Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG65-01 Room:423 Time:May 2 09:00-09:15

Reconstraction of paleostress states in the Walanae fault zone in South Sulawesi using the multiple inverse method with

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Paleostress analysis using the multiple inverse method with calcite twin data was performed in the East Walanae fault (EWF) zone in South Sulawesi, Indonesia. The geomorphic trace of the EWF can be recognised as a distinct line between the Bone Mountains and the Walanae Depression, around which an intensive deformation zone characterised by various scales of faults and folds are developed. Carbonate rocks with numerous calcite twins and mesoscale faults are ubiquitous around the EWF trace. Therefore EWF zone is a useful location for testing the inclusion of calcite twin data in the multiple inverse technique to determine paleostress states. One to three poles of differently oriented twin lamellae and c-axis orientation were measured for each grain from three mutually perpendicular thin sections for 11 samples using a U-Stage optical microscope. The data set for multiple inverse method consists of the attitude of the e-plane, gliding direction and sense of shear of e-twinning. We prepared data files not only for twinned e-planes but also for the remaining untwinned e-planes in a grain with one or two twin sets. We incorporated the untwinned e-plane data for determining stress states with the multiple inverse method using calcite twins. In the analysis, the identified stress states by twinned e-plane data were tested calculating misfit angle β, the angle on the untwinned e-plane between the calculated maximum shear stress direction for every identified stress state and the observed potential gliding direction. It is possible to say that the sampled rocks had never experienced stress states to activate any of the untwinned e-planes. Therefore, if most untwinned e-plane data (95% or more in this study) are incompatible($\beta >$30 degree) with the stress state identified from twinned plane data, then the stress state is viable for both the twinned and untwinned e-planes.

The analysis using calcite twin yielded reliable paleostress states similar and consistent with those from fault-slip data throughout the study area. Dominant and common stress states are characterized by NE-SW-to-E-W-trending σ1 and vertically to moderately-south-plunging σ3 with generally small values of stress ratio ϕ. These stress states were most likely caused by collision of eastern Sulawesi with the Australian fragments since the Pliocene, and they could have activated the EWF as a reverse fault with a dextral shear component, accounting for the contraction deformation structures and landforms along the trace of the fault. Calcite twin and mesoscale faults were activated predominantly during the fold tightening stage and subordinately before folding.

Keywords: multiple inverse method, calcite twin, Walanae fault zone

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SCG65-02 Room:423 Time:May 2 09:15-09:30

Capability of calcite twin for estimating stress magnitudes and orientations

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Calcite has three e-twin planes, each of which has a critical resolved shear stress at ~10 MPa along the twin gliding direction; and the planes and direction have certain crystallographic orientations (e.g., Lacombe, 2010). We quantified the tightness of the constraints from twin and untwin data on stress conditions. It is shown that twin and untwin data place tight constraints if differential stress is low and large, respectively. Their tightness converges to the same value with increasing differential stress. The constraint from a calcite grain becomes tighter with increasing number of twin sets in the grain. It is also shown to be important to cope with sampling bias to utilize untwin data: The number of twin data compared to the total of twin and untwin ones tend to be underestimated by ~25%. It is found that calcite e-twin loses resolution in determining stress magnitudes and orientations if differential stress is greater than ~200 MPa.

Keywords: twin, calcite aggregate, stress

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SCG65-03 Room:423 Time:May 2 09:30-09:45

Enhanced detectability of stress tensor inversion from heterogeneous fault-slip data with preferred orientations

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Fault planes occasionally have preferred orientations according to the slip tendency (e.g., Lisle and Srivastava, 2004), which is defined as the ratio between normal and shear stresses (Morris et al., 1996). In contrast, most stress tensor inversion methods calculate crustal stress states from fault-slip data on the assumption that faults slip along the resolved shear stress vectors on their surfaces. This assumption called Wallace-Bott (W-B) hypothesis allows low values of slip tendency on "misoriented" faults so as to consider faulting along pre-existing weak surfaces in rock masses. However, the weak assumption causes the loose constraint on stress. For example, when a set of conjugate faults is observed, one usually determines principal stress axes as bisectors of fault planes. On the contrary, W-B hypothesis permits only to constrain the axes within the angle between fault planes. Such a disadvantage severely lowers the detectability of multiple stress conditions from heterogeneous fault-slip data. To avoid this problem, this study proposes a new method of stress tensor inversion by combining the W-B hypothesis and the slip tendency.

This study employed a stress tensor inversion method called HIM (Yamaji et al., 2006; Sato 2006) which maximize the fitness between observed slip directions and shear stress vectors. The fitness value is modified to be the product of the conventional fitness and the slip tendency. Artificial fault-slip data are analyzed to examine the performance of the new method. The data set includes 200 faults compatible with N-S compressional stress and 50 faults compatible with E-W tensional stress. The former has random orientations of fault planes and the latter has a preferred orientation so that they have large values of slip tendency. As the result, the conventional HIM could not detect the latter stress, while the new method could detect both stresses.

The new method is applied to fault-slip data from Late Miocene Awa Group in eastern Boso Peninsula. Mesoscale faults in this area have at least two different origins; reverse-faulting stress and normal-faulting one (e.g., Angelier and Huchon, 1987). The new method successfully detected both stresses without a priori classification of faults into subsets.

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Keywords: stress tensor inversion, heterogeneous fault-slip data, slip tendency, orientation distribution

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SCG65-04 Room:423 Time:May 2 09:45-10:00

Reconstruction of absolute stress based on a condition of aftershock occurrence

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Absolute crustal stress is essential to understand the earthquake generation process. If focal mechanisms both before and after an earthquake together with the fault slip model of the earthquake are available, the magnitude of absolute stress can be constrained (e.g., Hardebeck and Hauksson, 2001; Wesson and Boyd, 2007; Yang et al., 2013). However the application of those methods is inherently limited, because background seismicity is generally low. In this study, we propose a method to reconstruct an absolute stress field incorporating a condition of aftershock occurrence, which is applicable to areas without enough pre-mainshock focal mechanisms.

We suppose that there are pre-existing weak planes represented by aftershock focal mechanisms. Because these planes were locked before the mainshock but afterwards activated, it is reasonable to expect that the slip-tendency, defined by the ratio of shear to normal stress acting on a given plane (Morris et al., 1996), increases after the occurrence of the mainshock. On the basis of this consideration, we search the best absolute stress field as follows.

(1) We assume a pre-mainshock homogeneous absolute stress field (**B**) in the study area. We then compute a post-mainshock stress field (**A**) at each aftershock location by combining the stress change due to the mainshock and the aforementioned pre-shock stress field.

(2) For the fault plane of each aftershock, we compute a pre- and a post-mainshock slip-tendency ($T_s{}^b$ and $T_s{}^a$, respectively) based on the pre- and post-mainshock stress fields, **B** and **A**, respectively. Regarding the computation of $T_s{}^a$, we adopt the component of stress acting in the slip direction on a fault instead of the shear stress itself. Therefore, $T_s{}^a$can have a negative value.

(3) We compute the summation of $T_s{}^a$ of aftershocks that satisfy the condition of $T_s{}^a > T_s{}^b$. If both nodal planes satisfy the condition, the larger $T_s{}^a$ is used for the summation.

(4) We repeat the procedure (1) to (3) by changing the initial stress field **B**, and search a stress field that has the largest sum of $T_s{}^a$.

Numerical tests of this method work well. It is noted that multiple candidates of stress fields were inferred, if we did not incorporate the condition of $T_s{}^a > T_s{}^b$, suggesting that the condition is important in the situation without pre-mainshock focal mechanisms. We then applied the method to the 2013 M6.3 Awaji Island earthquake. Focal mechanisms of 115 aftershocks were determined from P-wave polarity data as well as body wave amplitude. A finite fault slip model of the mainshock was derived from slip inversion analysis (see Uchide and Ide, 2007) of KiK-net strong-motion data. A preliminary analysis shows that the pre-mainshock stress field is characterized by a reverse-faulting regime with a WSW-ENE oriented maximum compression and the differential stress of 200-300 MPa.

Acknowledgements: Seismograph stations used in this study include permanent stations operated by NIED (Hi-net, KiK-net), JMA, ERI, and DPRI. We modified a program coded by Satoshi Ide to estimate the focal mechanism solutions. We thank Yoshimitsu Okada for the use of his code in our stress change computation.

Keywords: absolute stress field, aftershock, focal mechanism, 2013 Awaji Island earthquake, slip-tendency

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SCG65-05 Room:423 Time:May 2 10:00-10:15

Motions after rainfall in borehole tiltmeters and the azimuth of crustal stress before and after 2011 Tohoku Earthquake

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Shimada (1987) has revealed that in borehole telemeter generally the tilt motions after rainfall are tilting to a certain azimuth which is named 'rainfall component', and the perpendicular azimuth is named 'rainfall-free (RFF) component'. In the time series of the RFF component, very little motions are seen after rainfall. From the observations of tiltmeters in NIED Kanto-Tokai network, Shimada (1987, 1989) has found that the azimuths of the RFF component are generally coincided with the azimuth of the crustal maximum compressive stress obtained from the experiments of hydrofracturing and the mechanisms of middle or large scale earthquakes. This is interpreted that the azimuth of the strike of the nearby open crack of the borehole is generally coincided with the azimuth of the crustal maximum compressive stress.

In this study, we examine the azimuth of tilt motions after rainfall for Hi-net borehole high-sensitivity accelerometer (tiltmeter) in the periods from April to December in 2010, 2011, and 2012 before and after the 2011 Great Tohoku Earthquake in the region of the border of Ibaraki and Fukushima prefectures, and the time variations of the azimuth of the maximum principal crustal stress.

The left figure shows the azimuth of the RFF component of the seven borehole tiltmeters in this area obtained from the time series from April to December 2010. In IWEH site, the azimuth of the RFF component is almost N-S direction, suggesting in the nearby area of this site the maximum compressive stress was not E-W direction even before the 2011 Great Tohoku Earthquake. Among the sites south of IWEH site, in the sites near IWEH site and coastal sites the RFF components are generally almost NE-SW direction, suggesting in the area the maximum compressive stress does not coincide with E-W direction which is seen widely in NE Japan before the 2011 Great Tohoku Earthquake.

The right figure shows the azimuth of the RFF component of the same seven borehole tiltmeters obtained from the time series from April to December 2011 or 2012. In this period, there occurs many offsets and large drifts after those offsets arose by the induced earthquakes and aftershocks of the 2011 Great Tohoku Earthquake, and it is not so easy to detect the detections of the motions after rainfall and the azimuth of the RFF components comparing with the period in 2010. In HTAH and YBKH sites, there seems very little time variations in the azimuth of the RFF component. Also in IWEH site, the time variation of the azimuth of the RFF component is only 10 degree. In IWWH site, the azimuth of the RFF component changes significantly, and almost N-S direction. In DGOH site also the azimuth of the RFF component changes from the NE-SW direction before the earthquake to the NNE-SSW direction. In THGH sites, there are very large noises in N-S component in 2012, which is probably mechanical faults, and there seems very little time variations in the azimuth in 2011 compared with that in 2010. In JUOH site, very little tile motions are seen after rainfall, suggesting the closing of the crack opened in 2010 because of the time variations of the azimuth of crustal stress.

Estimating from the tilt motions after rainfall before and after the 2011 Great Tohoku Earthquake in the Hi-net sites in the area of the border of Ibaraki and Fukushima prefectures, it is suggesting that the area with the N-S direction maximum compressive stress is exist near the IWEH site even before the earthquake, and that mainly in the area west of IWEH site the maximum compress stress shifts near N-S direction after the earthquake.

Keywords: borehole tiltmeter, tilt motions after rainfall, azimuth of crustal stress, 2011 Great Tohoku Earthquake

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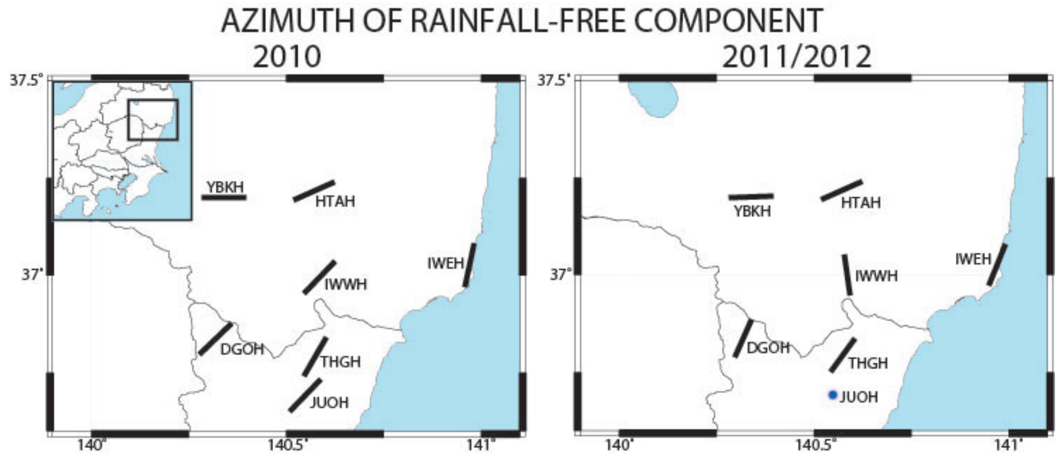

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SCG65-06 Room:423 Time:May 2 10:15-10:30

Evaluation of faults in the site of power plants and stress analyses

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The expert meeting on the investigation of fracture zones in the site of the Ohi power station of NRA (Nuclear Regulation Autority) concluded that the F-6 fault in the site is not an active fault. Stress tensor inversion was a key technique to make the conclusion during the discussion. In this talk, I will explain how stress tensor inversion was used to evaluate the faults.

It is difficult to evaluate faults based on paleoseismological techniques in the site of many of the power plants, due to the lack of young sediments and tectonic landforms. For the evaluation of the safty of the power plants, it is important to evaluate if the faults in the site are active. Degree of the activity of the faults is not always important. Stress tensor inversion based on the fault slip data is useful because the phenomenon is relatively clear.

There are two concepts to evaluate if the faults are active or not using stress analyses. One is to compare the structures in the fault with the present stress such as slip tendency. The other is that stress tensor inversion is used as a tool to construct the tectonic histories. The former concept may have a problem concerning the stability of stress, especially after large earthquakes. The later concept used stress tensor inversion to determine the sequence of tectonic stages. Tectonic stage is the period during which faults had repeated to move due to the control of similar stress condition. Once the structures in faults at different places were identified to be controlled by the same stress condition, those structures were formed during the same tectonic stage. The comparison of the result of this analysis with the result of fault trenching enables us to evaluate if the faults are active or not.

Keywords: power plant, fracture zones in the site, stress tensor inversion, tectonic stage

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SCG65-07 Room:423 Time:May 2 10:30-10:45

Stress rate dependency and effect of volatile element on seismicity of volcano-tectonic earthquakes

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Even in a quiescent period, magma is charged and discharged intermittently beneath volcanoes, and volcano-tectonic earthquakes often occur with ground inflation that is caused by upward migration of magma. Moreover, an increasing volatile element sometimes leads an increasing seismicity. Therefore, it is well known that the seismicity around a volcano is one of the well-established indicators of volcanic activities. Many evidences show that increasing seismicity is followed by volcanic eruptions or magma intrusions because magma migration makes large stress change. On the other hand, the increasing seismicity does not always result in volcanic eruptions. We need to evaluate seismicity quantitatively and discriminate some kinds of effects that generate earthquakes. At present, research in this field has not been established well. It is partly because we cannot propose the model that express temporal variation of seismicity quantitatively, and we do not have enough observation data except some volcanoes where dense observation networks are installed multi-disciplinary.

We proposed to apply the Rate and State Friction (RSF) law to the seismicity occurring at Izu Oshima volcano where dense GPS network as well as seismic one are installed. At the volcano, stress rate changes are observed every 1 to 2 years because of the intermittent magma charging and discharging processes. We presented in last fall meeting of volcanological and seismological society that a simple RSF law model cannot reproduce the observed seismicity fully. We try to revise the model and get remarkable improvement. Aim of this presentation is to reveal the effect of stress rate as well as the other effect, such as volatile element emitted from magma that affect the seismicity around volcanoes, and demonstrate that the seismicity has large potential to monitor the condition not only in the stress rate but also in the volatile density beneath volcanoes.

In Izu-Oshima volcano, seismicity is well correlated with stress rate caused by magma accumulation except the period after the long-term inflation is weaken in 2011. In several volcanoes, increasing volatile component causes decreasing normal stress at fault plane in seismogenic zone and earthquakes are generated intensely (e.g. Northern Volcanic Rift zone in Iceland, La Fossa volcano in Italy). The weakened inflation means that fresh magma is less supplied and emission of volatile decreases in Izu-Oshima volcano. Therefore, we added the effect of the increasing and decreasing volatile element in the previously proposed RSF law, and revised the model. Finally, we can complete successfully the revised model that realize the observed seismicity for all analyzed period.

In conclusion, temporal variation in seismic activity around volcano is mainly due to changes in stress field generated by the magma accumulation and partly caused by effect of volatile element that affects the confining pressure of the fault surface at seismogenic zone. The effect of the stress field is well modeled by ordinary RSF law, and its parameters can be estimated from the data in quiescent period. If observed seismicity exceeds the level that estimated from the model, the volatile element much emitted from magma and it may be precursor to the volcanic eruptions. Therefore, the difference between observed seismicity and the calculated one based on the RSF law is one of the powerful indicator to forecast volcanic eruptions. We propose that there are two kinds of earthquake generating mechanisms around the volcano. Further study at other volcanoes will be helpful to understand the volcano-tectonic earthquake systematically. In future, we should examine the model from direct observation of volcanic gas at volcanoes.

Acknowledgements: We are much grateful to GSI for providing GNSS data.

Keywords: volcano-tectonic earthquakes, seismicity, stress rate change, ground deformation, volatile element

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SCG65-08 Room:423 Time:May 2 11:00-11:15

Investigation into stress field and strength at hypocenters at South African gold mines

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We report on in-situ stress measurements at seven sites at South African gold mines. The depth ranged from 1.0 to 3.4 km (deepest level in the world where mining is in progress). The measured maximum stress ranged from to 146MPa. In the ranges of stress above 100 MPa have not been able to be measured before we introduced a downsized Compact Conical-ended Borehole Overcoring technique (CCBO; ISRM suggested) in South African gold mines, which has several advantages over the methods widely used in South Africa.

The in situ measurements were carried out at the sites with minimal disturbance by mining or geological features at depths of 3.3 and 3.4 km at Tau Tona and Mponeng mines, respectively, both allowing confirmation that the virgin stress assumptions in the mine were acceptable with slight modification. With the modified virgin stress assumptions, the loading conditions for seven seismic events (ML $>$2.9) over a 9-year period at Tau Tona mine were back-analyzed with an elastic boundary element method that allows non-linear ride and closure on displacement discontinuity elements (Map3D Fault-SlipR), successfully constraining the stress or the strength on the source faults. At the Pink and Green dykes at 116L at Mponeng mine, the rupture plane of a ML2.1 event was finely delineated by the Japanese-German acoustic emission (AE) network with eight AE sensors deployed within several tens of meters from the rupture plane. It was confirmed that, with the virgin stress assumption and the strength, Map3D was able to reproduce an area of ride consistent with the rupture plane delineated by the AE network. A hole of about 90m length was drilled to intersect the ML2.1 rupture plane to constrain stress by analyzing borehole breakout and core discing. The stress thus constrained was consistent with those estimated with Map3D although the former is a little bit larger than the latter. In situ stress measurements were carried out near seismic damage caused by a ML1.5 event, which took place in the area that a Map3D model with simplest geology structure could not predict high stress. The measured stress state was comparable to that evaluated at the above-mentioned seismic sources.

Seismicity is high at a shaft pillar at 1.0 km depth at Ezulwini mine, where BX CCBO stress measurement was carried out. The measured maximum principal stress was significantly higher than the stress at sites at 3.4km depth with no mining activities.

Keywords: SA gold mines, Seismogenic areas, Stress, Strength, In-situ observation