Cretaceous-Paleogene forearc basin structure and seamount subductions illuminated by the 2011 great Tohoku, Japan, earthquake

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November 22 2016 Mw=6.9 (Mj=7.4) Fukushima-oki earthquake, triggered ~2-meter-high tsunami to Sendai Bay, minds us of long-lasting off-fault aftershocks, continuous high seismic and tsunami hazards associated with the March 11, 2011 M9.0 Tohoku-oki earthquake. The Tohoku-oki earthquake has indeed turned on the shallow offshore and onshore normal faulting earthquakes in the Pacific Coast regions of southern Tohoku, as well as the abundant on-fault aftershocks. As the result of stress calculations, responding seismicity, geologic and geomorphic analyses, we here argue that the Tohoku-oki earthquake shed a light on complex structure associated with Cretaceous-Paleogene forearc basin structure and subsequent seamount subductions.

To understand the post-Tohoku-oki seismicity in the region, we first calculated coseismic static Coulomb stress change on the crustal faults on the overriding plate by the 2011 Mw=9.0 Tohoku earthquake using a variable slip model of Iinuma et al. (2012). As already reported by Toda et al. (2011), we found shallow normal faults onshore and offshore Fukushima brought 2-4 MPa closer to failure. Most Coulomb stress changes resolved on nodal planes of the post-Tohoku-oki earthquakes are positive, which is consistent with the high seismicity in this region. In contrast, thrust faults offshore Miyagi and Fukushima are calculated to have brought 0.5-3 MPa farther from failure. However, it is interesting to note that the Tohoku earthquake did not shut off the reverse faulting earthquakes near the Japan trench, which can be explained by stress increase to crustal reverse faults from the southern slip patch (Iinuma et al., 2012) of the Tohoku-oki earthquake

Another noteworthy feature in seismicity off-shore Pacific Coast of southern Tohoku is a significant contrast between very active seismic area (Fukushima-oki) and aseismic area (Sendai Bay).

About-100-km-wide NE-trending normal faulting active seismic zone, extending from onshore Fukushima-Hamadori to offshore Fukushima, is roughly parallel to the trend of Kashima-Daiichi seamount chain and outer-rise fracture zones on the subducting Pacific plate. In addition, detailed bathymetric shaded relief map (Izumi et al., 2012), showing numerous complex geomorphic features typically seen in other seamount collisions and subductions (e.g., cookie bite structure, Dominguez et al, 1998; Wang and Bilek, 2011), allows us to infer that a similar seamount chain of the Kashima-daiichi subducted in the past and left the complex fault networks into overlying crust. They are also superimposed on the forearc basin structure developed in the Cretaceous-Paleogene periods (e.g., Iwata et al, 2002). In contrast, seismicity in Sendai Bay is completely quiet and one could mistakenly point out seismicity in Sendai Bay is in a typical stress shadow. But the amount of stress increase for normal faults due to the Tohoku-oki earthquake in Sendai Bay is approximately the same as the one for offshore Fukushima. Because Sendai Bay is located off the Joban forearc basin and farther west of damaged zones of the seamount subduction, we interpret such no seismic response is probably due to a paucity of potential normal faults. We thus conclude the current seismicity offshore and onshore Pacific Coast of southern Tohoku is a product of a combination of inherited geologic structure and stress transfer from the 2011 Tohoku-oki earthquake.

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Keywords: Tohoku-oki earthquake, seamount subduction, Coulomb failure stress change

3D Discrete Element Simulation of Faulting and Crustal Thickening during the India-Asia Collision

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Understanding the discontinuous nucleation, growth, and interaction of large faults within continental collision zones remains a challenge. From 55 Ma onwards, the India-Asia (I-A) collision has produced the largest present-day continental deformation zone. The collision activated large strike-slip fault zones, and generated mountain ranges and the Tibetan plateau. Previous 2D analog experiments simulating the India-Asia collision successfully modeled the development and kinematics of large strike-slip faults within the Eurasian plate, but were dynamically unscaled with gravity and did not allow the development of topographic relief. Here, we use the YADE Discrete Element Modeling (DEM) code to produce a suite of 3D models scaled with gravity. These 3D DEM models simulate two plate-boundary size strike-slip faults that extrude and rotate coherent continental blocks. The locations, lengths, ages and offsets of these modeled faults are consistent with those of the Red River (RR) and Altyn Tagh (AT) mega-faults. In the model, the RR fault is observed to change sense after the activation of the AT fault, as was the case for the Red River fault. This is the first time any type of model or simulation of the I-A collision reproduces such a fundamental geological change. As in the Asian collision zone, the deformation of the model is observed to be fully 3D. In addition to strike-slip movement, large-scale thrust faults progressively generate the growth, from south to north, of a large plateau. This is in general agreement with the stepwise, northwards rise of the Tibet-Qinghai plateau. Analyzing the timing of the shortening accommodated by vertical and horizontal deformations suggests that they partly alternate. Our model results are thus broadly consistent with the observed topographic, tectonic and geological evolution of Eastern Asia in the last ~50 million years.

Keywords: SIMULATION, COLLISION

Shear stress and earthquake mechanism of a shallow subduction zone as inferred from elastic plate models

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1. nothing

Shear stress characteristics of a shallow subduction zone are investigated based on elastic plate models. One of the basic models examined is the plate model UMB-Plate (Yoshida, 2015; 2016). Young's moduli and Poisson's ratios for the oceanic (Plate 1) and continental (Plate 2) plates and the upper mantle (LMS) are adopted from those used in the study of earthquake cycle simulation in southwest Japan (Hori et al., 2004). Two transitional layers at the plate boundary (PB) between Pate 1 and Plate 2 and the upper mantle boundary (UMB) between Plate 1 and LMS are assumed in the model, which correspond to low viscosity layers (Seno, 2001). Young's modulus of mild steel of rubber-like-elasticity and Poisson's ratio of elastic rubber are used for the PB and UMB.
The shear stress is calculated using the finite element method in the case of plane strain. The plate model with the thickness of 30 km and the length of 60 km is rather close to the vertical cross section of the crust and upper mantle in the Tokai district, southwest Japan. The shear stresses calculated show that they are mostly negative for Plate 1 and positive for Plate 2 and PB. A positive shear stress zone exists in a deeper part beneath the trough at depths of 10-25 km. Comparing these shear stress pattern with several earthquake mechanisms near the Suruga trough (JMA, 2009), normal fault earthquakes are located inside the subduction zone of the negative shear stress area. On the other hand, reverse fault earthquakes are located at the land side of the positive shear stress area.
Shearing force is a couple of forces acting on two sides of a minute particle of matter. If the mechanical property of shearing force is taken into consideration, the shear stress pattern obtained in the present coordinates system suggests that the shearing force acts counterclockwise toward the oceanic side in the subduction zone while it acts clockwise toward the land side in the continental plate. The shear stress calculated depends on the elastic plate model. It is necessary for us to improve the subducting oceanic plate model so that we can appropriately represent the shear stress field near the Suruga trough.

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Keywords: shear stress, subduction zone, finite element method

Directivity moment tensor inversion toward automated estimates of earthquake rupture properties

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Rupture directivity is a first-order characteristic of the seismic source finiteness and observed ubiquitously for not only large but also small magnitude earthquakes. With directivity effect, seismic waves radiated in the direction of rupture could be greatly amplified, and even moderate magnitude earthquakes can sometimes cause serious damage. Thus, knowing directivity information of earthquakes is fundamentally important for ground shaking prediction and hazard mitigation, and is also useful for discriminating which nodal plane corresponds to the actual fault plane as if the event lacks aftershocks and outcropped fault traces. While the detailed rupture process of large earthquakes is commonly imaged by finite fault inversion and backprojection methods, for the small-to-moderate earthquakes the methods that utilize single source parameter (e.g. source duration, corner frequency, etc.) determined at stations at different azimuths to determining directivity are usually employed. However, these methods usually require sophisticated processing and good station distribution to obtain reliable results. Here, we propose a directivity moment tensor inversion method through direct waveform fitting with source time functions stretched for each station according to given rupture vector. By grid searching the rupture vector (i.e. directivity) in 3-D space, this method provides uncertainty estimation and is easily to be automated. The byproducts of derived rupture velocity and source duration can then be used for further estimates of rupture extent and stress drop. We perform extensive synthetic tests and real applications to the MW 6.2 Nantou, Taiwan earthquake, MW 7.0 Kumamoto, Japan earthquake, and MW 4.7 San Jacinto fault earthquake in southern California to validate the method. The obtained results show good agreement with previous studies and demonstrate the applicability of this method to a wide magnitude range of earthquakes.

Keywords: Rupture directivity, Rupture velocity, Stress drop, Realtime application

Importance of three-dimensional grids and time-dependent factors for the applications of earthquake forecasting models to subduction environments

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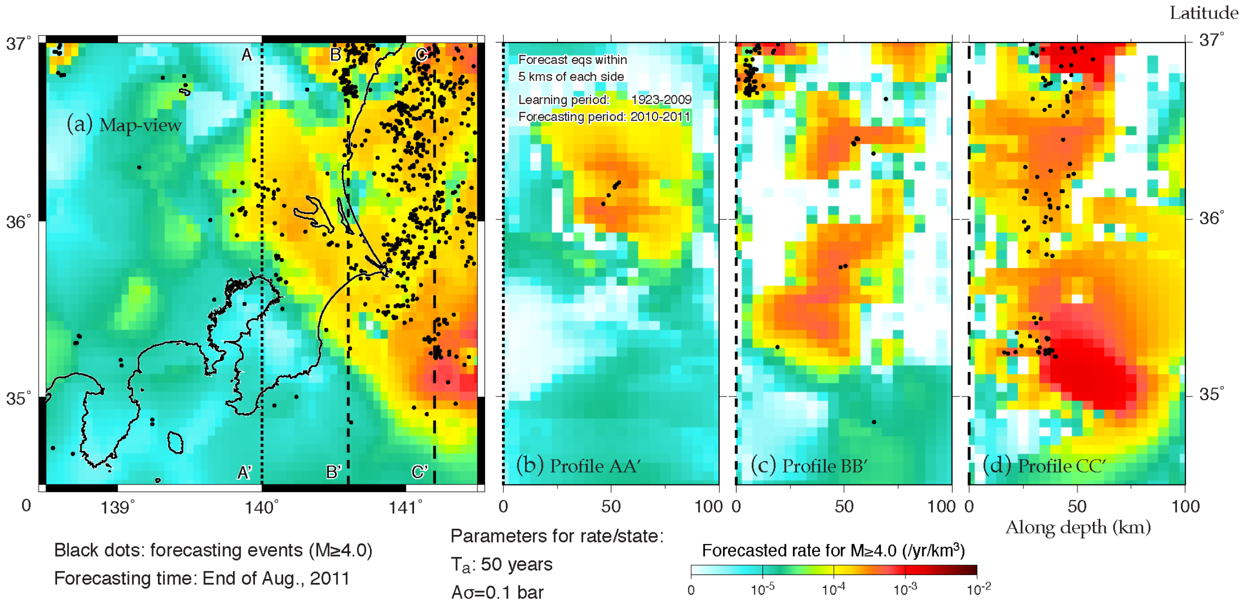
This study provides some new insights into earthquake forecasting models to the regions with subduction systems, including the depth-component for forecasting grids and time-dependent factors. To manifest the importance of depth-component, a forecasting approach, which incorporates three-dimensional grids, is compared with that with two-dimensional cells. Through applications to the two subduction regions, Ryukyu and Kanto, the approaches with three-dimensional grids always obtain better forecasting ability. I thus confirm the importance of depth-dependency for forecasting, especially for the applications to a subduction environment or a region with non-vertical seismogenic structures. In addition, this study discusses the role of time-dependent factors for forecasting models and concludes that time-dependency becomes crucial only during the period with significant seismicity rate change that follows a large earthquake.

Keywords: Coulomb stress change, earthquake forecasting, subduction zone



Nankai Gemechanical Model: the stress tensor determination in the vicinity of subduction zone

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In last five years, we processed the massive logging data and core samples in Nankai area for determining the stress evolution in this interseismic period after 1944 Tonakai earthquake. The 3D geomechanical model is developed by the slip deficit model and finite-element model in this research. These detailed models are used to determine the wide scale stress field in the Nankai. The drilled IODP well sites are designed to be the fine control points in our geomechanical models. Based on the multiple ICDP expeditions near the Nankai trough (C0002A, F, and P) in different depths, the one-dimensional stress profile can be confirmed with the lateral boreholes loggings. Even the recently drilling did not reach the subduction zone; the stress state in site C0002 is the best control point of Nankai. Our models provide the considerable results by the reliable boundary conditions. This model simulated the stress orientation and magnitude generated by the slip deficit model, area seismicity, and borehole loggings. Our results indicated that the stress state keeps in normal faulting stress regime in our research area, even near the Nankai trough. Although the stress magnitude is increasing with the depth, one of the horizontal principal stresses (Shmin) is hardly greater than the vertical stress (overburden weight) in the reachable depth (>10km). This result implies the pore-pressure anomaly would happen during the slip and the stress state would be varied in different stages when the event occurred.

Keywords: Slip deficit model, Stress state, Subduction zone, Geomechanical model, NanTroSEIZE

Stress inversion of orientation data from calcite twins: A clue to stress magnitudes

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Mechanical twins are usually observed in natural calcite under a microscope. Methods of their stress inversion are briefly reviewed in this paper. Unlike faults and seismic focal mechanisms, calcite twins provide us of the opportunity to estimate stress magnitudes.

The twins have a specific crystallographic orientation. Their formation results in the simple shear of a calcite grains along the lamellae. The twinning is allowed on condition that the stress component along the shearing direction is greater than a critical value, tau_c. Since the stress component depends on the orientations of planes in a crystal under a state of stress, the orientations of twinned planes in a calcite aggregate indicate the stress that formed the observed twin lamellae. The inversion determines not only the principal orientations and stress ratio, but also the non-dimensional differential stress normalized by tau_c. The inverse method based on this principle (Etchecopar, 1984) has been used mainly by French researchers. Some researchers applied it to such twin lamellae that were formed under different stress conditions in different tectonic phases. However, the conventional method is unsatisfactory for dealing with such heterogeneous data sets.

It was found recently that a geometrical condition on a sphere in five-dimensional space corresponds to the twinning condition (Yamaji, 2015a). Twin data are denoted by points on the sphere, a circular area of which stands for a deviatoric stress tensor normalized by tau_c. Yamaji (2015b) found that the stress inversion of heterogeneous twin data is achieved by the fuzzy clustering of the data points on the sphere. The clustering is performed by the present author using a statistical mixture model.

Unfortunately, the tau_c value at 10 MPa has been often used, but its temperature and grain size dependence is not well understood. Laboratory experiments are awaited to improve our understanding on the dependence and stress magnitudes.

Keywords: stress inversion, differential stress, statistical mixture model, polyphase tectonics

Estimate of the stress state in the source region of Mw 2.2 earthquake in a South African deep gold mine

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Introduction:
During the earthquake preparation process, the strength of a fault and the stress state around the fault evolve by interacting with each other through the fault slip. Therefore, to better understand the earthquake generation, it is important to investigate a temporal variation in stresses around the fault. Many attempts have been made to measure the stresses around faults by deep drillings. A variety of techniques are proposed to measure the stresses in the borehole or by using the core samples. However, techniques that can be applied to large depths (> 1km) are limited.
An earthquake of Mw 2.2 (mainshock, hereafter) occurred at 3.3km depth in Mponeng mine, a deep gold mine in South Africa, on December 27, 2007. The rupture plane of the mainshock diagonally cut a 30-m-thick gabbroic dyke. Yabe et al. (2013) drilled a borehole penetrating the source fault of the mainshock ~1.5 years after the mainshock. They evaluated the stress state in the source region based on the borehole breakout and the core discing. However, they could constrain only bounds of stress magnitudes, as well as the direction of principal stresses. That is, their resolution of stress magnitudes is very low.
In this study, we estimate the differential stress in a plane perpendicular to the borehole axis with a higher resolution by applying the DCDA (Diametrical Core Deformation Analysis, Funato and Ito, 2013) to core samples recovered from the above-mentioned borehole. Stress measurement by DRA (Deformation Rate Analysis) is also performed.

Method:
DCDA estimates the differential stress in the plane normal to the borehole axis from the azimuthal variation in diameter of a core sample which was induced by stress relief associated with drilling. Circumferential profile lines are set every ~2 cm on each core sample to measure diameter every 2 degree. DRA measures the axial stress parallel to the uniaxial loading to a sub-sample based on a non-linearity of its stress-strain curve.

Result:
When the azimuthal variations in diameter were incoherent among the profile lines on a single core sample, we regarded that the core sample was scraped during drilling and did not use data of such cores. Differential stresses were about 20 MPa in the host rock (quartzite) and in the dyke (gabbro) near the contact. On the other hand, it was ~100 MPa at the central portion of the dyke. These results fell between the upper and the lower limit estimated by Yabe et al. (2013). We determined the principal stress in a plane normal to the borehole axis by DRA. The maximum and the minimum compressive stresses were ~110 MPa and ~30 MPa at footwall-dyke region, respectively. The differential stress at same region is, then, calculated to be ~80 MPa, being consistent with the estimation by DCDA.

Discussion:

Considering its geological conditions, we divided the study region into three; quartzite, footwall-dyke and hanging-wall-dyke regions. Under the assumption that the stress state is uniform within each region, we conducted grid-search to find the principal stress in each region that satisfies the differential stress measured by DCDA and criteria of borehole breakout and core discing. We could constrain principal stress directions very well except for footwall-dyke region where no borehole breakout or core discing were observed.

Conclusion:
By applying the DCDA to drilling core samples recovered from a close vicinity of the source fault of Mw 2.2 earthquake occurred at ~3.3 km below surface in a South African deep gold mine, we successfully obtained a new constraint on the stress state in the source region of the Mw 2.2 earthquake, where only rough estimation has been made by Yabe et al. (2013). To improve the estimation in the footwall-dyke, we apply DRA.

Keywords: Republic of South Africa, gold mine, DCDA, DRA, estimate of the stress state, earthquake

Coseismic deformation and shear stress derived from pseudotachylytes in exhumed accretionary complexes

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Pseudotachylytes (solidified frictional melts produced during seismic slip) are expected to provide crucial information on earthquake faulting. We examined coseismic deformation and shear stress during earthquake faulting in subduction zones, based on field and laboratory analyses on pseudotachylytes in exhumed accretionary complexes of the Shimanto and Mino Belts, Japan. The Shimanto pseudotachylytes are typically ~1 mm thick and sharply cut the foliated cataclasite derived from the argillaceous mélange. Marginal melting of albite and K-feldspar grains, vesicles, and idiomorphic acicular microlites of mullite or muscovite are observed in the glassy matrix of the illite composition, suggesting frictional melting at temperatures higher than 1100 °C. The Mino pseudotachylyte is a few millimeters thick and bounds the fractured/brecciated gray chert above from the cataclasite below. The wall rocks of the pseudotachylyte are embayed/rounded or intensely cracked. Cracked gray chert fragments are commonly observed in the dark matrix. These cracked wall rock and fragments are absent in the Shimanto pseudotachylytes. The Raman spectra of carbonaceous material indicate advanced carbonization in the Shimanto and Mino pseudotachylytes relative to host rocks. However, the wall rock ~2 mm from the Mino pseudotachylyte also shows progress in carbonization. The measured thermal conductivities are several times higher in the host rock (gray chert) of the Mino pseudotachylyte than in the host rock (sandstone blocks in the argillaceous matrix) of the Shimanto pseudotachylyte. These features suggest thermal cracking associated with heat diffusion from the molten zone was pronounced within the gray chert, possibly representing off-fault damage during earthquake faulting. In contrast, the temperature in the molten zone may remain high due to the host rock with lower thermal conductivities. The coseismic shear stress determined from the correlation between experiment and Raman data is lower in the Shimanto pseudotachylyte than in the Mino, which may result from pronounced dynamic weakening promoted by less diffusive heat loss to the wall rock.

Response to the stress state as fault reactivation in SW Japan

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The stress state in the crust plays an important role in the crustal deformation. Especially, fault reactivation is one of the most important phenomena controlled by the crustal stress. The Japanese islands are located in the subduction zone where Philippine See Plate and Pacific Sea Plate are subducting beneath Eurasian Plate. The subducting system generates a heterogeneous stress state in Japanese islands. Previous studies revealed the distribution of the heterogeneous stress state in the Japanese islands (e.g., Seno, 1999; Terakawa and Mat' sura 2010; Yukutake et al., 2015). On the other hand, many active faults are known in Japan (The Research Group for Active Faults of Japan, 1991) and the distribution and the type of the fault (i.e., normal, reverse and strike fault) are also heterogeneous. In this presentation, we will discuss the relation between the crustal stress and active faults in Japan. Especially, in order to shed right on the response to the stress state as fault reactivation, we consider about the relation between the crustal stress and the non-active faults, which is not recognized as active faults. The contrast of the response to the crustal stress between the active fault and non-active fault will be the clue to understanding the crustal deformation induced by the heterogeneous crustal stress.

Keywords: crustal stress, active fault

Stress State around the Westernmost Ilain Plain of NE Taiwan and Its Implications

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Stress state is a key to understanding the dynamics of the solid Earth and also plays a vital role of manipulating plate tectonics, earthquake faulting, geological structures, and fracture conduit/barrier. Taiwan mountain belt is located at the conjunction of oblique convergence and subduction flip between the Eurasian and Philippine Sea Plates. The Ilan Plain of NE Taiwan contains high geothermal gradient (~60℃/km) due to the heat advection of rapid rock uplift and the backarc extension of the opening Okinawa Trough. It will be essential to recognize the spatial distribution of stress state around the westernmost Ilan Plain for exploring the geothermal energy and deciphering the interaction evolution between mountain building compression and backarc extension.
In-situ stress assessments from multi-scale observations such as regionally focal mechanisms, local paleostress, borehole-based methods and core-based methods, show the strike-slip stress regime with NNE-SSW compression in the westernmost Ilan Plain. Results of hydraulic fracturing tests indicate the Shmin gradient of 17.7MPa/km in 750-765m interval of the JY-1 drilling. Drilling-induced tensile fractures identified from the FMI of 363-2201m in HCL-1 deep drilling are only observed in the interval of 392-1233m within the slate formation. SHmax, Sv, and Shmin gradients deduced from DITFs are estimated as 25.6, 24.9 and 15.4MPa/km, respectively and SHmax is N-S orientation. Results of N-S compressive strike-slip stress regime suggested that the backarc extension has not strongly influenced the westernmost Ilan Plain yet. Based on the core observations, NNE-striking steep open-filling fractures post-date the south-dipping slaty cleavage and also attain high dilation tendency under in-situ stress state.
In-situ stress evaluations within the Cingshui geothermal area west of the Ilan Plain also show the strike-slip stress regime with NNE-compression. According to examination results on cores retrieved from the interval of 600-800m in the IC21 geothermal drilling, attitudes of NWW-striking closed fractures and NNE-striking open-filling fractures are consistent with the predicted attitudes of fluid barriers and conduits respectively. Based on Bingham statistics computed from the distribution of open-filling fractures, the paleo-stress orientations and ratio can be determined. Provided with rock mechanical data from experiments and fluid pressure from fluid inclusion analysis, and the simulation of appropriated differential stress below failure criteria, the complete parameters of paleo-stress state can be obtained. Bootstrap simulation can further afford the statistic constraints of paleo-stress state. Our results suggest that the development of open-filling fractures was at the depth of ~4.6km with NNE-compressive stress regime and fluid pressure of 54MPa and geothermal gradient was about 36-59℃/km, which is lower than the current geothermal gradient of 69℃/km.
Our results illustrate that although backarc extension has not intensely affected the westernmost Ilan Plain yet, the geothermal gradient of the Cingshui geothermal area is already begun to increase. These

establishments between in-situ stress and fluid conduits can explain the current results of geothermal exploration and deliver the important information for developments of the enhanced geothermal system in Taiwan. Moreover, outcomes of this study shed the lights on evaluating the interaction processes between of mountain building compression and backarc extension.

Keywords: Stress State, Enhanced Geothermal System, Ilan Plain, Taiwan

Elastic stress field reconstruction in the Nankai Trough area based on WSM and drilled data

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We use the stress trajectories method (STM) to evaluate the stress state in the vicinity of the Nankai Trough. The approach allows estimating the principal horizontal stresses distribution in horizontal plane based on the discrete data on principal stresses orientations. We use World Stress Map (WSM, 2008) to reconstruct the stress state. 10 data of A-C quality have been detected in the area (1°x1°). The number of data allows using complex polynomials of up to second degree for approximation of the complex potentials in the plane elastic problem. It has been found that the linear approximation provides minimum residual from data. The reconstructed fields present the stress trajectory pattern (shown in Figure 1(a)) and the normalized field of maximum normalized shear stress (Figure 1(b)).
Then we used 11 in-situ stress measurements from the wells in Nankai Trough Seismogenic Zone (NanTroSEIZE expeditions 314-316, 319, 322, 338, 348) for comparison with the reconstructed stress trajectories. These are shown in Figure 1(a) by blue segments with a small circle at its middle, while the red segments represent the WSM data. It is evident from the figure that the included data agrees well with the reconstructed trajectories.
The results presented in the figure demonstrate the existence of an isotropic point where the principal stresses are equal to each other. In the vicinity of this point we can observe a sharp change in the stress trajectories. It is evident from Figure 1(b) that in the vicinity of this point the maximum shear stress magnitudes are much smaller than at the periphery of the examined area. The isolines of maximum shear stress are close to ellipses. It is worth to note that the long semi-axes of these ellipses are sub-parallel to the plate margin located in the investigated area. Bearing in mind that the dip of the subducting crust has N-W orientation which is orthogonal to the family of the stress trajectories shown in Figure 1 and therefore it is sub-parallel to the second family of trajectories which mechanically means that the shear stress on the plate margin is relatively small. This result requires further discussion from the geomechanical point of view.

Keywords: NanTroSEIZE, In-situ stress, Stress trajectories method

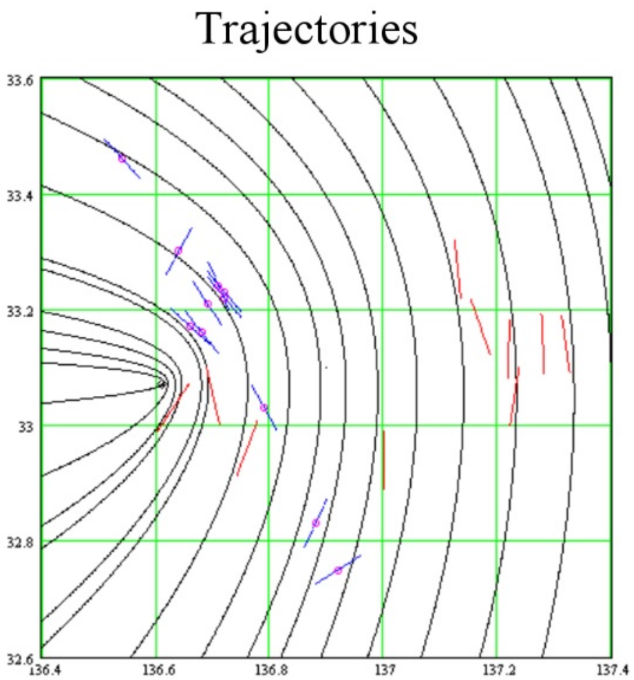
Trajectories
33.6
33.4
33.2
33
32.8
32.6
136.4
136.6
136.8
137
137.2
137.4

Fig. 1(a)

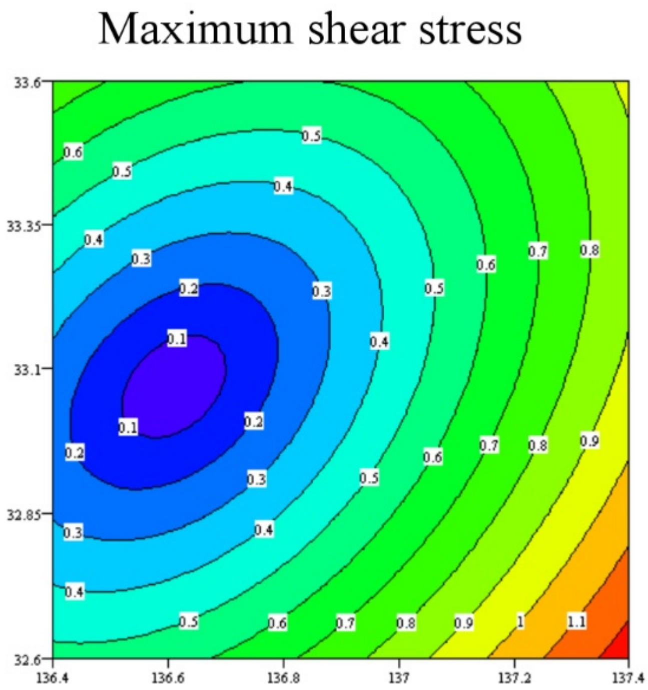
Maximum shear stress
33.6
33.35
33.1
32.85
32.6
136.4
136.6
136.8
137
137.2
137.4
TT-1.01

Fig. 1(b)