of determining paleostress from dykes or veins

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Orientations of dykes and veins are clues to ancient tectonic stress states. Newly formed open fractures in intact rock masses are expected to be perpendicular to the minimum compressive principal stress ( $\sigma_3$ ) axis. Jolly and Sanderson (1997) extended this concept for re-opening of pre-existing fractures. Their model allows us to infer orientations of three principal stress axes and stress ratio  $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$ , and it provides a basis for the determination of stress magnitudes (Andre et al., 2001). The difficulty of this method is in the recognition of border of orientation range since the frequency of fractures gradually decreases toward the border in most cases. Yamaji et al. (2010) solved this problem by fitting the Bingham (exponential) distribution to the orientational frequency of fractures. This method need not specify the border of orientation range. The basic assumption of their method is the monotonous decrease of fracture frequency against the tectonic normal stress.

However, there can be a fracture distribution of which frequency decreases not exponentially. This study proposes two modified methods. One employs a shifted power type of stochastic model, which has a larger degree of freedom and can express various types of decreasing function flexibly. It should be noted that the shifted power model has an advantage in determining relative value of fluid pressure  $\lambda = (P_f - \sigma_3) / (\sigma_1 - \sigma_3)$ , where  $P_f$  is the fluid pressure. Another modified method is non-parametric and does not use a stochastic model. This method searches for an optimal stress state which minimizes the rank correlation coefficient between fracture frequencies and normal stress magnitudes at all possible orientations. The advantage is in the exclusion of extra assumption on the type of orientation distribution.

For the purpose of testing the new methods, we analyzed simulated fracture datasets. Firstly, the three methods were applied to a simulated dataset obeying a Bingham distribution. As results, correct principal stress orientations and stress ratio were commonly obtained within confidence ranges. The precisions and accuracies of Bingham and shifted power models were equivalent and higher than those of non-parametric method. Secondly, a simulated dataset obeying stepwise distribution were analyzed to find that the shifted power model was superior to the other two methods in precision and accuracy. Consequently, the shifted power model generally performs well, while the non-parametric method is also useful with acceptable precision for its fewer assumptions.

We applied the methods to the Early Miocene andesitic dyke swarm intruded into Mino-Tamba Belt around Tsuruga city, Fukui Prefecture (Hoshi and Takagawa, 2009). The three methods commonly resulted in a normal-faulting stress regime with a NW-SE trending  $\sigma_3$  axis. The precisions of Bingham and non-parametric methods were similar, while that of shifted power method was superior to them. The type of frequency distribution of dykes was nearly linear, and a stress ratio of  $\Phi = 0.66 \pm 0.19 / -0.22$  and a relative fluid pressure of  $\lambda = 0.76 \pm 0.06 / -0.16$  were obtained. Although the shifted power model cannot deal with a complicated frequency distribution in comparison to non-parametric method, it is useful for the objective determination of relative fluid pressure which is an important parameter to investigate crustal dynamics.

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Keywords: stress tensor inversion, dyke, vein, fluid pressure, non-parametric statistics

## Paleostress analysis using healed microcracks in the Ryoke granites, southern Chubu District.

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Paleostress analysis using 3-D orientation distribution of healed microcracks (HC) in quartz grains was carried out for the Ryoke granites in the southern Chubu District, central Japan. From the previous microthermometry analyses on the fluid inclusions forming HC in the Ryoke (Toki) granite (Takagi et al., 2008), the healing temperature were estimated about 300-400deg.C near the blocking temperature for the K-Ar system of biotite. The samples analyzed are Busetsu, Inagawa and Obara granites that are distributed between previously analyzed Shinshiro tonalite and Toki granite bodies in which the sigma-3 orientations of HC are very different in both granitic rocks (Aizawa and Takagi, 2008, Takagi et al., 2008). The orientation distributions of HC show two or three maxima nearly orthogonal each other. This orthogonal concentration pattern is probably due to the transposition of principal stress during microcrack formation. To clarify the orthogonal concentration pattern, we used cluster analysis and reconstructed sigma-3 orientations. The angles of sigma-3 orientations with respect to the strike of the Median Tectonic Line (MTL) tend to increase gradually towards the MTL from around 30deg. plus or minus 40deg. in the Toki granite (northernmost) to 83deg. plus or minus 27deg. in the Shinshiro granite (southernmost) near the MTL.

The sigma-Hmax orientations (normal to the sigma-3 orientation on the horizontal plane) intersect the strike of MTL at a distance from the MTL in the Toki and peripheral areas suggest the regional compressive stress field caused by the movement of subducting Pacific Plate at early Paleogene (K-Ar biotite ages for the Toki granite). On the other hand, sigma-Hmax orientations subparallel to the strike of the MTL near the MTL suggest the changes in stress field by the activity of the MTL and/or the influence of the uplift of the high-P/T type Sanbagawa metamorphic terrane underlying the Ryoke terrane by the MTL (Takagi et al., 2008).

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Keywords: Healed microcrack, Paleostress analysis, Median Tectonic Line, Ryoke granite

## Modeling of fold-and-thrust belt by analogue experiment and simulation considering erosion

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Fold-and-thrust belt is modeled by sandbox experiment and distinct elemental method considering erosion. As a result of experiment, over burden stress variation by erosion makes an effect to the geological deformation. In the simulation we could observe that stress concentrates just before thrust occurs and stress is released by thrust's activity.

Keywords: structural deformation, fold-and-thrust belt, sandbox experiment, distinct element method, erosion, stress change