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


SSS30-01 Room:Main Hall Time:April 28 09:30-09:45

# Long-term seismic quiescence and activation anomalies preceding to the 2004 Sumatra and the 2005 Nias earthquakes

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I find long-term precursory seismic quiescence and activation anomalies before the 2004 Sumatra ($M_w$9.1) and the 2005 Nias ($M_w$8.6) earthquakes. An earthquake catalog created by International Seismological Center is analyzed between 1964 and 2004, including 1153 earthquakes shallower than 100 km with the body wave magnitude of $5.0 \leq M \leq 6.0$. A detailed analysis of the earthquake catalog using a gridding technique (ZMAP) shows that the 2004 Sumatra and the 2005 Nias earthquakes are preceded by not only a seismic quiescence anomaly started in December 1987, but also a seismic activation anomaly started in July 1989. The quiescence and activation areas are located very closely each other between 2S and 6N, which cover the area around the rupture initiation point of the 2004 Sumatra earthquake and the whole area ruptured by the 2005 Nias earthquake. The observed spatial pattern of quiescence and activation can be explained by stress perturbation due to a long-term slow slip event located on the two main shock faults, which is predicted by a numerical simulation [*Kato et al.,* 1997].

Kato, N., M. Ohtake, and T. Hirasawa (1997), Possible mechanism of precursory seismic quiescence: Regional stress relaxation due to preseismic sliding, Pure Appl. Geophys., 150, 249-267.

Keywords: The 2004 Sumatra earthquake, The 2005 Nias earthquake, seismic quiescence, seismic activation, ZMAP, ISC

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SSS30-02 Room:Main Hall Time:April 28 09:45-10:00

# Spatial heterogeneity of the frictional property on the Pacific plate off south-east of Hokkaido, Japan

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The stress drop is an indicator of the difference of the shear strength and the dynamic frictional stress. We analyzed 330 middle-size earthquakes to investigate the spatial heterogeneity of the frictional property on the Pacific plate off south-east of Hokkaido.

Large earthquakes have been occurring repeatedly off south-east of Hokkaido, Japan, where the Pacific Plate subducts beneath the Okhotsk Plate in the north-west direction. For example, the 2003 Tokachi-oki earthquake (Mw8.0) recently took place in the region in 2003. Yamanaka and Kikuchi (2003) analyzed the slip distribution of the earthquake and concluded that the area with a large slip during the 2003 earthquake was mostly overlapped with the area of the 1952 Tokachi-oki earthquake. Miyazaki *et al*. (2004) reported that a notable afterslip was observed at adjacent areas to the coseismic rupture zone of the 2003 earthquake, which suggests that there would be significant heterogeneities of strength, stress and frictional properties on the surface of the Pacific Plate in the region. In addition, some previous studies suggest that the region with a large slip in large earthquakes permanently have large difference of strength and the dynamic frictional stress level and that it would be able to predict large slip areas by analyzing the stress drop of small earthquakes (e.g. Allmann and Shearer, 2007 and Yamada *et al*., 2010).

We estimated stress drops of 330 earthquakes ($4.2 \leq M \leq 5.0$), using S-coda waves of Hi-net data. The 330 earthquakes were the ones that occurred from June, 2002 to December, 2012 off south-east of Hokkaido, Japan, with the latitude from 40.5N to 43.5N and the longitude from 141.0E to 146.5E. First we selected the closest earthquakes with magnitudes between 3.0 and 3.2 to individual 330 earthquakes as empirical Green's functions. We then calculated source spectral ratio of the 330 pairs of interested earthquakes and EGFs by deconvolving the spectra of S-coda waves. We finally estimated corner frequencies of earthquakes from the source spectral ratios by assuming the omega-squared model of Boatwright (1978) and calculated stress drops of the earthquakes by using the model of Madariaga (1976). The estimated values of stress drop range from 3.0×10ˆ(-1) MPa to 2.0×10ˆ(2) MPa independent of the seismic moment. Figure shows the spatial distribution of estimated stress drops.

We found spatial difference of estimated values. The average value of stress drop in the afterslip area at the 2003 Tokachi-oki earthquake, where the small displacement was observed, was 1.2 MPa. On the other hand, the value in the source area of the 2004 Kushiro-oki earthquake was 2.0 MPa. In addition, the average values of stress drops in the deeper and shallower parts of the source area of the 1973 Nemuro-oki earthquake were 1.0 MPa and 2.1 MPa, respectively, and the difference was statistically significant. These differences would reflect the spatial heterogeneity of the frictional property on the Pacific plate.

Acknowledgments: We used Hi-net waveform data (http://www.hinet.bosai.go.jp/) and the slip distribution of large earthquakes (EIC seismic note; http://www.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/index.html)

Keywords: Pacific plate, Friction, Spatial heterogeneity, Stress drop

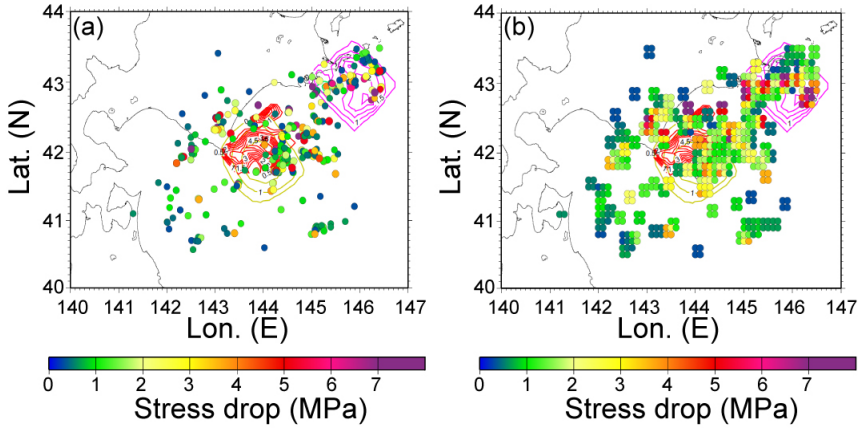


Fig. (a) Estimated stress drops of analyzed 330 middle-size earthquakes ($4.2 \leq M \leq 5.0$). Each circle shows the stress drop for each earthquake. Contours indicate slip distributions of past four large earthquakes off south-east of Hokkaido (EIC seismic note, http://www.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/index.html). (b) Spatial pattern of the averaged stress drop. Individual circles indicate averaged values of stress drop for every 0.1 degree, which were calculated from the values of earthquakes in areas with 0.2 x 0.2 degrees.

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SSS30-03 Room:Main Hall Time:April 28 10:00-10:15

# Seismically inferred rupture process of the 2011 Tohoku-Oki earthquake by using 3D and 2.5D Green's tensor waveforms

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The March 11, 2011 Tohoku-Oki earthquake (GCMT Mw9.1) generated strong ground motions and large tsunamis, and caused devastating damages in the northeastern Japan. The rupture process of this event provides important clues for understanding the geophysical condition of the generation of mega-thrust earthquakes and the mechanism of the excitation of the large tsunamis.

We analyze "seismic" rupture process of this event by using a non-linear full-waveform inversion method. We incorporate the effect of the near-source laterally heterogeneous structure on the synthetic Green's tensor waveforms because the analysis can result in erroneous solutions if the effect is not considered [1]. Also, in order to increase the resolution we use the teleseismic and the strong-motion seismograms jointly: the distribution of strong-motion station is one-sided and analysis with only the strong-motion records may result in reduced resolution near the trench axis [2]. For the teleseismic P-wave synthetics we use a 2.5-dimensional finite-difference method [3]. For the strong-motion synthetics we use a full three-dimensional finite-difference method that incorporates topography, oceanic water layer, three-dimensional heterogeneity and attenuation. Our simulation is accelerated by GPUs used in parallel [4]: we use the TSUBAME GPU supercomputer in Tokyo Institute of Technology.

In the previous study [5] we used only a single structure model (i.e., a single vertical slice of the 3D heterogeneous structure) to generate all the 2.5D Green's functions. In this paper we have updated the 2.5D structure models. That is, we extracted twenty-three vertical slices from the 3D structure model: each slice was (nearly) perpendicular to the trench axis and was taken along the nodes of the grid that formed the fault plane. By using these new models the 2.5D Green's functions and 3D Green's functions are now "consistent" with each other.

We computed Green's tensor synthetic waveforms for 31 teleseismic and 32 strong-motion components. We used 640 GPUs of the TSUBAME supercomputer for the calculation of each strong-motion synthetics. The inferred slip distribution has large slips near the JMA epicenter with the maximum slip of about 32 m. The amount of slips at the areas close to the trench axis is smaller than that of the land-ward area (i.e., near the JMA epicenter). Inversion results similar to these features have been obtained by previous study [2] but it is remarkable that our joint "seismic" inversion using 2.5D-teleseismic and 3D-strong-motion Green's tensor waveforms resulted in the solution with these features (i.e., land-ward large slips and trench-ward small slips). These features have important implications for tsunami studies because large slips near the trench axis are expected for large tsunamis. In order to verify the solution we will inspect the resolution by using simulations of inversion and the effect of the choice of the Green's tensor waveforms on the solutions.

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Keywords: Tohoku-Oki earthquake, rupture process, GPU computing, seismic waveforms

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SSS30-04 Room:Main Hall Time:April 28 10:15-10:30

# Seismic velocity and attenuation tomography of the source zone of the 2011 Tohoku-oki earthquake (Mw 9.0)

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Detailed 3-D P and S wave velocity (Vp, Vs) and attenuation (Qp and Qs) tomography of the crust and upper mantle under the entire Northeast Japan arc from the Japan Trench to the Japan Sea coast is determined (Zhao et al., 2011; Huang and Zhao, 2013; Liu et al., 2014). The suboceanic earthquakes under the Pacific Ocean and the Japan Sea are used in this work and they are relocated precisely using sP depth phases. Vp and Vs tomography is determined using a large number of high-quality arrival times, whereas the Qp and Qs tomography is obtained using a large number of t∗data measured precisely from P and S wave spectra of local earthquakes. Our results reveal the high-V and high-Q subducting Pacific slab, and significant low-V and low-Q anomalies in the crust and mantle wedge under the volcanic front and the back-arc area. Large megathrust earthquakes (M >6.0) during 1900-2013 including the great 2011 Tohoku-oki earthquake (Mw 9.0) sequence are generally located in high-V and high-Q patches which are surrounded by low-V and low-Q anomalies in the megathrust zone. The high-V/high-Q patches in the megathrust zone generally exhibit large coseismic slips of megathrust earthquakes and large slip deficit on the plate interface. We think that these highV/high-Q patches represent asperities in the megathrust zone, whereas the low-V/low-Q anomalies reflect weakly coupled areas. These results suggest that structural heterogeneities in the megathrust zone control the interplate seismic coupling and the nucleation of megathrust earthquakes.

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Keywords: earthquakes, slab, fluids

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SSS30-05 Room:Main Hall Time:April 28 10:30-10:45

# A Study on Seismicity before and after the Tohoku Earthquake around its Southern Boundary Using Dense OBS Array Data

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The southern boundary of the 2011 Tohoku earthquake, the source area of the largest aftershock, and a subducting seamount are located around off Ibaraki in the Japan Trench subduction zone. It is important to evaluate the spatial and temporal distribution of seismicity which provides key information about the seismic energy release. However, the seismicity is not well constrained due to a large distance offshore from the onshore network. Therefore, estimating seismic energy release off Ibaraki by using ocean-bottom seismometer (OBS) data is essential to understand the characteristics of the main shock rupture propagation. In this study, we estimated seismicity distribution around off Ibaraki region before and after the 2011 Tohoku earthquake using dense OBS array data.

It is difficult to apply methods that have been designed for on-land seismic stations due to the large ambient noise and effects of thick seafloor sediments. Furthermore, conventional manual picking is difficult because of the occurrence of many aftershocks. We therefore applied a semblance analysis to OBS waveform data with theoretical P-wave travel-time table obtained by the construction of an original 3-D P-wave velocity structure model.

To evaluate the validity of event identification and the accuracy of the epicenter distribution, I conducted comparisons of our epicenters with the JMA epicenters and synthetic tests using theoretical waveforms with several different sets of signal-to-noise ratio and focal depths.

As results of epicenter determination by the semblance analysis, we found that a lot of earthquakes occurred in the vicinity of the frontal region of the subducting seamount after the 2011 Tohoku earthquake. Next, there exists an along-strike density contrast of seismicity, and the inactive region possibly corresponds to the seismically quiet band previously revealed by a seismic observation. Furthermore, we applied the semblance analysis to OBS waveform immediately after the main shock and estimated the spatial and temporal transition of detailed seismicity. We found that the seismicity around the subducting seamount was activated after the largest aftershock rather than between the occurrences of the main shock and the largest aftershock. It puts constraints on the southern boundary of the 2011 Tohoku earthquake.

Keywords: dense OBS array data, seismicity, the southern boundary of the 2011 Tohoku earthquake

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SSS30-06 Room:Main Hall Time:April 28 11:15-11:30

# Large shallow slip during the 2011 Tohoku-Oki earthquake: New insights from JFAST and high-velocity friction experiments

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The Japan Trench Fast Drilling Project (JFAST), Integrated Ocean Drilling Program (IODP) Expeditions 343 and 343T were conducted to understand the coseismic deformation mechanisms and dynamics of large shallow slip during the 2011 Tohoku-Oki earthquake. The drill site is located at the toe of the frontal prism near the Japan Trench axis. Observations and analyses of recovered core samples as well as logging-while-drilling data indicate that the plate-boundary fault is highly localized in pelagic clay less than 5 m-thick. The smectite content in pelagic clay is ˜78%. The deformations in the plate-boundary fault are marked by distributed shear along anastomosing scaly foliations and localized slip along the boundary between red-brown and dark-brown scaly clays with different fabric orientations. On the microscopic scale, injection structures and mixing of clays of different colors without shear surfaces are observed along the localized slip zone, suggesting fluidization during the localized slip. High-velocity (1.3 meters per second) friction experiments on core samples taken from smectite-rich clay of the plate-boundary fault, show a small stress drop with very low peak and steady-state shear stress. The very low shear stress can be attributed to the abundance of smectite and thermal pressurization effects. Steady-state shear stress is independent of normal stress, and the microstructures after the experiments show evidence for fluidization. These features suggest that the fault material behaved like a fluid during high-velocity shearing due to thermal pressurization of pore fluid. Our results indicate that large shallow slip resulted from coseismic fault lubrication, and the similarity of microstructures between natural and experimental shear zones may represent the fluidization of fault material during earthquake faulting. Seismic slip could be promoted even in plate-boundary faults at shallow depths, as the slip propagates through the smectite-rich fault material.

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SSS30-07 Room:Main Hall Time:April 28 11:30-11:45

# Trace element and isotope characteristics of core samples from the Japan Trench Fast Drilling Project (JFAST)

ISHIKAWA, Tsuyoshi[1*] ; MATSUOKA, Jun[2] ; KAMEDA, Jun[3] ; MORI, James[4] ; CHESTER, Frederick[5]

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The Integrated Ocean Drilling Program (IODP) Expedition 343 drilled three holes through the plate boundary near the Japan Trench to investigate the cause of very large fault slip during the 2011 Tohoku-Oki earthquake. In this paper, we report trace element and Sr-Nd-Pb isotope compositions of core samples, including plate-boundary fault rocks, recovered from Hole C0019E.

The rocks in C0019E are lithologically subdivided into seven units (Chester et al., 2013): Units 1 to 3, wedge sediments of upper plate; Unit 4, plate-boundary fault; Units 5 to 7, sediments of lower plate. The clay-rich plate-boundary fault rocks (Unit 4) are characterized by elevated concentrations of rare earth elements (REE) and some refractory metals, and are distinct from any other JFAST samples in terms of trace element characteristics. Brown mudstones of the lower plate (Unit 5) show trace element characteristics (e.g. REE pattern) roughly similar to those of the upper plate sediments (Units 1 to 3), but they are still distinguishable from each other. Pelagic sediments in the lower plate (Unit 6) show highly varied trace element compositions with a large Ce anomaly. The Sr, Nd and Pb isotope data show variations that are essentially consistent with trace element characteristics observed for each unit.

The clear relationship observed between lithological units, trace element and isotope compositions and radiolarian ages of the JFAST samples provides a key for understanding the origin of the shallow fault zone of the Tohoku-Oki earthquake and the frontal wedge at the Japan Trench. Geochemical characteristics of the JFAST samples will be discussed along with those of sediments from DSDP site 436, which is a nearby input site, for elucidating the origin of the JFAST rocks and for evaluating coseismic/interseismic processes possibly recorded in the plate-boundary fault rocks.

Keywords: Earthquakes, Fault rocks, Trace elements, Isotopes, IODP

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SSS30-08 Room:Main Hall Time:April 28 11:45-12:00

# Paleomagnetic analyses of core samples from the plate-boundary thrust obtained during the IODP JFAST

MISHIMA, Toshiaki[1*] ; YANG, Tao[2] ; UJIIE, Kohtaro[3] ; KIRKPATRICK, James[4] ; CHESTER, Frederick[5] ; MOORE, Casey[6] ; ROWE, Christie[7] ; REGALLA, Christine[8] ; REMITTI, Francesca[9] ; KAMEDA, Jun[10] ; WOLFSON, Monica[11] ; BOSE, Santanu[12] ; ISHIKAWA, Tsuyoshi[13] ; TOY, Virginia[14]

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IODP Expedition 343, Japan Trench Fast Drilling Project (JFAST), drilled through the plate-boundary dècollement of the Japan Trench, where large slip occurred during the 11 March 2011 Tohoku-Oki Earthquake. In order to reconstruct the deformation of the sediments at the cm scale and less, we conducted paleomagnetic measurements of the core sample from the plate-boundary dècollement zone.

The plate-boundary core sample has a scaly fabric and is composed of bicolored clay layers with sharp contacts. We prepared slabs for thin sections across the contacts with typical dimensions of 3x3x5 $cm^3$ from the core sample. We measured remanent magnetization of 16 slabs. The slabs were subjected to natural remanent magnetization (NRM) measurements in 0.5-1 cm intervals and progressive alternating field demagnetization (AFD) up to 80 mT with a 2G755 pass-through superconducting rock magnetometer at Kochi University.

Typically, two paleomagnetic components were isolated during the AFD of slab samples up to 80 mT. One component (‘soft’ component) was demagnetized below 20-30 mT, and another component (‘hard’ component) was not demagnetized even up to 80 mT. For multiple slab samples cut from the same whole-round sample, the hard component generally has a consistent paleomagnetic direction. Contrastingly, the direction of the soft component is not so consistent between adjacent slabs, and even varies within a single slab.

The direction variation of the soft component possibly reflects the cm-scale rotation of competent phaccoids during deformation within the slab samples from the plate-boundary thrust zone. The consistency of the hard component directions implies that the hard component was remagnetization during/after the rotation, and was possibly carried by newly-formed magnetic minerals during the deformation.

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SSS30-09 Room:Main Hall Time:April 28 12:00-12:15

# Change of permeability caused by 2011 Tohoku earthquake detected from pore pressure monitoring

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We have monitored pore and atmospheric pressures at the Kamioka mine in Gifu Prefecture, central Japan since 2005 to study relationship between groundwater and earthquake. Pore pressure decreased after the 2011 Tohoku earthquake (M9.0) occurred on 11 March 2011, which may be attributed to expansion of the crust west of the epicenter or a permeability increase. To evaluate rock permeability changes, we analyzed the Earth tide response of pore pressure before and after the earthquake. Pore pressure fluctuates associated with the meteorological effects, Earth tides and crustal deformation. We assumed that without the change of aquifer conditions tidal response of pore pressure is constant. We compared the tidal response before and after the event. We extracted amplitude and phase lag of M2 and O1 constituents from pore pressure by tidal analysis program, BAYTAP-G. These amplitudes decreased and phases changed after the earthquake. It was in accord with pore pressure decreases. We estimated the hydraulic diffusivity using the poroelastic theory and diffusion equation. If we assume that the poroelastic coefficient is constant, the hydraulic diffusivity increased from 8.9 to 65.0 $m^2/s$ at the time of the Tohoku earthquake. We also analyzed data before and after the Noto Hanto Earthquake (M6.9) which occurred in the northwestern part of Ishikawa Prefecture, central Japan on 25 March, 2007. The epicentral distance of the Noto Hanto Earthquake from our observation site is 112 km. No hydraulic diffusivity change is detected. The causes of the hydraulic diffusivity change are potentially related to a static and/or dynamic stress change. In order to discuss the difference in hydraulic diffusivity change between the Tohoku and Noto Hanto earthquakes, we analyzed other earthquakes to relate the hydraulic diffusivity changes, and the amount of static and dynamic strain changes.

Keywords: hydraulic diffusivity, pore pressure, Earth tide

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SSS30-10 Room:Main Hall Time:April 28 12:15-12:30

# Enigmatic phase lead of pore pressure: 11+ years of ACORK monitoring at the frontal decollement of Nankai Trough

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[1]JAMSTEC, [2]Kyoto Univ. DPRI

For more than 11 years we have been conducting a continuous monitoring of downhole pore pressures at multiple sub-bottom intervals in ODP Holes 808I and 1173B situated landward and seaward of the deformation front in the Nankai Trough off Cape Muroto. We found that the pressure response to the semi-diurnal ocean tide (M2), both amplitude and phase, gradually change during the observed period. The M2 amplitudes at most depths in Hole 808I decay as their phase delay (up to 45 degrees), ONLY IF the amplitude is larger than ˜0.2 of that for the seafloor. On the other hand, we observe an anomalous phase LEAD (up to -40 degrees) if the relative amplitude is lea than ˜0.2. We hypothetize that the recorded pore pressure is a combination of two components; one with larger amplitudes and phase-delay and the other with small amplitude and phase-lead. The former can be interpreted as the decrease in formation compliance relative to that of the system, or as the decrease in hydraulic diffusivity around the sensors. The mechanism of the latter variation remain still enigmatic. Existence of gas-rich layer next to the sensor, as suggested by wang and Davis (1996), is difficult to generate such a large phase lead. The predicted earth tide at this site does not coincide with the observed phase. Thermal expansion/contraction caused by the flow within the casing, induced by tidal loading, may cause this phase shift, but a simple thermal/hydrological diffusion cannto explain both the amplitude and phase simultaneously. A complex process including some unknown mechanism may be in operating at Hole 808I.

Keywords: Nankai Trough, ACORK, ODP

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SSS30-11 Room:Main Hall Time:April 28 14:15-14:30

# The increase in missing waveform images of the F-net seismographs preceding the 2004 off Kii peninsula earthquake

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[1]No institution affiliation

1. Introduction

The F-net is a broadband seismograph network constituted of 73 STS-1 and 2 seismometers. Natural frequency of the seismometers is 120 seconds (STS-2) and longer, thus they can detect long-period ground motion. On its website, waveform images of the stations for a day or an hour are provided. The analyses on their file size have shown long-period vibrations (Sue, 2010).

2. Analysis

Variation recorded in waveform images may mean variation of ground motion. Thus operational status of the F-net is investigated. There are two sources on it.

a. Data acquisition trouble log: This is the formal information covering from instantaneous to long-lasting loss of data. Reasons for troubles are shown. While, update of the information is irregular.

b. Missing of waveform images: The website displays the message ”Waveform image does not exist”. It is surmised that this situation is caused by continuous loss of data exceeding 1 day (Daily plot) or 1 hour (Hourly plot). The reasons are not shown. While update of the information is regular.

So far, analyses on ”missing of waveform images” for the 2011 Tohoku earthquake (M=9) has been done (Sue, 2013). As a next step, the 2004 off Kii peninsula earthquake (M=7.4), which occurred on September 5, 2004 at the Nankai trough, is carried out. For details, for the period of about 3 months from June 1, 2004 to September 10, 2004, the F-net stations located in the area between Itoigawa - Shizuoka tectonic line and Okinawa island are investigated (The one in Noto peninsula is excluded).

3. Results

Fig. 1 shows the result. During June - first half of July, 2004, which is more than 1.5 month before the main shock, the most frequent number of the image-missing station is 1, and it was stable condition. From last half of July and later, the number varied.

On August 30 and 31, which are 6 and 5 days before the earthquake, there were large increases of the number. Further, arrangement of image-missing stations is mainly in southern part and east coast of the Kyushu island respectively.

On Sept. 4, which is the previous day of the main shock, there were 3 image-missing stations, located from Shikoku island to Kyushu island alongside the Nankai trough (Fig.2).

After the earthquake, number of image-missing station decreased to zero.

The major reasons for missing images are ”Network trouble” and ”Electric power supply trouble”.

4. Discussion

Number of F-net station with missing waveform images increases before an earthquake. The phenomena appear not only close to the epicenter, but wide area surrounding it. The phenomena are also observed at the 2011 Tohoku earthquake, thus they may usually appear before a large earthquake. Similar phenomena as shown in this paper might be observed at the anticipated Nankai trough earthquake.

Missing images of all 73 stations happened on 23 to 25 in July (Fig.1). Same phenomena appeared at the 2011 Tohoku earthquake, thus the phenomena may be a sign of unstableness of the F-net system.

It is assumed that increases of the missing waveform images preceding a big earthquake was because the F-net could not withstand possible long-period variation of the earth’s surface. ”Network trouble” and ”Electric power supply trouble” might be causes for such situation. Such phenomena are not observed for the Hi-net seismograph network, probably because of its characteristic (NF = 1 sec).

When the DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) detects anomaly, malfunctioning of the F-net may appear at the same time or even earlier.

The area formed by the F-net stations with missing images may have certain relation with magnitude of the earthquake.

Acknowledgement

The author thanks NIED for using the data of the F-net.

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Yoshiki Sue, 2013, The increase in missing waveform images of the F-net broadband seismograph network preceding the 2011 Tohoku earthquake, JpGU2013, S-SS30-P01.

Keywords: F-net, broadband, seismograph network, long period, waveform, Nankai trough

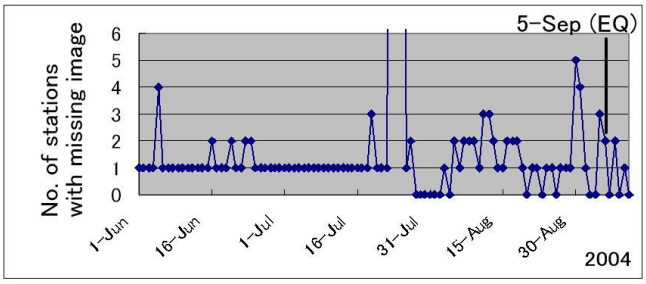


Fig.1. No. of stations with missing waveform images for June 1 to September 10, 2004. No. is 73 on July 23-25. Day is on UT.

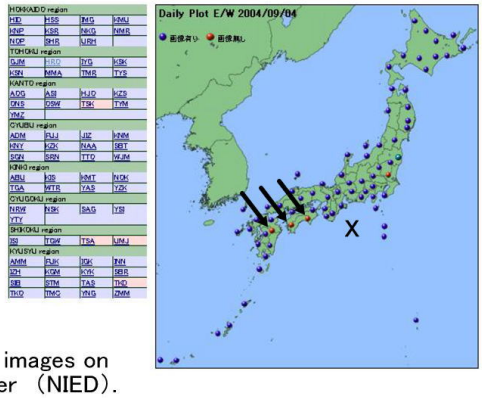


Fig.2. The staions with of missing waveform images on Spetember 4, 2004 (Arrow) and the epicenter (NIED).

Japan Geoscience Union Meeting 2014
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SSS30-12 Room:Main Hall Time:April 28 14:30-14:45

# Heat flow distribution along the Nankai Trough: Influence of the structure of the Shikoku Basin oceanic crust

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The thermal structure of the Philippine Sea plate (Shikoku Basin) subducting along the Nankai Trough, one of the most important factors controlling the temperature structure around the plate interface, significantly affects physical/chemical processes in the seismogenic zone of subduction earthquakes. Surface heat flow observed on the floor of the Nankai Trough should reflect the thermal structure of the incoming Shikoku Basin. Previous surveys showed that heat flow on the trough floor is extremely high for the seafloor age between 135$^o$E and 136$^o$E (south of the Kii Peninsula), while it is comparable to the value expected from the age in the neighboring area to the east of 136$^o$E. The transition zone from high to normal heat flow lies in the vicinity of the rupture segmentation boundary between the 1944 Tonankai and the 1946 Nankai earthquakes, across which seismicity on the landward side of the trough significantly changes, implying influence of the temperature structure on subduction earthquake processes.

For further investigation of the along-strike variation in heat flow on the trough floor, we conducted heat flow measurements around the Nankai Trough off the Kii Peninsula and off Shikoku in 2011 to 2013. Most of the measurements were made in the area around 136$^o$E, where the high to normal heat flow transition occurs, and on the trough floor to the south of Shikoku, where the existing data were very sparse. 39 new heat flow data on the trough floor allowed us to delineate heat flow variation along the trough. A conspicuous change in heat flow distribution was found at around 136$^o$E. On the west of 136$^o$E, heat flow is extremely high and variable, ranging from 130 to 250 mW/m$^2$,while on the east of 136$^o$E, heat flow monotonously decreases eastward from 200 to 100 mW/m$^2$ in about 50 km with no appreciable scatter. On the trough floor south of Shikoku, west of 134.5$^o$E, no significant change was observed along the trough in spite of westward increase in the seafloor age.

The heat flow distribution described above appears to be correlated with the structure of the Shikoku Basin oceanic crust. The high and variable heat flow area between 134.5$^o$E and 136$^o$E corresponds to the youngest part of the Shikoku Basin which was formed by spreading in NE-SW direction, whereas the neighboring areas with less scattered heat flow, east of 136$^o$E and west of 134.5$^o$E are the older parts formed by E-W spreading. The thickness of the oceanic crust and the basement relief also change around 136$^o$E, in the vicinity of the heat flow transition boundary. Spinelli and Wang (2008) proposed a model for the high heat flow around 135$^o$E that vigorous pore fluid circulation in a permeable layer in the subducting oceanic crust efficiently transfers heat upward along the plate interface. We may infer that the permeability structure of the oceanic crust changes at the transform boundaries between the E-W and NE-SW spreading, which yields variations in vigor and/or pattern of pore fluid circulation, resulting in the contrasting heat flow distributions. Since heat transfer by fluid circulation in the subducting oceanic crust lowers the temperature of the plate interface, the along-strike variation in the trough floor heat flow could indicate corresponding variation in the temperature distribution in the seismogenic zone.

Keywords: Nankai Trough, heat flow, pore fluid, oceanic crust, temperature structure, seismogenic zone

Japan Geoscience Union Meeting 2014
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SSS30-13 Room:Main Hall Time:April 28 14:45-15:00

# Reevaluation of temperature at the updip limit of locked portion of Nankai megasplay, inferred from IODP Site C0002 tem

SUGIHARA, Takamitsu[1*] ; KINOSHITA, Masataka[2] ; ARAKI, Eiichiro[3] ; KIMURA, Toshinori[3] ; KYO, Masanori[1] ; NAMBA, Yasuhiro[1] ; KIDO, Yukari[1] ; SANADA, Yoshinori[1] ; MOE, Kyaw thu[1]

[1]CDEX/JAMSTEC, [2]KCC/JAMSTEC, [3]DONET/JAMSTEC

Temperature near the updip limit of the locked zone still has large uncertainties due to lack of knowledge about thermal and hydrological properties at depth.

In 2010, the first Long-Term Borehole Monitoring System was deployed at ˜900 m below sea floor (mbsf) above the updip limit of seismogenic fault zone in the Nankai Trough off Kumano (Site C0002).Four temperature records show that the effect of drilling diminished in less than 2 years and they all reached thermal equilibrium by 2012. From in-situ temperatures and thermal conductivities measured on core samples, the temperature and heat flow at 900 mbsf are determined as 37.9 ℃ and 56.1 mW/m2, respectively. This heat flow value is in excellent agreement with that from shallow borehole temperature corrected for rapid sedimentation in the Kumano Basin. We use these values to constrain the temperature below 900 mbsf to the mega-splay and plate boundary fault zones.

To extrapolate temperature downward, we use LWD bit resistivity data as a proxy for porosity and the thermal conductivity is modeled from this porosity using a geometrical mean model. Upon integration by the 1-D thermal conduction we included the radioactive heat and frictional heat production. Estimated temperature at the megasplay ranges between 132 to 149 ℃, depending on thermal conductivities and radioactive heat. It is significantly higher, by up to 40 ℃, than previous 2-D numerical model predictions that can account for the heat flow across the deformation front. The discrepancy may be explained either by increasing the effective frictional coefficients along the fault zones or by introducing a lateral fluid flow along the permeable layers somewhere in the sedimentary layer. Revision of 2-D simulation by introducing our new boundary conditions will also be useful. Ultimately, reaching the megasplay fault and in-situ temperature measurement in the drilled hole is required to understand seismogenesis in the Nankai subduction zone.

Keywords: Seismogenic zone, Nankai Trough, Megasplay fault, Thermal regime, IODP, NanTroSEIZE

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SSS30-14 Room:Main Hall Time:April 28 15:00-15:15

# Preliminary Scientific Results of IODP Expedition 348: Ultra-deep Riser Drilling into the Nankai Accretionary Prism

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The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a multi-disciplinary scientific project designed to investigate fault mechanics and seismogenesis along subduction megathrusts through seismic imaging, direct sampling, in situ measurements, and long-term monitoring in conjunction with laboratory and numerical modeling studies. International Ocean Discovery Program (IODP) Expedition 348, the latest advance of the NanTroSEIZE project, started on 13 September 2013 and was completed on 29 January 2014. During Expedition 348, the drilling vessel *Chikyu* advanced the ultra-deep riser hole at Site C0002, located 80 km offshore of the Kii Peninsula, from a depth of 860 meters below sea floor (mbsf) to 3058.5 mbsf, the world record for the deepest scientific ocean drilling, and cased it for future deepening. The drilling operation successfully obtained data on formation physical properties from logging while drilling (LWD) tools, as well as from lithological analyses of cuttings and core from the interior of the active accretionary prism at the Nankai Trough. IODP Site C0002 is the currently only borehole to access the deep interior of an active convergent margin.

Preliminary scientific results of Expedition 348 include:

(1) Fine-grained turbiditic mudstones with coarser silty and sandy interbeds, exhibiting steep dips (between ˜60 and 90 degrees) are predominant in the prism down to ˜3000 mbsf. The biostratigraphic age of the sediments in the lowermost part of the hole is thought to be 9-11 Ma, with an assumed age of accretion of 3-5 Ma.

(2) Slickenlined surfaces, deformation bands and mineral veins are present throughout the drilled interval, while well-developed scaly clay fabrics are increasingly observed below ˜2200 mbsf. A substantial fault zone with well-developed foliation was successfully cored from the deep interior of the prism at ˜2205 mbsf.

(3) Porosity generally decreases from ˜60% to ˜20% from the seafloor to 3000 mbsf. However, physical properties including grain density, electrical conductivity and P-wave velocity suggest fairly homogeneous properties in the interior of the prism between ˜2000 and 3000 mbsf.

(4) Drilling mud gas analysis during the riser drilling indicates that a source of hydrocarbon gas shifts from microbial origin to thermogenic at around 1700-2300 mbsf.

Lithological and structural characterizations, the style of deformation, and downhole physical properties all indicate a complex structural evolution and will provide unprecedented insights into the mechanical state and behavior of the prism at depth.

Keywords: IODP, NanTroSEIZE, Nankai Trough, accretionary prism

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SSS30-15 Room:Main Hall Time:April 28 15:15-15:30

# Levels of frictional heat along deep to shallow parts of the megasplay fault : a Raman spectroscopic analyses of CM

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Estimation of frictional heating of deep to shallow portion of ancient megasplay fault is important for understanding of weakening mechanism (e.g., thermal pressurization, melt lubrication) of present plate boundary fault and megasplay fault. In this study, we performed microstructural observation and Raman spectroscopic analyses of carbonaceous materials (CM) in the fault rock of 2.5-5.5 km depth of an ancient megasplay fault (an out-of sequence thrust in the Shimant accretionary complex) and 1-4 km depth of a thrust in the Emi group, Hota accretionary complex. We also conducted heating experiment of CM in host rock of these fault with anaerobic condition (rate of temperature increase: 20 K/min) in order to investigate the effects of fast heating rate like frictional heating during earthquake.

Raman spectrum of CM of both fault is similar to spectrum of 400∼600 ℃ heating experiment of CM. This result shows that both fault had heating history of 400∼600 ℃ by frictional heating. Further examination for effect of shearing to molecular stricter is needed for more detailed evaluation of frictional heating history.

Keywords: ancient megasplay fault, heating experiment

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SSS30-16 Room:Main Hall Time:April 28 15:30-15:45

# Upper plate geology controls the rupture area segmentation -A case study of the Nankai Trough

KIMURA, Gaku[1*] ; HASHIMOTO, Yoshitaka[2] ; KITAMURA, Yujin[3] ; YAMAGUCHI, Asuka[4] ; HAMAHASHI, Mari[1] ; KOGE, Hiroaki[1] ; MORITA, Sumito[5]

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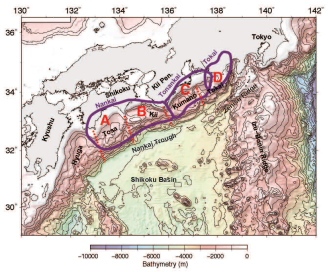
What controls the earthquake rupture area of megathrust is one of the most fundamental questions in geodynamic research of subduction zone. In the case of the Nankai Trough, Japan, three major controlling factors have proposed so far, surface topography of the subducting plate like seamount, locally strong rigidity of upper plate due to igneous rock composition, andfriction property of the plate boundary megathrust including abnormal pore fluid pressure distribution. Such controlling factors are applicable to other subduction zone in general. For example, the topographic high like seamount is proposed to control the location of asperity due to stronger coupling. The topographic-high worked as an asperity contacts with upper plate and rupture could be propagated when the contact breaks. The topographic-high also works as a barrier in the difficult case to be broken. From the geological point of view, plate boundary megathrust in the seismogenic zone must be composed of fault rock in brittle regime because of its temperature range from ~150 ℃ to ~350 ℃, which is cooler than the temperature for the plastic deformation of quarts, feldspar and other rock forming minerals of oceanic crust except for clayey phyllosilicates. In this temperature range, tectonic melange like fault rock with highly pressurized interstitial fluid is expected. Seismic observation showing a reflector with intensive amplitude of negative reflection coefficient suggests a plate boundary fault layer with abnormal fluid pressure. The friction behavior of the fault rock and pore fluid effect is a recent main concern in the subduction zone. The third factor is the mechanical property of the upper plate for the plate boundary megathrust in subduction zone. It is used to treat that the upper plate is a mechanical uniform media saving the elastic energy for theseismic slip along the megathrust. The mechanical property of the upper plate changes for a geological long time scale due to the growth of accretionary prism or tectonic erosion. In addition to such subduction mode of accretion vs erosion, some peculiar tectonic events (e.g. change in convergent direction, some obstacle collision, spreading ridge collision and rapid magmatic accretion etc.) modify the mechanical property of the upper plate and its heterogeneity in space. In the case of the Nankai Trough, a pultonic body is situated beneath the place of epicenter and is suggested to have been functioned as an asperitiy of 1944 Tonankai and 1946Nankaido Earthquakes. We examined the on-land geology of the Shikoku island and the Kii Peninsula, SW Japan, basement structure and composition beneath the forearcKumano Basin on the basis of recent results of ocean drilling by IODP (Integrated Ocean Drilling Project) and other investigations to infer the geologic composition of the upper plate. As a result we conclude that the key geologic event was middle to late Miocene episodic and rapid growth of forearc crust, mainly due to the magmatic intrusion and extrusion. This event was casued by the eastward migration of the T-T-T triple junction. Such ancient event now controls therupture area of the great earthquake in the subduction zone.



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SSS30-17 Room:Main Hall Time:April 28 15:45-16:00

# The research project on the extended Nankai seismogenic zones towards disaster mitigation of the mega-thrust earthquakes

KANEDA, Yoshiyuki[1*] ; FUKUWA, Nobuo[2] ; FURUMURA, Takashi[3]

[1]Japan Agency for Marine-Earth Science and Technology, [2]Nagoya University, [3]The University of Tokyo

The recurrence of Nankai trough mega thrust earthquakes and tsunamis are the very severe problem to Japan. Therefore, MEXT of Japanese government has implemented the research project during a period from FY2008 to 2012 to evaluate seismic linkage around the Nanakai trough mega thrust earthquake seismogenic zones. We have obtained many significant scientific results, such as the extended seismogenic zone, in this previous research project. In the 2013 fiscal year, a new project launched aiming mitigation of disaster caused by the Nankai trough earthquakes in the extended seismogenic zone. This new project is composed of three research fields which are the disaster mitigation research filed, observational research filed and the simulation research field. According to lessons learned from the 2011 East Japan Earthquake, the disaster mitigation research filed are progressing 5 sub-themes which are precise seismic hazard estimation, providing research results to local government/community for disaster measures, investigating recovery and revival methodologies based on social environmental changes, and constructing redundant hazard information database. The observational research field reveals structures of crust and plate, seismicity, and historical tsunami events in the Nankai trough. In the simulation research field, investigations will be conducted for recurrence cycle simulation of mega thrust earthquakes, data assimilation method that improves reliability of the simulation, seismic and tsunami wave simulations for disaster mitigation. We must surely progress each sub-theme at the beginning and finally integrate them for disaster mitigation around the extended Nankai trough sesimogenic zones. In this talk, we will introduce the outline of new project and the present progress.

Keywords: Nankai trough seismogenic zone, Seismic linkage, Disaster mitigation

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SSS30-18 Room:Main Hall Time:April 28 16:15-16:30

# Ogasawara Bending Slab and Mantle Convection

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Ogasawara Slab is not only steeply dipping, but also, bending concentrically and reaching to bottom of upper mantle, which are shown with the hypocenters of 14 May 2013 M7.3 (619 km depth) and 7 February 1998 M6.4 (552 km depth).

Pacific Plate is spreading along East Pacific Rise, and subducting along Japanese Islands down to bottom of upper mantle as slab. If we consider the mass balance in upper mantle on Plate motion with accompaning beneath mantle, the mantle should convect from subduct area toward spreadin area.

The allover concentric bending within the upper mantle realizes overturn of the slab. The slab surface contacts with upper surface of lower mantle where upper mantle minerals change phase for higher pressure. The coldest slab surface in the upper mantle could not change the phase, and might float on the surface of lower mantle toward opposit direction of Plate motion. The return flow of the upper mantle, induced by the floating slab surface, might allow the high speed of the largest Pacific Plate motion.

Izu Slab, north extend of Ogasawara Slab, is bending concentrically above ca. 410km of depth and unbending blow the depth as flat slab. The geometry of the shape from Ogasawara Salb to Izu Salb should intercalate discontinuous part of the slab. Nishinoshima erupted in Nobember 2013 on the slab discontinuous part. The forcal mechanisms on the slab discontinuous part change before and after the East Japan Super Erthquake.

Keywords: Ogasawara Slab, Concentric Bending, Mantle Convection, Upper Mantle Bottom, Nishinoshima Eruption

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SSS30-19 Room:Main Hall Time:April 28 16:30-16:45

# Rectified tidal loading: Control on earthquakes manifested by deep tremors

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Earthquakes occur due to plate motion, but it remains unclear as to what controls the plate motion. A clue to this problem is provided by a recently discovered cluster of deep tectonic tremors or tiny earthquakes that are occurring in western Japan. Here we demonstrate that tremor activity is strongly correlated with tide levels observed at a nearby station. The correlation is interpreted as representing a nonlinear relationship between stress and slip, which is similar to the rate-dependent friction law. An empirical relationship and observed tide records explain the temporal changes in tremor activity over a period of nine years. The nonlinear fault rheology rectifies oscillating tidal stress and amplifies small changes in tidal amplitude. This mechanism of rectified tidal loading may control temporal changes in plate motion and earthquake occurrence. Remarkably, the background seismicity in the present study area matches the predicted tremor rate obtained from tidal observations over the past 50 years. This mechanism may also explain the weak periodicity of large earthquakes, and is likely to be helpful in probabilistic forecasting of future seismicity.

Keywords: tremor, tide, rectification, slow slip, seismicity, Nankai earthquakes

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SSS30-20 Room:Main Hall Time:April 28 16:45-17:00

# Structural mechanics model of plate-interface fracture at subduction zones

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There are unidentified and unveiled properties concerning the physical process of greater inter-plate earthquakes at subduction zones. We, here, present a stochastic fracture model of the plate-interface with dynamic discrete interaction blocks. The stochastic treatment in this study is mainly based on structural mechanics. Here, in the four-dimensional point of view, regarded as significant long-wavelength components of the mechanical inter-plate coupling, we assign several discrete lattice-like blocks being connected each other on a hypothesized plate boundary system. The representative mechanical interaction vector (or tensor) for each discrete block should be variable on the plate boundary system. The total number of the discrete blocks and their nesting pattern should also vary with time during the long-term subduction process with intermittent greater seismic events.

Hereafter, we treat the inter-plate coupling at discrete blocks, using parameters such as failure probability *(Psf)* and safe probability *(Pss)* of the total system of the plate boundary. Here, $Psf + Pss = 1$.

The system fracture for the case of parallel connecting blocks is defined as the breakdown of all parallel blocks. Whereas, for the case of a series connecting block system, the system fracture is defined as the failure of one of the series block, or more. The system failure probability of a simple mechanical system being coupled in parallel $N$ blocks is given as a product of $p(i)$ from $i = 1$ to $i = N$. Here, $p(i)$ is the failure probability of the *i-th* block of the system. For the case of a mechanical system connected in series $N$ blocks, the system safe probability becomes a product of $\{1-p(i)\}$ from $i = 1$ to $i = N$. For a mechanical system composed of both parallel and series blocks, the system failure probability and system safe probability can be estimated with the above definition. Then, we assume that the inter-plate shear coupling of the plate-interface progresses only at discrete blocks of brittle fracture.

We consider two different configuration models for a two-by-four matrix *(2x4)* system of discrete coupling blocks, consist of four columns in the trench-parallel direction and two rows of deep side and a shallow side in the dip direction, as follows.

Configuration model $A$ is a series-connected system of both the shallower parallel-connected column blocks and the deeper parallel-connected ones.

Configuration model $B$ is a parallel-connected system of the four columns of the shallower and deeper rows being directly series-connected in the dip direction.

By setting the failure probability, $p(i,j)$, of *(i,j)-th* block, we can estimate the system failure probability *(Psf)* and system safe probability *(Pss)* for the configuration models, $A$ and $B$. For the configuration models $A$ and $B$, the system safe probability, *Pss(A)* and *Pss(B)* can be obtained. In the case of p(i,j) less than 0.5 for all blocks, *Pss(A)* becomes larger than *Pss(B)*, indicating that the configuration model $A$ is safer than the model $B$. When the representative pattern of the inter-plate coupling changes from the configuration model $A$ to $B$, or vice versa, we should carefully estimate the system probabilities.

We also demonstrated the detailed hypothetical expression form of p(i,j) by considering the effect of preceding larger seismic ruptures at blocks and the subsequent healing process, etc.

Keywords: subduction zone, inter-plate coupling, structural mechanics, system failure probability, system safe probability

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SSS30-21 Room:Main Hall Time:April 28 17:00-17:15

# Seismicity rate variations in subduction zones related to forearc topography

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There are clear variations in seismicity among subduction zones worldwide in terms of such as the frequency of earthquake occurrence and maximum earthquake magnitude. These variations have been attributed to differences in tectonic properties in subduction zones, such as relative plate velocity and subducting plate buoyancy. For example, Ide [2013] demonstrate proportionality between relative plate velocity and background seismicity rate — the frequency of seismic events excluding aftershocks. Given that earthquakes occur to release strain in the crust accumulated by relative plate motion, we can intuitively understand this proportionality.

The overriding plate is also an important control on earthquake occurrence in subduction zones. Seismological observations and studies of tectonics have suggested the relationship between forearc topography and frictional properties on the plate interface, such as interplate locking and pore fluid pressure. Given this relationship, variations in forearc topography may reflect differences in frictional properties on the plate interface among subduction zones worldwide. However the relation between forearc topography and variations in seismicity among subdcuction zones is still unclear. In this study, we compare forearc slope and background seismicity rate in subduction zones worldwide. The forearc slope is based on Smith and Sandwell [1997], and the background seismicity rate is estimated using the epidemic type aftershock sequence (ETAS) model [Ogata, 1988]. We show the correlation between forearc slope and background seismicity rate. Subduciton zones with steeper forearc slopes have higher seismicity rates. Furthermore, subduction zones that are outliers of the proportionality between relative plate velocity and background seismicity rate [Ide, 2013], such as Cascadia and South Chile trench, also appear to obey this correlation.

According to the critical taper theory [Davis et al., 1983; Dahlen, 1984], which explains the relationship between forearc topography and frictional properties on the plate interface, and sand box experiments [e.g., Gutscher et al., 1996], steep forearc slope is associated with high basal friction. When we take these studies into account, our results suggest that the seismicity rates are high in subduction zones with steep slopes and high basal friction. This can be explained by considering erosion and accretion processes and geometrical irregularities on the plate interface. Erosional margins tend to have steeper forearc slopes [Clift and Vanucchi, 2004]. Because of thin trench sediments in erosional subduciton zones, geometrical irregularities on the subducting plate are not smoothed. Such irregularities may cause high basal friction at the tip of the forearc wedge and steepen the forearc slope. In the seismogenic zone, these irregularities act as numerous small asperities, and these asperities result in many seismic events in the erosional subduction zone. In contrast, accretionary margins generally have gradual slopes. Thick trench sediments smooth subducted seafloor, and it results in low basal friction at the tip of the forearc wedge and the gradual forearc slope. The smoothed plate interface may act as one large asperity in the seismogenic zone, and fewer earthquakes occur in the accretionary subduction zone. Furthermore, these variations in number and size of asperities among subduction zones worldwide may cause differences in megathrust earthquake occurrence.

Our results reveal the relation between forearc topography and seismity, and suggest that the frequency of seismic events in subduction zones is controlled by not only the mechanical factors such as relative plate velocity and the strain accumulated in the crust, but also the material factors such as erosion and accretion processes, trench sediments, and geometrical irregularities on the plate interface.

Keywords: seismicity rate, subduction zone, forearc topography, erosion and accretion, asperity

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SSS30-22 Room:Main Hall Time:April 28 17:15-17:30

# Feasibility of acoustic monitoring of strength drop precursory to earthquake occurrence

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[1]Earthquake Res. Inst., Univ. of Tokyo, [2]Ministry of Education, Culture, Sports, Science and Technology

Rate- and state-dependent friction law (RSF), proposed on the basis of laboratory experiments, has been extensively applied to modeling of earthquake stick-slip cycles. A simple spring-slider model obeying RSF predicts a significant decrease of the frictional strength Phi (the state of contact) that is localized within a few years preceding the earthquake occurrence. On the other hand, recent laboratory experiments successfully monitored the history of the strength by simultaneously measuring P-wave transmissivity |T|across the frictional interface using a 1MHz transducer. This suggests a possibility of earthquake forecast by monitoring the strength of a natural fault by acoustic methods.

The present paper explores the feasibility of such monitoring in the field on the basis of the physics of RSF combined with the linear slip model (LSM) employed in the classical acoustic methodology for monitoring an imperfectly welded interface. The characteristic frequency f_c, around which |T|(or reflectivity |R|) has a good sensitivity to the interface strength, is shown to be proportional to the strength and inversely proportional to the representative scale of real contacts.For natural faults f_c is estimated to be 1 to 100Hz, which is practicable in the field. The changes of |T|and |R|depend on the ratio of the strength drop to the absolute strength level, the latter of which is not constrained by RSF simulations. Expected changes in wave amplitude in the preslip period would be several percent for strong faults and several tens percent for weak faults, which may be detectable by acoustic methods such as seismic reflection surveys.

Keywords: fault strength, earthquake cycle, rate- and state-dependent friction, precursor, linear slip model, acoustic monitoring

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SSS30-23 Room:Main Hall Time:April 28 17:45-18:00

# Semi-quatitative analysis of change in stress state in Chelung-pu Fault, Taiwan

HASHIMOTO, Yoshitaka[1*] ; TOBE, Kota[1] ; YEH, En-chao[2]

[1]Kochi Univerisity, [2]National Taiwan Normal University

Semi-quantitative stress state before and after earthquake in Chelung-pu fault, Taiwan

Stress change caused by earthquake is important to understand size and nature of an earthquake. Detailed waveforms of the 1999 Chi-Chi earthquake were taken along the Chelung-pu fault. In the aftermath of the earthquake, Taiwan Chelungu-pu Fault Drilling Project (TCDP) was conducted to take core with the seismogenic fault. In this study, we estimated paleo-stress condition semi-quantitatively using micro-fault inversion method and stress polygon. Then we discuss the relationship between spatial and temporal changes of stress with seismic cycles.

We used Multiple inversion method (MIM) (Yamaji, 2000) and k-means clustering (Otsubo et al., 2006) to estimate paleo-stress. As a result, we obtained four solutions of stress state (c1-c4) from TCDP core. To estimate the range of stress conditions we used stress polygons on the basis of the Anderson theory of faulting as used in Lin et al. (2007). We projected our paleo-stress orientations to the directions of SHmax, Shmin and SV. In addition to that, using stress ratio and a definition that SHmax is larger than Shmin, we can restrict the stress conditions for the paleo-stress in the stress polygons.

Two stress conditions (c1 and c3) were comparable with that from Lin et al. (2007) as a present state and post-seismic condition in normal stress regime. The range of stress condition for c2 is obviously higher than others, and the stress condition is in revere fault regime. The differences of stress condition possibly indicate the change in stress magnitude in the seismic cycle. Stress drops were estimated as -7.94˜2.60MPa for c1 and c2, and 2.71˜13.68MPa for c2 and c3. The calculated stress drop is comparable with estimated average stress drop from slip distribution in Chi-Chi earthquake (Ma et al. 2000).

Keywords: stress, micro-fault inversion, stress drop, Chelung-pu fault

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SSS30-24 Room:Main Hall Time:April 29 14:15-14:30

# Fluid transport property and diagenetic microstructure of chert in the Mino Belt

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Pore fluid pressure along plate boundary megathrust is controlled by both fluid supply and fluid transport property, and it affects on faulting and earthquake mechanics. In the case of subduction zones where relatively old (older than 50 m.y. in age) oceanic plate subducts, oceanic crust is covered with thick pelagic siliceous sediments composed of diatomic and/or radiolarian oozes. In the Japan Trench, Kimura et al. (2012) pointed out that the volume of dehydrated fluid during silica diagenesis from opal-A to quartz through opal-CT is significant compared to that from clay mineral (smectite-illite) transition. However, fluid transport property of siliceous sediments has not been well-understood yet. In this study we conducted both permeability measurement and microstructural/microchemical observation of bedded chert from Inuyama-section in the Mino belt, Jurassic accretionary complex in Japan, as an on-land analog of subduction zone where old oceanic plate subducts.

Initial porosity of chert samples at atmospheric pressure is 0.4 to 2.2 %. Permeability was measured at room temperature under isostatic confining pressures of 5 to 120 MPa, by the steady state flow method with nitrogen gas as a pore fluid. Water permeability was then obtained by using Klinkenberg equation. At effective pressure of 5 MPa converted water permeability is $10^{-17}$ to $10^{-19}$ $m^2$, decreases with increasing effective pressure down to the ranges of $10^{-20}$ to$10^{-21}$ $m^2$.

Optical and electron probe microanalyzer (EPMA) analyses show that chert is composed of radiolarian fossils filled with quartz and chalcedony, and red-colored matrix. Red matrix shows ˜95 wt.% of $SiO_2$, whereas >99 wt.% of $SiO_2$ are commonly observed from inside part of the radiolarian fossils. Such high concentration of $SiO_2$ within radiolarian fossils indicates that dissolved silica was precipitated into cavities maintained by radiolarian tests. This process would be related with silica diagenesis, occurring as dissolution-precipitation processes.

Silica mineral precipitation onto pore spaces would contribute to construct characteristic low porosity and permeability of chert. Our result shows that silica diagenesis works as not only a fluid source but also as a process for porosity/permeability reduction in convergent margins characterized by old subducting oceanic plate.

Keywords: subduction zone, diagenesis, permeability, chert

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# Mechanical properties of the shallow Nankai Trough accretionary sediments

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We report the results of triaxial compression and friction experiments of clayey mudstone, silty mudstone, sandstone and tuff samples, which are cored from the shallow (1000-1500 mbsf) Nankai Trough accretionary prism at IODP Sites C0002 and C0009, at room temperature, and confining pressures and pore water pressures close to their in situ conditions.

Triaxial compression experiments at these conditions and an axial displacement rate of 10 $\mu$m/s reveal that the failure strength is ≈300 MPa for a sandstone sample, ≈48 MPa for a tuff sample, ≈20 MPa for a silty mudstone sample, and ≈14 MPa for a clayey mudstone sample. The sandtone, tuff and silty mudstone samples failed relatively rapidly within 20 s, while the clayey mudstone sample failed slowly for ≈40 s. Another silty mudstone sample did not fail, and deformed ductilely at a strength of ≈15 MPa. The sandstone sample is strongly lithified by being cemented by calcite, which makes this sample's failure strength very high. The ductilely deformed silty mudstone sample seems not lithified enough to fail. A probable increase in pore pressure during compression of the clayey mudstone sample due to its low porosity (≈11 %) and permeability (≈$10^{-19}$ $m^2$) in addition to its intrinsic weakness due to the abundance of clay minerals (≈42 wt%) likely makes this sample weak and promotes its slow failure. Such failure in clayey mudstone is a possible source for slow slip events observed in the shallow Nankai Trough accretionary prism.

Friction experiments at these conditions and axial displacement rates changed stepwise among 0.1, 1 and 10 $\mu$m/s reveal that frictional properties of these samples change systematically according to the content of clay minerals. The content of clay minerals is ≈6 wt% in the sandstone sample, ≈17 wt% in the tuff sample, 29-34 wt% in the silty mudstone samples, and ≈42 wt% in the clayey mudstone sample. Steady-state friction coefficient at the axial displacement rate of 1 $\mu$m/s decreases with increasing content of clay minerals, from 0.87 of the sandstone sample, through 0.71 of the tuff sample and 0.53-0.56 of the silty mudstone samples, to 0.25 of the clayey mudstone sample. Slip-dependent frictional behavior also changes from slip hardening to slip weakening with increasing content of clay minerals. Although all samples exhibit velocity-strengthening behavior upon stepwise changes in sliding velocity, the ratio of $(a - b)$ value to the velocity dependence of steady-state friction decreases with increasing content of clay minerals, which implies that the friction component decreases while the flow component increases accordingly. Thus, faulting in the shallow Nankai Trough accretionary prism is likely controlled by the content of clay minerals in sediments as well as in fault zones.

Keywords: Nankai Trough, accretionary sediments, failure properties, frictional properties

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# Velocity weakening behavior observed for friction of the shallow subduction zone fault material

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Recent observations of slow earthquakes along faults within shallow part of subduction zones, for example the very low frequency earthquakes at the Nankai Trough [Ito and Obara, 2006; Sugioka et al., 2012], has demonstrated that faulting there is slow yet seismic; suggesting that frictional velocity dependence along the fault at the shallow portion must be negative. However, previous experimental results have repeatedly shown that velocity dependence of the expected fault zone material is generally estimated to be positive. Here, we present our recent experimental results showing that velocity dependence of the friction of the shallow subduction zone faults are not necessarily be positive.

We have performed a series of rotary-shear large displacement (>150 mm) friction experiments on the following shallow fault simulating material: clayey fault material form the shallow megasplay fault zone within the Nankai accretionary prism, input pelagic siliceous to calcareous sediments to the Costa Rica subduction zone, and simulated artificial gouge of montmorillonite/quartz mixtures (20-40 wt% of montmorillonite). Experimental results reveal that these material do exhibit velocity weakening behavior at a range of velocities from 0.003-0.3 mm/s. Velocity weakening of these material is mostly characterized by a small degree of the friction velocity dependence (the absolute value of (a-b) is typically <0.005.

The SSEs are often described as conditionally stable sliding of faults [e.g., Shelly et al., 2006]. High pore fluid pressure could alter a velocity-weakening fault with a small value of (a-b) to conditionally stable regions by reducing the effective normal stress [Scholz, 1998]. The presented velocity weakening property with a small value of (a-b) could be responsible for generating shallow slow seismic slip events in subduction zones. Textural observation reveals the importance of studying effects of both the clay content and shear-induced deformation textures on the frictional velocity dependence.

Keywords: Nankai Trough, subduction zone, frictional velocity dependence, slow earthquakes

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SSS30-27 Room:Main Hall Time:April 29 15:00-15:15

# Frictional properties of simulated faults containing amorphous silica/calcite mixtures

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Various seismic behaviors such as large earthquakes, episodic slow slip events, or silent earthquakes are observed in subduction zones. Knowledge of the frictional properties of input material to subduction zones would help to understand the complicated seismic behaviors. On the Cocos plate, which subducts beneath the Caribbean Plate at Middle America Trench offshore Costa Rica, input sediments containing clay, silty clay sediments and silicic to calcareous ooze were collected during the IODP expedition 334. We have been studying the frictional properties of the collected input material to the Costa Rica subduction zone. In order to better understand frictional processes of a fault in silicic to calcareous ooze, we have performed a series of friction experiments on a simulated fault gouge containing mixtures of amorphous silica and calcite.

Frictional experiments were performed at a constant slip velocity of v = 0.28 mm/s, and also under a velocity-stepping condition. The silicic to calcareous ooze sample showed the following characteristic behavior. The friction coefficients at 0.28 mm/s showed initial peaks at 0.4?0.6 and subsequent little decrease, followed by a gradual increase to attain a constant friction value at 0.6?0.8. The analogue gouge containing 40?80 wt% of calcite reproduced such frictional behavior well. The experimental samples of the input ooze material required only about 40 mm of displacement to attain constant steady-state friction level. However, the calcite/amorphous silica mixtures needed larger displacement to attain steady-state friction. Furthermore, the calcite/amorphous silica mixtures could not reproduce friction velocity dependence observed for the collected ooze samples. The result suggests the importance of studying effects of grain size distribution and the grain morphologies on the frictional properties of the silicic to calcareous ooze material.

Keywords: subduction zone, frictional experiment, CRISP

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# Effect of temperature on frictional behavior of smectite and illite: Implication for the updip limit for seismogenic zon

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Introduction: Along plate boundary subduction thrusts, the transformation of smectite to illite within fault gouge at temperatures of ˜150C is one of the key mineralogical changes thought to control the updip limit of seismicity. Saffer and Marone (2003) reported illite shale exhibited only velocity-strengthening behavior, opposite to the widely expected, potentially unstable velocity-weakening behavior of illite. They concluded transformation of smectite to illite is not responsible for the seismic-aseismic transition in the updip limit of subduction zones. However, their experiments were limited at room temperature although the updip limit of seismogenic zone is thermally controlled that occurs at temperature around 150oC. Therefore, in this study, we determined the effect of temperature of frictional properties of smectite and illite and discuss whether the smectite-illite transition accounts for the updip limit of seismogenic zone along subduction thrust.

Experimental methods: Frictional experiments were performed using a biaxial frictional testing machine at Hiroshima University. The powder materials of clays were placed on the simulated fault surface and two side blocks were placed together to produce a double-direct shear configuration. Normal stress was applied via a hydraulic ram on the side block with 15, 40, 60 MPa, and then, shear stress was applied by advancing the central block downward at a constant velocity. The sample assembly was heated by an external furnace up to 200oC that is monitored by thermocouples located close to the central block. Mechanical data were recorded continuously with a sampling rate of 10 Hz and the frictional coefficient was calculated from the shear force divided by the normal force assuming zero cohesion.

In the frictional experiments, we determined the velocity dependence of sliding friction, which is a key parameter for stable or unstable sliding (e.g., Dieterich, 1979). After steady-state sliding, the loading velocity of 3 $\mu$m/s was abruptly changed to 30 $\mu$m/s in each frictional experiments to determine the velocity dependence of these clay minerals. We calculated the velocity dependence of sliding friction as follow:

$$(a-b)=d\mu(d \ln V)$$

where a,b is the frictional parameter and V is sliding velocity. The velocity dependence is important to show seismic slip, in which negative values of (a-b) reflect velocity-weakening behavior, whereas positive values of (a-b) reflect velocity-strengthening behavior and thence stable (aseismic) sliding.

Results and Discussion: In comparison of steady-state fictional strength of clay minerals, the value of frictional strength of smectite is nearly half as large as that of illite. The effect of temperature on the frictional strength is rather weak, and the steady state friction is slightly increased at high temperatures. Our results suggest that the shear stress required to initiate sliding is much lower for smectite than illite, and smectite could not accumulate much strain energy.

The velocity dependence at room temperature shows always positive at normal stress higher than 40 MPa, which is similar to the results of Saffer and Marone (2003). However, at temperature of 200C, illite shows negative values of (a-b), suggesting that illite exhibits unstable velocity-weakening behavior. This results explains smectite is potentially aseismic for stable sliding at the subduction thrust, whereas illite becomes seismic due to a negative velocity dependence and unstable sliding at high temperatures. These experimental results indicate that the smectite-illite transition potentially account for the updip limit of seismogenic zone along subduction thrust, which is opposite to the previous results at room temperature.

Keywords: updip limit, smectite-illite transformation, effect of temperature, velocity dependence

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SSS30-29 Room:Main Hall Time:April 29 15:30-15:45

# Frictional properties of basalt-derived fault rocks and implications for subduction earthquakes

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Recent seismic reflection surveys in subduction zones such as Nankai Trough suggest that subduction earthquakes mostly occurred along the upper part of oceanic crust composed of basaltic rocks (e.g., Bangs et al., 2009). Hence, frictional properties of basalt appear to be keys for understanding earthquake nucleation and rupture propagation during subduction earthquakes, yet they remain poorly understood. In the Upper Shimanto accretionary complex of eastern Shikoku, basalt and tectonic melange are repeated by thrusts, representing duplex structure associated with underplating (Ikesawa et al., 2005). Underplating-related thrusts develop in basalt and consist of basalt-derived foliated cataclasite and ultracataclasite. Fluidization of comminuted material and mineralogical signatures of frictional heating were reported from a few centimeters-thick ultracataclasite (Ujiie et al., 2007; 2008; Kameda et al., 2011). We examined the frictional velocity dependence at slip rates of 0.0028-0.28 mm/s and high-velocity (1.3 m/s) frictional properties of disaggregated pillow basalt and basalt-derived foliated cataclasite and ultracataclasite. The samples from pillow basalt show velocity-weakening behavior, while those from foliated cataclasite and ultracataclasite exhibit velocity-strengthening behavior. All samples show slip weakening behavior during high-velocity friction experiments, with the samples from ultracataclasite marked by smaller stress drop, slip weakening distance, and fracture energy. The compositions of materials and preliminary microstructural observations suggest that velocity-weakening samples show lower clay content (21 wt.%) and grain-size reduction, while velocity-strengthening samples exhibit relatively high clay content (29-50 wt.%) and clay foliations. Our results suggest that earthquake nucleation likely occurs in subducting basalt, but slip tends to be stable when clays and clay fabrics are formed by hydrothermal alteration and shear deformation, respectively. The results of high-velocity friction tests suggest that earthquake rupture propagates easily through ultracataclasite rather than foliated cataclasite and pillow basalt, which is consistent with the fact that the geological evidence of earthquake faulting was found from the ultracataclasite.

Keywords: subduction earthquakes, basalt, frictional velocity dependence, high velocity friction

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# Amorphization of clay minerals by wet and dry grinding

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Nanoparticles in fault zones are recently paid much attention since they give significant influences on the frictional properties (Ma et al., 2006). Nanoparticles are considered to be formed not only by mechanical grinding but also by mechanochemical processes. Amorphous nanoparticles were found in Iida-Matsukawa fault, Central Japan (Ozawa and Takizawa, 2007). It is well known that clay minerals are easily transformed into amorphous phase by mechanochemical processes. We conducted pulverization experiments of some clay minerals under both dry and wet conditions to clarify the characteristics of the pulverized materials and the mechanism of amorphization.

We used kaolinite saponite and sericite as starting materials. Pulverization experiments were conducted using planetary ball mill and characterization of run products were conducted by XRD, FT-IR, TG-DTA and FE-SEM. Three minerals were completely transformed into amorphous materials by dry grinding. XRD peaks were weakened but still remain after one day wet drying as for kaolinite and sericite. On the contrary, as for saponite, XRD peaks do not show remarkable change under wet condition. Probably amorphization rate is reduced because impact energy in the ball mill is decreased in the presence of water. Presence of interlayer water affects on the behavior of saponite.

Keywords: clay minerals, kaolinite, sericite, saponite, amorphous

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SSS30-31 Room:Main Hall Time:April 29 16:15-16:30

# Fluid inclusion as fossil fluid in seismogenic zone, trap mechanism and interpretations for fault science

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A fluid inclusion, fluid-fill capsule within rigid crystal, preserves density and chemical composition of fluid in deep crust. This records pressure, temperature and other information of the fluid when the fluid trapped. Pore fluid pressure drop due to rapid fluid ejection along the fault was discussed in Kodiak accretionary complex (Vrolijk et al., 1988). CH4-H2O fluid inclusions are reported at pseudotachylyte bearing Nobeoka Thrust, Shimanto accretionary complex (Kondo et al., 2005). Thermal stretching of fluid inclusions due to seismic frictional heating were found at seismogenic Mugi Melange, Shimanto accretionary complex (Ujiie et al., 2008). Though fluid inclusion tells us fluid condition in deep crust, trapping mechanism within crystal is still uncertain. The fluid inclusion is one of crystallographic defect, but general size from sub-micron meter to several mm is much greater than crystal lattice. A crystal tend to growth without large defect, and it seems irregular process to be formed a fluid inclusion. The trap mechanism is significant to interpret the fluid inclusion data.

We succeeded to make artificial fluid inclusion in calcite during hydrothermal experiment. A calcite crystals are nucleated and grown with temperature decrease in autoclave. Fluid inclusions were never formed in simple cooling procedure, but many large fluid inclusions were found at the overgrowth zone formed by re-heating process. Surface condition of artificial calcite of re-heating and overgrowth process were observed using SEM. Etched pattern covers the surface of re-heated calcite crystal. Some depressions are wide shallow and others are small deep. Many growth steps were found on surface of over-growth calcite. The calcite surface may have been advanced with lateral motion of growth steps. This growth step covers most of the etched depressions except small deep one. These small deep depressions are surrounded by new grown surface and became increasingly deep. Some depressions may make large pore within overgrowth zone in this process.

This observation shows that the fluid inclusion were made during overgrowth after surface etching, and this requires temporary solubility change in crystal growth process. The fluid inclusions may record pore-fluid condition after the event of pressure, temperature and/or chemical change in deep crust.

Keywords: Fluid inclusion, trap mechanism, artificial calcite

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# New fluid flow mechanism at seismogenic depth in subduction zone

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Since pore fluid pressure may concern with seismogenesis, large amount of articles are published for fluid flow research, and -previous researches have been focused only crack flow in deep crust. In general, a pore between sedimentary grain decreases with depth, and fluid flows only within crack in deep crust. This study shows new fluid flow mechanism that doesn't depend on crack in the rocks. This produces new perspective of fluid flow of seismogenic depth in subduction zone.

The Shimanto accretionary complex at SW-Japan, formed at seismogenic depth suffers pressure solution deformation and generally includes brittle failure of web structure and crack-filled veins. The carbonate matrix is lacked in the sediments due to deposition below CCD.

Some sandstones in the late Cretaceous Nonokawa Formation, includes spotted carbonate deposit. This carbonate deposit occurs limited area less than several meters square within sandy layer without crack-filled vein. Microscopic observation shows following features as below.

The spotted carbonate minerals overprint with embayment structure in pressure-solution deformed sandy grains, and these are cut by web structure and crack-filled veins. The fluid may have dissolved the sandy grains, and carbonate minerals were deposited at latest stage of lithification process between pressure solution deformation and brittle failure. These occurrences suggest that fluid can flow with dissolution of rock-forming grains in rigid crust without crack.

Keywords: fluid flow, accretionary complex

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# Generation of high-temperature fluid and its spatial distribution in an ancient megasplay fault

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An ancient megasplay fault outcrop is identified within Kure region of the Shimanto accretionary complex and has been formed at 2.5 – 5.5 km depth. Recent works show pseudotachylyte produced by frictional melt, fluid-rock interactions at high temperatures (>350 ℃) and enrichment of incompatible element concentrations on the fault. However, spatial distribution of pseudotachylyte and high-temperature fluid is not investigated. These informations are important to understand an earthquake is able to produce extensively high-temperature fluid and thermal pressurization. Accordingly, we performed deformation structures analysis and obtained 46 rock samples from the outcrop and analyzed these samples by vitrinite reflectance measurement, powder X-ray diffraction-RockJock mineral composition analyses and trace elements compositions measurement. Therefore, analyses of black gouge samples from the slip zone indicate fluid-rock interactions at high temperatures, whereas footwall sandstone samples that are close to fault gouge indicate enrichment of quartz and decrease of rare-earth element concentrations. These contrasts may be regarded as mobilization of elements derived from seepage of yielded high temperatures fluid within the slip zone.

Keywords: Nankai trough, megasplay fault, Shimanto accretionary complex, fault rocks, fluid-rock interactions, X-ray diffraction

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# Multiple damage zone system of an exhumed subduction zone megasplay fault

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More than 90% of the major earthquakes and tsunamis are known to occur at plate convergent margins, along plate boundary faults and megasplay faults. Investigating the mechanical properties and deformation patterns of these megathrusts are important to understand the generation of earthquakes and the dynamics on the subduction plate interface. Large displacement faults contribute to the reduction of steady-state strength at mid-crustal levels, and cause the frictional-viscous deformation at depth. As the candidate for such weak faults, foliated, phyllosilicate-rich fault rocks have been prevalently recognized in many tectonic settings. However, whether foliated fault rocks behave as weak structures in the longer terms and their roles in the strain localization and fault evolution, are poorly understood.

Exhumed fault zones are helpful to constrain fault strength and deformation process of foliated cataclasites formed at upper-midcrustal depths over geological time. One of the well-studied exhumed major fault zones in subduction settings is the Nobeoka Thrust, a fossilized megasplay fault in Kyushu Shimanto Belt, southwest Japan, which exposes foliated fault rocks that were formed under the temperature range of ~180-350 ℃ (Kondo et al., 2005). During the Nobeoka Thrust Drilling Project in 2011, core samples were retrieved containing both consolidated fault rocks and less consolidated, brecciated fault rocks, preserved from surface weathering and less likely to be drilling-induced. The core samples are expected to provide a different aspect on fault rock strength from previous geological studies on exposed, consolidated outcrops. In the current study, given the unique opportunity to determine the coexistence of cohesive and less cohesive fault rocks in a single fault system, we conduct macroscopic and microscopic structural observation and physical property measurements on the core samples, synthesizing with geophysical logs obtained from the drilling of the Nobeoka Thrust to characterize the damage zone architecture of the fault rocks formed in the frictional-viscous regime along the megasplay fault.

The hanging wall consists of the shale-dominant intervals of dense development of phyllitic cleavages, the sandstone-dominant intervals of disturbed foliations, and the damage zone above the fault core characterized by cataclastically broken phyllite with thick abundant sandstone blocks. The observed density of brittle fractures, breccias, and mineral veins is increased at the sandstone-dominant intervals and near the fault core, whereas brecciated and less brittle/ductile structures are abundant within the shale dominant intervals. The brittle deformation near the fault core may have caused the wearing away of the shale-rich zones by abrasion, and as a result, the sandstone-rich zones that have relatively larger strength, remained and deformed cataclastically near the fault core. On the other hand, the footwall in the drilled range consists of six sets of fracture zones, all of which include a ”brecciated zone” intensively broken in the center, sandwiched by a ”surrounding damage zone” with abundant cohesive faults, mineral veins, and sandstone blocks. The surrounding damage zone is characterized by the increase in fault and fractures with distance from the fault core, and interestingly associate with the increase in resistivity, P-wave velocity, and density and decrease in porosity. The deformation in the surrounding damage zone is inferred to occur in a strain-hardening manner, strengthening with distance from the fault core. Shear localization may initiate more easily in the sandstone-rich area later forming the surrounding damage zone, and eventually develop an intensively deformed fault core in the center. These insights would enable to reinterpret the deformation processes and weakening mechanisms that occur in foliated fault rocks along the megathrust in subduction zones.

Keywords: subduction zone, megasplay fault, physical property of rock, damage zone, structural observation, rock deformation

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# Damaged coasts of the tsunami of the Enpo Boso-Oki Earthquake of November 7, 1677

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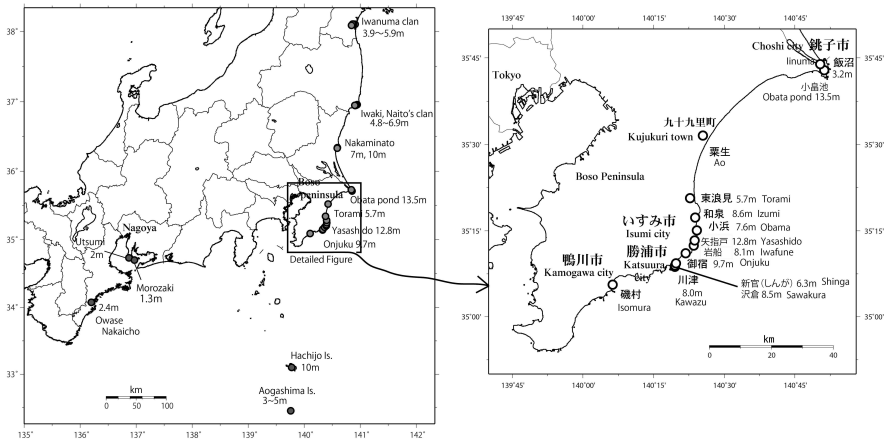
The Enpo Boso-Oki earthquake of November 7th, 1677 occurred in the sea area of the south east offing of Boso peninsula, Kanto district, Central Japan. The shaking of the earthquake was weak, and no damage occurred due to the shaking. The shaking was felt only on the Boso Peninsula and at Edo (Tokyo). Though the shaking was small, but a huge tsunami hit the coasts of Boso peninsula, and north to Iwanuma city about 20 kilometers south of Sendai. Detailed house and human damage was recorded in "Gyokuro-So", one of the fundamental chronologies of the Tokugawa Government. In Katsuura city on the coast of Boso Peninsula, at Kawazu, Sawakura, and at Shinga villages 47 houses were destroyed, and 7 people were killed in total. Inundation heights of the tsunami at those three villages are estimated at 8.0, 8.5 and 6.3 meters, respectively. At Onjuku fishery village, 30 houses were destroyed and 57 people were killed, and tsunami height was estimated at 9.7 meters. At Yasahido village, where total number of houses was about 30, 25 houses were swept away and 13 people were killed, and tsunami height was 12.8 meters. In Choshi city, sea water rushed into Obata Ike pond. We measure the height of the saddle point separating the pond from the open sea, and we found out that tsunami height was 13.5 meters there. The tsunami height at Iwaki City, Fukushima Prefecture was 4.8 to 6.9 meters. On Hachijo Island, about 300 kilometers south of Tokyo, the residential area of Yato behind Yaene port was flooded by sea water and the inundation height is estimated at about 10 meters. The tsunami wave affected west to Ise Bay, Nagoya City. At Utsumi port in Minamichita town about 25 ships were wrecked due to the tsunami. Tsunami also recorded at Owase city on the south east coast of Kii peninsula. The authors of the present study wish to express their thanks to JNES for its financial support in promoting our research.

Keywords: historical earthquake, historical tsunami, the 1677 Boso-Oki earthquake, metropolotan area, Ise bay, Kii peninsula



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


SSS30-36 Room:Main Hall Time:April 29 17:30-17:45

# Crustal movement associated with the 1703 Genroku earthquake

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We analyzed historical documents on the 1703 Genroku earthquake to estimate the crustal movement associated with the earthquake in the Tokyo Bay area, central Japan.

Keywords: 1703 Genroku earthquake, Tokyo Bay, crustal movement

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SSS30-37 Room:Main Hall Time:April 29 17:45-18:00

# A Reproduction of 1707 Hoei Tsunami with long rupture duration, referring to 2011 East Japan Pacific Ocean Earthquake

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Hoei earthquake in 1707 was the largest earthquake in the Edo period that gave the tsunami damage to a wide area along the Pacific Ocean, from the Izu Peninsula to the Southwest Japan. It was assumed that in Hoei earthquake, the source areas of Ansei Tokai and Nankai earthquakes ruptured subsequently within a very short time [e.g. Usami (2003)], or the source areas of the two earthquakes of Ansei were broken at a time [e.g. Ishibashi (2004)]. However, the recent detailed study of historical records revealed that the crustal deformation and the seismic intensity distribution tell that the western and eastern margins of the Hoei source region did not overlap with the two earthquakes in Ansei [e.g. Matsu'ura (2012)]. Hoei earthquake was the exceptionally huge earthquake, which should be called "Western Japan Pacific Ocean Earthquake" in Edo period.

In order to explain very high tsunami of Hoei in the Western Japan, Aida (1981) set the doubled slip to the source area off the cape Ashizuri. Furumura et al. (2011) even expanded the source area further west towards Kyushu. However, their models cannot match the intensity distribution in Kyushu and arrival times of tsunami to villages along the east coast of Kyushu. We suspect that the commonly used tsunami simulation method does not work for a M9-class huge tsunami like Hoei. The theoretical calculation program of crustal deformation of a rectangular fault in a semi-infinite medium [e.g. Sato and Matsu'ura (1973)], which is widely used for the tsunami simulation, inevitably produces singular margins. When the source area was huge, the singularity should affect coastal areas. When the shallow part near the trench is included in the source area, using the same elastic constants as the deeper part should result in an unrealistic deformation solution for a tsunami simulation.

To avoid these limits to applications of the theory used, we put aside obtaining crustal deformation of the sea floor from a dislocation source model, and calculate tsunami from the model of sea floor upheaval and subsidence, which evolve in time. For a test, we first examine the case of the East Japan Pacific Ocean Earthquake of 2011. In order to avoid the detailed topography along coasts, we only used data from GPS buoys and pressure gauges located offshore. We used the ocean bottom upheaval and subsidence obtained by Saito et al. (2011) as the final crustal deformation of the 2011 huge quake. From the known epicenter, the deformation spreads gradually, with the intermittent of 20 seconds, which was observed by GPS as the stop of movement. Paying the attention for the physical plausibility, the movement starts when the rupture reaches, and continues moving until the rupture reaches the edge of a source area. Since the small smooth subsidence spreads over wide area around the major large upheaval area in Saito's model, most tsunami waveform features were reproduced only from the major upheaval area and the smaller upheaval zone protruding toward Japan Trench.

Then we did for Hoei tsunami. As the source of upheaval, we use the source region proposed by Matsu'ura et al. (2011). The topography in Hoei period, we stripped down claimed lands like the islands of Kansai International airport, and Tenpozan, which are apparently made after Hoei period. We also increased the depth of Sakai port, which had been buried by depositions carried by Yamato River since 1704. Examining tsunami for two cases of hypocenter, one at the east end of the source area near Zenisu, and the other at Kumano-nada, we realized that it is impossible to distinguish a hypocenter from limited tsunami information obtained for historical earthquakes. Even with our rough model, Hoei tsunami can go up to canals in Osaka and in the Lake Ryujin in Hazako, Oita. Our experience tells that we shall leverage the recent high power of ordinary computers for a tsunami simulation and molt to go beyond the 40-year-old theoretical crustal deformation.

Keywords: Hoei Earthquake in 1707, East Japan Pacific Ocean Earthquake in 2011, rectangular source fault model, huge tsunami, historical earthquakes

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SSS30-P01 Room:Poster Time:April 29 18:15-19:30

# Close examination of universality of matter off Miyagi that earthquakes advanced toward the east

MASE, Hirofumi[1*]

[1]none

I explained how the surrounding of the plate boundary is always compressed(1). I reproduced the Off-Miyagi by the easy experiment(2). I understood earthquakes off Miyagi gradually climbed the slope of the plate boundary. The head within range where small earthquakes occur advanced toward the east gradually and went beyond the hypocenter of 3.11 in November, 2010.(3)

Therefore, the model of off Miyagi is the following. The earthquake of M7 class occurs in several decades by one degree. In every case the hypocenter of it moves east. And, the rear side of it slips to a deep point. The moderate quake guides the earthquake of M7. And, the front of crack is formed. Slip-all-together occurs if the front of crack arrives at a proper place. The feature of this model is to be able to give the answer to the following three large problems at a time. (a)A lot of people think that it is generated repeatedly within the specific range. (b)The cause of the swerve that causes large slip in every case is not discovered. (c)Finally happening is that a shallow part is destroyed at a time.

I want to think about (IC)Off Iwate-Chubu,(IH)Off Iwate-Hokubu,(AT)Off Aomori-Toho,(TK)Off Tokachi referring to (MY)Off Miyagi(Fig.1). The 1968 Tokachi-oki earthquake and the 1994 Sanriku-Haruka-Oki earthquake occurred in (IH)(AT). The co-seismic slip distributions on the map of (4) is interesting. Though the rupture starting point and the main rupture zone can be understood of those relation of upper-lower part on slope, both are considerably away. This is a feature and it is necessary to be clarified. I interpret that a main rupture zone is the peak of slip nearest the trench. The 1968 earthquake has two large slip zone. The main rupture zone in the south is located in lower part of the main rupture zone of the 1994 earthquake on slope. I want to pay attention to that. I think the 1968 earthquake went with the earthquake that had to happen ahead of the 1994 earthquake. The earthquakes that occurred in the vicinity in the past(5) have the possibility that there were rupture zones in lower part of the 1968 earthquake or the earthquake that had to happen ahead of the 1994 earthquake on slope. Therefore, I think that (IH)(AT) walks on the road similar to (MY). And, that a shallow part can slips and timing is only waited for. We should think that the earthquake similarly climbs the slope also in region (TK).

Range (39N-40N,143E-144E) in region (IC) is the earthquake-prone zone of small and medium-sized earthquakes after 1923. It is seen that there are a lot of intraplate earthquakes(12). The lower plate always collapses due to the earthquakes and the material overflows up and accretionary wedge will be made. The upper plate relatively becomes long and swells because the lower plate shortens. And, the vicinity of the surface comes into a expansion field. And, steep cliffs are formed and fall because the upper plate surges to the trough. This will explain the geographical features of (IC) shown by (9) and the cause. The expansion field in the vicinity of the surface causes the occurrence of the lateral-fault type(10). The structure of the cliff where the sudden falls easily happen reacts sensitively to peripheral earthquakes. In addition, it has the possibility that is an efficient tsunami generator. This harmonizes with the result of (11).

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SSS30-P01 Room:Poster Time:April 29 18:15-19:30

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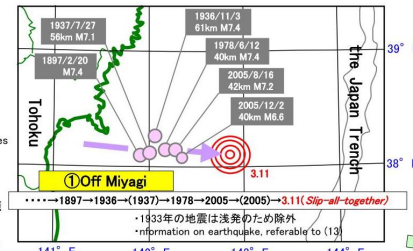


Fig.1 earthquakes climbed up (Off Miyagi)

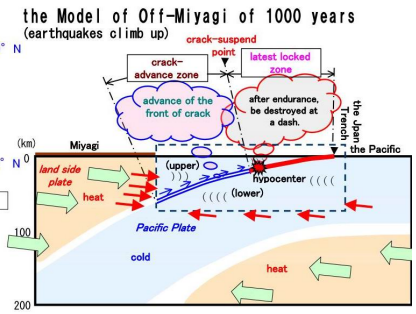
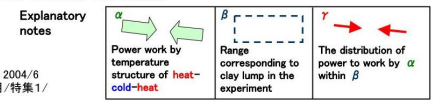


Fig.2 Model cross section intersecting squarely in the Trench and crossing over Miyagi



Japan Geoscience Union Meeting 2014
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SSS30-P02 Room:Poster Time:April 29 18:15-19:30

# Diversity of outer-rise earthquakes: As an example of the Off-Fukushima earthquake on 26 October 2013

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Earthquakes occurring in the outer-rise of a subducting plate are associated with the ruptures of the subduing plate itself, that is, intra-plate earthquakes. Such outer-rise earthquakes have been considered to excite much larger high-frequency than earthquakes in the plate boundary of the subducting and overriding plates, because the outer-rise earthquakes should break a lithospheric part where no peculiar weak zones exist.

A M7.1 earthquake occurred off the coast of Fukushima on 26 October 2013, which was probably associated with the 2011 great Tohoku-oki earthquake. We analyzed broadband seismic waveform data of this event recorded by F-net and other seismic networks. Compared with other large outer-rise earthquakes, the high-frequency component (>1Hz) of all the stations along the Pacific coast of eastern Japan is not abundant although slightly larger than plate-boundary earthquakes of low-angle thrust faulting. In contrast, there was the excitation of several impulsive wave packets of several seconds in period. Since only high-frequency waves are abundant at common stations for aftershocks of this outer-rise earthquake, the above features should not be originated by either propagation path or site effect.

Unlike the other outer-rise earthquakes, the rupture process of this earthquake was unique, relatively smooth with several strong patches on a rather homogeneous fault. The breakout of these patches should have been connected without any complex unbroken areas on the fault in the end, in order to explain the observed waveforms. Although we do not deny the break of a virgin (without any peculiar weak planes) lithosphere in this case, several distinguished large strong patches are likely to characterize the heterogeneity in the fault region of this outer-rise earthquake.

Among recent large outer-rise earthquakes along subduction zones near Japan, we have found another example similar to the Fukushima-oki earthquake: for the M7.0 outer-rise event on 14 March 2012 at the junction between Kuril Trench and Japan Trench, several impulsive waveforms with minor high-frequency waves. The state stress of this subducting Pacific plate should be very complex, which might lead to its non-standard rupture process. We shall need to investigate broadband frequency excitation patterns carefully for large outer-rise earthquakes.

In summary, there should be a wide variety of heterogeneities and/or stress state within a subducting lithosphere, which may be important to consider not only the source process of outer-rise earthquakes but also their tsunami generations.

Keywords: outer-rise earthquake, intra-plate earthquake, high frequency seismic waves, fault rupture, heterogeneity of oceanic lithosphere

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# High resolution seismic profiling in the northern Japan Trench axis area

NAKAMURA, Yasuyuki[1*] ; KODAIRA, Shuichi[1] ; MIURA, Seiichi[1] ; YAMASHITA, Mikiya[1] ; FUJIE, Gou[1] ; SHIMOMURA, Norio[1] ; IWAMARU, Hikaru[1]

[1]Japan Agency for Marine-Earth Science and Technology

Marine geological and geophysical surveys and analysis of their results have revealed that the ruptured area of the 2011 Tohoku earthquake extended up to the vicinity of the trench axis along the plate boundary fault. To investigate the geological structure, especially the faults and the deformation of the sediments, we have conducted reflection seismic surveys in the trench axis area of the Japan Trench off Miyagi and Iwate prefectures. Three seismic cruises have been carried out in 2011 and 2013 along 81 E-W (dip) lines and 17 N-S (strike) lines. We have used 320 or 380 inch$^3$ cluster air guns and a 1200 m long streamer cable to obtain high resolution seismic data. Surveyed area covers the trench axis area along the trench strike from seaward of the hypocenter of the Tohoku earthquake around 38 N at south, to ˜40 N at north. Seismic profiles around 38 N show that the trench axis is located on a graben with sediments which have been deformed by reverse faulting. Similar deformation structure is observed around 40 N, but the trench axis is located on a horst not a graben there. The thickness of the incoming sediments on the Pacific plate typically ranges ˜0.3 ? 0.5 s in two way time, however it is reduced down to $<$0.2 s around 39.5 N where the basement of the oceanic crust shows higher relief and trench inner wall is significantly steep. The thickness variation of the incoming sediments can be traced seaward and corresponded with along strike variation of the structure in the outer rise. These high resolutions seismic data served for the site selection of the JFAST drilling project by IODP and also contributes to the JTRACK proposal for future drilling in the Japan Trench following success of the JFAST.

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SSS30-P04 Room:Poster Time:April 29 18:15-19:30

# Seismic surveys in the ruptured area of the 2011 Tohoku earthquake

NAKAMURA, Yasuyuki[1*] ; KODAIRA, Shuichi[1] ; KAIHO, Yuka[1] ; NO, Tetsuo[1] ; FUJIE, Gou[1] ; SATO, Takeshi[1] ; YAMAMOTO, Yojiro[1] ; KASAYA, Takafumi[1] ; OBANA, Koichiro[1] ; MIURA, Seiichi[1] ; TAKAHASHI, Narumi[1]

[1]Japan Agency for Marine-Earth Science and Technology

We have conducted seismic surveys in the ruptured area of the 2011 Tohoku earthquake off Miyagi prefecture in 2011 and 2013 using JAMSTEC's R/V Kairei. Three multi-channel reflection seismic (MCS) surveys were conducted in 2011 with R/V Kairei's 7800 inch$^3$ tuned air gun array and ˜6 km long streamer cable. The MCS profiles along 14 E-W (dip) lines and two N-S (strike) lines were acquired during these surveys. Another seismic survey was carried out in 2013 around the JFAST drill site along one dip line and two strike lines. Time migrated sections demonstrated characteristic structure in the Japan Trench subduction zone; the Pacific plate deformed by normal faults (horst and graben structure), frontal prism with seismically transparent or chaotic feature, strong landward dipping reflections corresponding to the backstop interface, "deep sea terrace" in the upper landward trench slope covered with younger sediments mainly deformed with normal faults. Our survey area covers ˜150 km in the trench strike direction around the epicenter area, which is rather small compared with the entire rupture zone (400 ? 500 km in the strike direction) of the Tohoku earthquake, however the structure is considerably variable from south to north. We have selected 6 dip lines, including the JFAST dip line, to apply pre-stack depth migration (PSDM). The PSDM sections provide higher quality profiles and interval velocity models in depth domain which are suitable for understanding the structural framework of the Japan Trench subduction zone. In 2013 survey, we also used four ocean bottom seismographs (OBSs) in addition to the MCS system. The P to S converted wave was clearly observed in the horizontal component seismograms, and the Vp/Vs in the sediment layer around the JFAST drill site was estimated at $>$4.5.

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# Determination of Three Thermal Properties in Japan Trench Fast Drilling Project (JFAST)

LIN, Weiren[1*] ; TADAI, Osamu[2] ; FULTON, Patrick[3] ; HARRIS, Robert[4] ; TANIKAWA, Wataru[1] ; KINOSHITA, Masataka[1]

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The 2011 Mw 9.0 Tohoku-oki earthquake produced a maximum coseismic slip of >50 m near the Japan Trench. Japan Trench Fast Drilling Project (JFAST) as the Integrated Ocean Drilling Program (IODP) Expedition 343 and 343T drilled through the plate boundary fault ruptured during the Tohoku-oki earthquake at site C0019 approximately one year after the earthquake. The most highlighted objective is to detect residual positive temperature anomaly induced by the coseismic frictional heat. To interpret measured temperature anomaly and to calculate coseismic shear stress on the ruptured fault from the temperature anomaly, the full three thermal properties (thermal conductivity, thermal diffusivity and specific heat; only two thermal properties among the three are independent) are necessary. We measured the three thermal properties using four whole round core samples retrieved from borehole C0019E at 177, 697, 802 and 828 mbsf (meter below seafloor), respectively by a transient plane heat source method (also called Hot Disk method). Independently with Hot Disk method, thermal conductivity were also measured by a line heat source method for 45 half core samples using a TEKA half-space probe onboard the D/V Chikyu and by a divided bar technique using 38 crushed core samples (particle samples) in onshore laboratory. The thermal conductivities determined independently by the three methods were consistent each other. Also, the Hot Disk measurements revealed very little anisotropy in thermal conductivity and thermal diffusivity.

Acknowledgments: This research used core samples provided by IODP. We thank all Expedition 343 and 343T scientists and the drilling and logging operation staff on board the D/V Chikyu during expedition 343 and 343T.

Keywords: Thermal Prpperty, JFAST, Thermal conductivity, Thermal diffusivity, Specific heat

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# Modeling slow and seismic slips off Tohoku considering low to high speed friction behavior of the shallow plate boundary

SHIBAZAKI, Bunichiro[1*] ; IKARI, Matt[2] ; NODA, Hiroyuki[3]

[1]International Institute of Seismology and Earthquake Engineering, Building Research Institute, [2]Marum, Center for Marine Environmental Sciences, [3]Japan Agency for Marine-Earth Science and Technology

Ikari et al. (2013) examined low to high speed frictional properties of fault zone material from the shallow plate boundary in the Tohoku region obtained by the IODP Expedition 343 (JFAST). They found velocity-weakening frictional behavior at slip velocities slower than $10^{-6}$ m/s and velocity-strengthening at higher slip velocities. This frictional property is considered to be a mechanism that causes slow slip events and stress accumulation during the period between slow slip events. We investigate the effects of this frictional property on generation of slow slip events and megathrust events.

We use a rate- and state-dependent friction law with cut-off velocity to an evolution effect to represent this frictional behavior. Based on the experimental results (Ikari et al., 2013), we set the cut-off velocity at $10^{-6}$ m/s. We also consider dynamic weakening due to thermal pressurization at high slip velocity. We perform three-dimensional quasi-dynamic modeling of slip processes. Numerical results show the occurrence of slow slip events at intervals of several ten years at the shallow plate boundary. During the period between slow slip events, stress accumulation proceeds. When an earthquake nucleates at the deeper region, coseismic slip propagates into this region, which results in larger slip compared to the case where a simple velocity-strengthening friction law is considered.

Ito et al. (2012) detected slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. Shallow very low frequency earthquakes off Tohoku were detected by Matsuzawa et al. (2012). In addition, along the shallow plate boundary off Tokachi, sequential activity of very low frequency earthquakes occurs at intervals of several years (Asano et al., 2008). These observations suggest that the transitional friction behavior investigated by Ikari et al. (2013) occurs along the shallow plate boundary off Tohoku.

Keywords: off Tohoku, shallow plate boundary, low to high speed friction behavior, slow slip, seismic slip

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# Friction properties beneath the frontal wedge near the Japan Trench: deduction from topographic variation

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The 2011 Tohoku-oki earthquake (Mw 9.0) produced a fault rupture, extending to the Japan Trench. Deformation and frictional properties beneath the forearc are the keys to elucidate this unusual event.

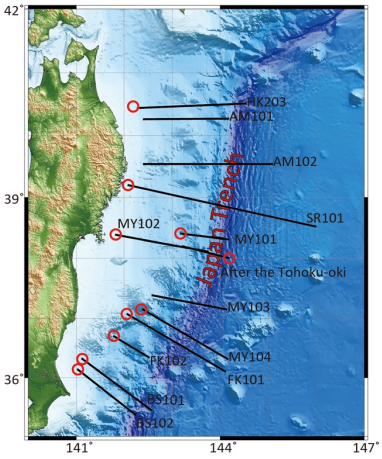
In this study, to obtain frictional properties ($\mu_b$'; the coefficient of effective basal friction), we extracted shape-related parameters from the cross sections of the frontal wedge which are obtained from surveys across the trench that span sporadically along the axis of the Japan Trench. The following two methods were adopted for this study; Critical Taper Theory (CT) and Critical State Theory (CS). Both of the theories are based $\mu_b$' From the Critical Taper Theory. Near latitude 36.1, the taper angles (slope angle + decollement dip angle) has been developed . A possible seamount subduction may differentiate this area. However, near the latitude 38.15 where the largest slip was reported with the 2011 earthquake, the taper angle has also been large without any seamounts. The calculated [or estimated] value of $\mu_b$' in this area is larger than that of the other area, suggesting that the larger strain energy was accumulated in comparison with the other wedges.

From the Critical State Theory, the value of $\omega$ (angle between the basal decollement and backstop interface) becomes smaller toward the north. The results of CS show the increase of the $\omega$ associate with the increase of the $\mu_b$', suggesting that strain energy is more stored toward the North.

Both results show that the $\mu_b$' has decreased after the earthquake. The change in $\mu_b$' may be due to the earthquake.

It is possible to know friction properties of before the earthquake and that of after the earthquake with bathymetry.

Keywords: Japan Trench, Critical Taper Theory



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SSS30-P08 Room:Poster Time:April 29 18:15-19:30

# Long-term crustal movement in the Rikuzentakata area, southern Sanriku coast, based on geomorphological/geological featu

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In the northeast Japan forearc, strain rate estimated based on by geological feature is different from that by geodetic feature. Thus, marine terrace suggests that the Sanriku coast has uplifted at the rate of 1 mm/yr since the late Quaternary. On the other hand, this area has subsided at the maximum rate of 10 mm/yr during the past 100 years based on geodetic data. This disaccord indicates the possibility that the giant mega-thrust earthquake causes the Sanriku coast to uplift. However, the 2011 Tohoku-Oki Earthquake (Mw9.0) was accompanied by subsidence along the Sanriku coast. This fact led us to reexamine long-term crustal movement.

We conducted geomorphological/geological analyses in the Sanriku coast, especially the southern part of the coast, where long-term crustal movement is unknown because of lack of widely distributed Pleistocene marine terrace. In this presentation, we will report preliminary results of consideration of long-term crustal movement in the Rikuzentakata area, southern part of Sanriku coast.

Keywords: marine terrace, southern Sanriku coast, long-term crustal movement, alluvial plain

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# Large-scale simulation of coseismic and postseismic crustal deformation using a high-fidelity finite element model

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Postseismic crustal deformation of a subduction zone earthquake is an essential factor in such studies as interseismic slip deficit rates and stress-field change of the focal area of inland earthquakes. The viscoelastic behavior of the asthenosphere largely affects postseismic crustal deformation. Several studies have used analytical models or three-dimensional (3D) finite element (FE) method to simulate postseismic crustal deformation, considering the viscoelasticity. Yet because of the large computational cost, simulations using a realistic model of crustal structure have not been carried out, despite that detailed crustal data are available. Based on the technique of high performance computing, we performed large-scale finite element simulations using 3D FE models of higher-fidelity (High-fidelity model: HFM) to available crustal data. We used the data of JTOPO30, which was constructed in a 900 m resolution by MIRC (JTOPO30, 2003), for modeling the ground surface and CAMP standard model (Hashimoto et al. 2004) for the interplate boundaries. By using this data, we constructed a one-kilo-meter-resolution HFM with the size of 1700 x 2600 x 400 km, which includes the whole of the Japanese Islands. The model has 30km thick crust and the underlying viscoelastic mantle wedge, where the Philippine Sea and the Pacific plates are subducting beneath the Eurasian and the North American plates. Because the target area was large, we also took into consideration the curvature of the earth. We expect a large degrees-of-freedom in our HFM. Therefore, to compute the time history of the crustal deformation with such a large-scale model, we used the K computer, the fastest supercomputer in Japan.

In the session, we will show the simulation of the 200-year time history of postseismic crustal deformation using the HFM. In addition, by comparing the results of various sizes of temporal and spatial discretization, we will demonstrate that our method can compute the solution with discretization fine enough for numerical convergence.

Keywords: postseismic crustal deformation, high-fidelity finite element model of crustal structure, large-scale simulation

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# Tsunami simulation in the Western Pacific Ocean and East China Sea from the hypothetical M9 Nankai earthquake models

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We computed tsunamis in the Western Pacific Ocean and East China Sea from the hypothetical models of the giant Nankai earthquake proposed by the Cabinet Office of Japanese government (2012). The maximum tsunami heights on the New Guinea coasts, Philippine Islands coasts, and Shanghai coasts in China are about 1.0-5.0 meters, 1.0-7.0 meters, and 0.5-2.0 meters, respectively. They are up to twice large as those computed from the 1707 Hoei earthquake (the largest earthquake along the Nankai trough in Japanese history). The simulation also shows that tsunami heights on the coasts in this area depend on the slip amounts on the Nankai fault.

Responding to the unexpected occurrence of the 2011 Tohoku earthquake, the Cabinet Office of Japanese government (2012) assumed 11 models of the giant Nanakai earthquake (Mw 9.1), computed tsunami heights along the Japanese coasts, and estimated the human and economic disasters. The tsunami heights exceed 10 m on the coasts of 13 prefectures, with a maximum height of 34.4 m.

Tsunamis from such a gigantic earthquake may impact the coasts in the Western Pacific Ocean and East China Sea. Harada and Satake (2012, AOGS; 2013, "Tsunami Events and Lessons Learned", Springer) performed numerical tsunami simulations in these oceans by using various fault models of the past Tokai and Nankai earthquakes.

In this study, we carried out the same simulations from the 11 fault models of the M9 Nankai earthquake. Tsunami propagations were computed by the finite-difference method for the non-linear long-wave equations with Corioli's force (Satake, 1995) in the area of 115-155 deg. E and 8 deg. S to 40 deg. N using the GEBCO 30-second bathymetry data. Initial tsunami heights computed by the Cabinet Office were used. A Manning's roughness coefficient of 0.025 $m^{-1/3}s$ was assumed for the friction and a computation time step of 1 s is used to satisfy the stability condition of the finite-difference method. We simulated tsunamis for 24 hours after the earthquakes.

We thank the Cabinet Office of Japanese government for providing the hypothetical models of the giant Nankai earthquake.

Keywords: sunami numerical simulation, Western Pacific Ocean, East China Sea, maximum tsunami heights, hypothetical M9 Nankai earthquake

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# Stress concentration in the C0002 borehole of the NanTroSEIZE Project, Nankai Trough

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Wellbore instability is a major challenge for the engineer evaluating borehole and formation conditions. Instability is especially important to understand in areas with high stress variations, significant structure anisotropy, or pre-existing fracture systems. Borehole (in)stability is influenced by rock strength, structural properties, and near-field principal stresses. During drilling, the borehole conditions also impact borehole integrity. Factors that we can measure in the borehole during with logging while drilling (LWD) to understand these conditions include Mud Weight, mud loss, ROP (Rate of Penetration), RPM (Rotation Per Minute), WOB (Weight on Bit), and TORQ (Power swivel torque value). By observation the resistivity images, we can utilities the significant features under the interactions of effective stresses and formation.

We conducted stress analysis for Site C0002F of the Nankai Trough transect based on riser and riserless drilling data during IODP Expedition 338. Rock strength and basic physical properties, including velocity, density and porosity are obtained from core samples. The borehole shape, determined from LWD resistivity images, indicates that most of drilling occurred in stable environments, however, in a few instances the bottom hole assembly became stuck. We used our stress profile model to evaluate the mud weight required to drill a stable borehole for the measured rock strength and physical properties. Based on our analysis, we constrained the stress magnitude and possible orientation during IODP Expedition 338 by the drilling parameters. The enlargement and collapse in the borehole indicated that mud weight plays the essential role in the drilling.

Keywords: NanTroSEIZE, LWD, Breakout, Drilling, Borehole Instability

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# Preliminary results of lithology examined during IODP Expedition 348 in the accretionary wedge of the Nankai Trough

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International Ocean Discovery Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) Expedition 348 took place from 13 September 2013 to 29 January 2014. This expedition was primarily designed to extend riser Hole C0002N to 3600 mbsf (in the event, C0002N sidetrack Hole C0002P was drilled to 3058.5 mbsf). We collected cuttings, core samples, mud gas, and logging data. Here we report the preliminary shipboard lithological results of IODP Expedition 348.

Four lithologic units were identified at Site C0002 based on geological and geochemical characteristics of core and cuttings samples: Unit II (475-512.5 mbsf in Hole C0002M), Unit III (875.5-975.5 mbsf in Hole C0002N), Unit IV (975.5-1665.5 mbsf in Hole C0002N), and Unit V (1665.5-2325.5 mbsf in Hole C0002N, and 1965.5-3058.5 mbsf in Hole C0002P).

Lithologic Unit II is dominated by fine-grained turbiditic deposits. Silty claystone is the main lithology, with subordinate fine-grained sandstone and sandy siltstone. Lithologic Unit III is dominated by silty claystone with trace amounts of very fine loose sand, containing common glauconite grains. Those units are interpreted to be the Kumano forearc basin sediments. Lithologic Unit IV is dominated by silty claystone, with sandstone as a minor lithology. Sandstone cuttings in this unit are generally very weakly consolidated, and occur as disaggregated loose sand. Lithologic Unit IV is divided into five subunits based on sand content and interpreted as the upper accretionary prism sediment. Lithologic Unit V is dominated by silty claystone. Fine-grained and moderately cemented sandstone was a minor component. In Hole C0002P, clay-size content in the silty claystone increases at the depth up to 2625.5 mbsf. The fine silty claystone becomes the dominant lithology from 2625.5 mbsf. This unit is possibly interpreted to be the trench or Shikoku Basin hemipelagic deposits.

Keywords: IODP Expedition 338, NanTroSEIZE, Site C0002

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# Physical properties of Nankai accretionary prism sediments at Site C0002, IODP Expedition 348

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Integrated Ocean Drilling Program (IODP) Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) Expedition 348 focused on deepening the existing riser hole at Site C0002 to ˜3000 meters below seafloor (mbsf) to access the deep interior of the Miocene inner accretionary prism. This unique tectonic environment, which has never before been sampled in situ by ocean drilling, was characterized through riser drilling, logging while drilling (LWD), mud gas monitoring and sampling, and cuttings and core analysis. Shipboard physical properties measurements including moisture and density (MAD), electrical conductivity, P-wave, natural gamma ray, and magnetic susceptibility measurements were performed mainly on cuttings samples from 870.5 to 3058.5 mbsf, but also on core samples from 2163 and 2204 mbsf.

MAD measurements were conducted on seawater-washed cuttings (”bulk cuttings”) in two size fractions of >4 mm and 1-4 mm from 870.5 to 3058.5 mbsf, and hand-picked intact cuttings from the >4 mm size fractions within 1222.5-3058.5 mbsf interval. The bulk cuttings show grain density of 2.68 g/cm3 and 2.72 g/cm3, bulk density of 1.9 g/cm3 to 2.2 g/cm3, and porosity of 50% to 32%. Compared to the values on bulk cuttings, the intact cuttings show almost the same grain density (2.66-2.70 g/cm3), but higher bulk density (2.05-2.41 g/cm3) and lower porosity (37-18%), respectively. The grain density agreement suggests that the measurements on both bulk cuttings and intact cuttings are of good quality, and the differences in porosity and density are real, but the values from the bulk cuttings are affected strongly by artifacts of the drilling process. Thus, the bulk density and porosity data on handpicked cuttings are better representative of formation properties. Combined with the MAD measurements on hand-picked intact cuttings and discrete core samples from previous expeditions, porosity generally decreases from ˜60% to ˜20% from the seafloor to 3000 mbsf at Site C0002.

Electrical conductivity and P-wave velocity on discrete samples, which were prepared from both cuttings and core samples in the depth interval of 1745.5-3058.5 mbsf, range 0.15-0.9 S/m and 1.7-4.5 km/s, respectively. The electrical resistivity (a reciprocal of conductivity) on discrete samples is generally higher than the LWD resistivity data but the overall depth trends are similar. On the other hand, the P-wave velocity on discrete samples is lower than the LWD P-wave velocity between 2200 mbsf and 2600 mbsf, while the P-wave velocity on discrete samples and LWD P-wave velocity are in a closer agreement below 2600 mbsf. The electrical conductivity and P-wave velocity on discrete samples corrected for in-situ pressure and temperature will be presented.

The shipboard physical properties measurements on cuttings are very limited but can be useful with careful treatment and observation.

Keywords: IODP Expedition 348, NanTroSEIZE, accretionary prism

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# Effects of frictional heating and comminution on coal maturation

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The detection of friction heating on faults is crucial to estimate frictional heat during earthquakes. Recently, vitrinite reflectance (Ro) has been used to detect friction heating along faults. However, the factors controlling increase in Ro on faults remain poorly understood. Moreover, the application of the commonly used kinetic model to the estimation of temperature rise during short-lived thermal events such as frictional heating on faults has not been convinced. Here, we conducted friction experiments on a mixture of 95 wt% clay-rich material from the host rock of the megasplay fault gouge and 5 wt% coal grains from the forearc basin in the Nankai subduction zone at slip rates of 0.15 mm/s-1.3 m/s under dry (room humidity) and wet (water-saturated) conditions. After the experiments, we examined microstructures, Ro and size of coal grains and then compared with those obtained from in and around the megasplay fault gouge. The results show that Ro does not increase by rapid heating alone; grain-size reduction due to comminution is required for increase in Ro. The combination of comminution and heating is the most effective for increase in Ro, possibly due to enhanced mechanochemical reaction associated with an increase in surface area of coal grains. The application of the results to the Nankai megasplay fault gouge is that increased Ro in the fault gouge results from frictional heating and comminution, while that in adjacent to the gouge are mainly derived from comminution. The Ro calculated from the chemical kinetic model is higher than that measured after the experiments. Ro is an useful tool to detect past frictional heating on faults, but the estimation of temperature rise from Ro is problematic; the new kinetics model considering the effects of frictional heating and comminution is necessary to estimate amount of frictional heat.

Keywords: vitrinite reflectance, frictional heating, comminution, Nankai Trough

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# Receiver function analysis using OBS data: modeling 3-D structure of the Philippine Sea plate off the Kii Peninsula

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Megathrust earthquakes have repeatedly occurred beneath the southwestern Japan, on the subducting Philippine Sea plate, in cycles of 100-150 years [Ando, 1975]. The rupture boundary of the latest two megathrust earthquakes, the 1944 Tonankai and 1946 Nankai earthquakes, is located at the south of the Kii Peninsula. Although some structural heterogeneity was proposed as factors of the rupture boundary [Mochizuki et al., 1998; Kodaira et al., 2006], the question of why rupture propagation stops there is still open in light of our little knowledge about 3-D geometry of the subducting Philippine Sea plate at offshore region.

In this study, we aim to construct 3-D structure model of the subducting Philippine Sea plate by receiver function (RF) analysis, using data of ocean-bottom seismometers (OBSs) deployed from 2003 to 2007 off the Kii Peninsula [Mochizuki et al., 2010; Akuhara et al., 2013]. These OBSs have three-component velocity sensors with natural frequency of 1 Hz, and their orientations were determined in this study from particle motion of regional P-wave. The difficulty of our RF analysis using OBS data is summarized by the following two factors. The first is that noise is dominant within a low-frequency band (1 <Hz), the most stable band for estimating RFs. The second is that the number of teleseismic events is limited because of short observation periods and low S/N ratio.

To overcome these problems, we calculated RFs with the aid of multi-taper correlation (MTC) method [Park and Levin, 2000]. The method is resistant to spectral leakage and able to estimate frequency-dependent uncertainties for RF, which is suitable for noisy OBS data and for high-frequency analysis. We binned resultant RFs by back azimuths, and computed time-domain uncertainties of the RFs from the frequency-dependent uncertainties estimated by the MTC method, using jackknife resampling within each back azimuth bin [Leahy and Collins, 2009]. This uncertainty estimation makes the following phase identification more reliable, even though the number of teleseismic events is limited.

Our preliminary results show some coherent peaks throughout all back azimuth bins, whose amplitude is larger than one-sigma uncertainties. Some of them have moveout, implying existence of dipping layers, and have arrival times roughly corresponding to the depth of the slab mantle. Although more detailed identification process for these peaks is largely left for our future work, these peaks might be converted phases from the slab mantle.

Keywords: ocean-bottom seismometer, receiver function, subduction zone

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# Three-dimensional velocity model for the Nankai Trough seismogenic zone based on structural studies

NAKANISHI, Ayako[1*] ; TAKAHASHI, Narumi[1] ; YAMAMOTO, Yojiro[1] ; TAKAHASHI, Tsutomu[1] ; OBANA, Koichiro[1] ; KODAIRA, Shuichi[1] ; KANEDA, Yoshiyuki[1]

[1]JAMSTEC

Coseismic rupture area of the great interplate earthquake concerned about its occurrence along the Nankai Trough presumed by government of Japan is now wider to the west, north and south than the former assumption. Although the new estimation is based on seafloor topography, source area of the past largest megathrust event, present seismic activity and so on, structural information has not always been enough reflected yet. In order to estimate precise coseismic rupture area of the Nankai megathrust earthquake, it is necessary to improve a physical model of the Nankai Trough seismogenic zone based on the geometry of the subducting plate and velocity structure model.

Japan Agency for Marine-Earth Science and Technology had conducted the large-scale high-resolution wide-angle and reflection seismic survey and long-term observation from off Kyushu to Tokai between 2008 and 2012. Layered velocity structure models are now obtained along grid two-dimensional seismic profiles from the Hyuga-nada to the Kii channel area. A three-dimensional seismic tomography using active and passive seismic data observed both land and ocean bottom stations had been also performed for the western Nankai Trough.

In this study, we constructed a three-dimensional velocity model of the Nankai Trough with the procedure as follows;

1) Sampling the velocity structural information along each seismic profile with interval of ˜1km in horizontal, and ˜100m in vertical directions

2) Preparing the geometry model of each interface included in layered models, e.g., basement, plate boundary, Moho, etc.

3) Setting minimum and maximum velocities of each layer based on the velocity models along two-dimensional seismic profiles

4) Interpolating sampled velocity information considering layered structure

(Landmark DecisionSpaceDesktop is used for constructing 3-D modeling)

Previously published layered models are also used to make up for insufficient structural information for the eastern Nankai Trough.

Reliability of the three-dimensional model was confirmed by comparing calculated travel-times with observed travel-times along each seismic profile. We will also try to evaluate the reliability of the model by comparing the hypocenter distribution using three-dimensional velocity model obtained in this study with that determined by three-dimensional seismic tomography using active and passive source data. We will plan to revise our 3D model with additional structural information and construct more precise and detailed model for the entire Nankai Trough area so that the model can be applied to more realistic numerical simulation.

This study is part of 'Research concerning Interaction Between the Tokai, Tonankai and Nankai Earthquakes (FY2008-2012)' funded by Ministry of Education, Culture, Sports, Science and Technology, Japan.

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# Seismic observations off Kii Peninsula

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In the Nankai Trough subduction zone, megathrust earthquakes of M 8 class occur repeatedly. There are three main seismogenic segments (Tokai, Tonankai and Nankai earthquake regions), and these segments have ruptured sometimes simultaneously and sometimes individually. To understand the control factor of the seismic linkage among these segments and Hyuga-nada segments, Japan Agency for Marine-Earth Science and Technology has been carried out a series of wide-angle active source surveys and local seismic observations from 2008 to 2012, as a part of Research concerning Interaction Between the Tokai, Tonankai and Nankai Earthquakes' funded by Ministry of Education, Culture, Sports, Science and Technology, Japan. In this study, we show the results of two local seismic observations off Kii peninsula, the one is in the Kii channel and the other is in the Kumano-nada. The boundary of the Tonankai and Nankai segments is located in this region (Baba and Cummins, 2005), and the existence of the high velocity plutonic rock in the landward plate just beneath Shionomisaki is considered as the control factor of historical rupture variation (Kodaira et al., 2006). Japan Meteorological Agency (JMA) catalogue also indicates the spatial relationship between the seismic activity and seismogenic segments; shallow microseismicity seems to be more active in the Nankai region than in Tonankai region.

The observation in the Kii channel has been performed in FY2010 and was composed of 155 short-tern (about 1.5 months) ocean bottom seismographs (OBSs) and 19 long-term (about 10 months) OBSs. First, we relocated the JMA catalogue earthquakes by using three-dimensional velocity model obtained by active source surveys and adding the first arrival time data at OBSs. As a result, the earthquakes near the trough axis were generally relocated 10-20 km shallower than JMA location. Then, we attempt to detect the earthquakes by using long-term OBS records and found the active intraslab seismicity, especially in the up-dip part of the subducted seamount (Kodaira et al., 2000). The observation in the Kumano-nada has been performed in FY2011 and was composed of 150 short-tern (about 2.5 months) OBSs and 14 long-term (about 8 months) OBSs. Now we perform the first arrival picking of these data with the seismograph data of Dense oceanfloor network system for earthquakes and Tsunamis (DONET), according to the JMA catalogue earthquake list. We will show the preliminary results of hypocenter distribution in the Kumano-nada at the presentation.

Keywords: Nankai Trough, ocean bottom seismographic observation, seismicity

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# Seismic observation and active-source seismic surveys on southern Ryukyu arc

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The Ryukyu arc is an island arc located on southeast of the Eurasian plate. The Philippine Sea plate is subducting northwestward at Ryukyu trench. Many large earthquakes (M7˜8) occurred on this arc, and some of them generated tsunamis. The 1771 Yaeyama earthquake (M7.4) caused a large tsunami of which a maximal height is 30m. For detailed examinations of fault rupture zones and mechanisms of large earthquakes in this arc, it is important to know the seismicity, lithospheric structures and plate geometry. In 2013, Japan Agency for Marine-Earth Science and Technology (JAMSTEC) launched a series of seismic observations and active-source seismic surveys at the Ryukyu arc as a part of research project funded by Ministry of Education, Culture, Sports, Science and Technology, Japan. In FY2013, we conducted refraction and reflection wide-angle seismic surveys and seismic observation on southern Ryukyu arc.

Active source seismic data were acquired on two survey lines. The one is a 480km-long line across the island arc from the south of Ryukyu trench to Okinawa trough. The other is a 100km-long line in Okinawa trough at northwest of Iriomote island. We conducted a refraction survey on the former survey line with 60 ocean bottom seismographs (OBS), and multichannel seismic reflection (MCS) surveys on both lines. Retrieved data shows clear wave trains propagating in the Philippine Sea plate and island arc. Normal faults in Okinawa trough were clearly observed in MCS data.

For seismic observation, we deployed 36 seismic stations including 30 OBSs and 6 onshore stations. All OBSs are equipped with short period geophones. Onshore stations are deployed at Miyako, Tarama, Ishigaki, Iriomote, Kuroshima and Hateruma islands. They are composed of broadband and/or 2Hz seismometers. We also retrieved seismic data from 60 OBSs that was deployed for the active source refraction survey. Observed seismic waves of small earthquakes show path dependences of waveforms that suggest spatial variations of random inhomogeneities and attenuation. For example, OBSs in Okinawa trough did not record clear S-wave for most of earthquakes. However, they observed clear S-wave and long-lasting coda waves for some shallow earthquakes occurred at north of Iriomote and Yonaguni islands. These waveforms suggest strong random inhomogeneities at the shallow part and high apparent attenuation (due to scattering and intrinsic attenuation) at deeper part underneath the Okinawa trough. In this presentation, we outline our observations and notable features of obtained data.

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# A plate boundary earthquake model with consideration on submarine active faults

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Active faults observed on seafloor along Japan Trench are resultants of repeated large earthquakes. We discuss on the relation between large earthquakes and their source faults based on a detailed active fault map along Japan Trench. Judging from the location and continuation of active faults in the earthquake source area, we consider that one of the extensive thrust faults which extends from off-Sanriku to off-Ibaraki for about 500km, is directly related to the source fault of the 2011 off the Pacific coast of Tohoku Earthquake.

The 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0) generated large tsunami with massive pulsating pattern of waves (Maeda et al. 2011). A leading hypothesis believed among many seismologists is that rupture of two extensive asperity patches surrounded by stable sliding area on the plate boundary generated the earthquake. One of the asperity patches in depth caused the strong motion and the other near the surface caused fault rupture along the axis of Japan Trench and generated gigantic tsunami. Large displacement ˜50m eastward and ˜7 to ˜10m upward was estimated from comparison of data obtained before and after the earthquake in 2004 and 2011 by multi-narrow beam bathymetric surveys across the trench (Fujiwara et al. 2011). Satake et al. (2011) explained the large tsunami height by simultaneous faulting on two different fault planes that fit with the above-mentioned asperities. Since most of the workers hypothesized without any doubt believed that the earthquake was caused by the fault ruptured up to the trench axis, existence of submarine active fault is rather overlooked so far. However, we consider the large displacement is due to landslide and do not find any extensive fault scarp on the trench axis.

We simulated pattern of seafloor deformation associated with the earthquake using a simple dislocation model for a single fault plane with uniform slip that dips 14 degree in depth and 33.6 degree beneath the tectonic bulge related to the extensive active fault. A result shows that an area of large uplift agrees more or less with the location of tectonic bulge with width of about 20km.

The record of tsunami first wave obtained by the GPS wave gage set on about 200m deep seafloor off Kamaishi on southern Sanriku Coast (Port and Airport Research Institute, 2011). The record suggests that after gradual sea-level rise of 2m during 6 minutes, acute sea-level rise of 4m took place within 4 minutes, and then sea-level abruptly dropped by 4m within 2 minutes. The length of pulsating tsunami wave is estimated about 17km from tsunami propagation velocity at 200m deep sea and total duration of pulsating pattern of tsunami, i.e. 7 minutes. This tsunami wave pattern resembles the pattern of seafloor deformation we calculated above.

We also simulate crustal movement and tsunami height along the Tohoku coast by an earthquake source fault model based the location of the submarine fault with fault-slip deduced from tectonic scarp height that is regarded as cumulative fault-slip. Our simulation explains the observed co-seismic subsidence and large tsunami height along the coast better than many other simulations based on various inversion models.

Based on these observations, we propose active fault model for plate boundary earthquake that large earthquakes are characteristically caused from submarine active faults in the island arc crust that overlap each other above the plate boundary in the narrow sense.

Keywords: plate boundary earthquake, asperity model, active fault model

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# The last 6000 years record of tsunami events in the Kaniga-ike pond along the Nankai Trough

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In order to reveal pre-historic record of Nankai Trough earthquakes, we collected 46 vibrocore samples from the Kaniga-ike pond. Stratigraphical study and radiocarbon dating of these samples revealed that sediment of Kaniga-ike pond recorded 17 tsunami events during the last 6000 years. These 17 events repeated almost constant intervals through 300 years. A 2000 years ago event formed remarkable thick tsunami sequence, and also shows an exclusive event in the past 6000 years.

Keywords: Nankai Trough, Tsunami sediment

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# Estimate of the contact state of microcrack from the elastic wave velocity measurement

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Birch (1960) studied about the relationship between the confining pressure and the elastic wave velocity. It was indicated that the elastic wave velocity increases with the increasing confining pressure because the microcrack is closed at high pressure. The velocity includes the effect of microcracks at low pressure. We must the elastic wave velocity without the effect of microcrack to know the elastic constants of a rock. To do that, it is necessary to know the process of closing microcracks and the contact state of microcrack.

The power-law relation between the elastic wave velocity and confining pressure is expressed with pressure exponent of $\mu$ (Kobayashi and Kozumi, 1976). They assume that the microcrack has single contact in this model. It is necessary to take account in multiple contacts because the microcracks of a rock have multiple contacts. We applied the single contact model to multiple contacts model with the previous study (Archard, 1953). The microcrack has the point contact, ball contact and plane contact when $\mu$ is 2/3, 3/5 and 1/2 respectively. The microcrack contacts plastically if $\mu$ is $<$1/2. We measured the elastic velocity of rocks with gas medium high pressure apparatus to discuss the effect of the confining pressure.

We measure the velocity with the pulse transmission technique. We set the assembly, composed of a sample between two metal jig pasted piezoelectric transducers, in the pressure vessel. The sample height is about 15-40 mm and diameter is 20 mm. The frequency of transmission wave is 2 MHz. We recorded it $10^{-9}$s rate. We measured Vp and Vs of the gabbro and granite during pressurization and depressurization to a maximum confining pressure of 200 MPa. The velocity increased drastically with the increase in the confining pressure up to 100 MPa. When confining pressure is lower than about 100 MPa, $\mu$ of the gabbro and granite is about 2/3, indicating that the contact state of microcrack is point contact. However, under pressure higher than 100 MPa, $\mu$ becomes under 1/2, indicating that all microcracks are closed plastically in the experiment with gas medium high pressure apparatus. So the velocity at pressure higher than 100 MPa does not include the effect of microcracks. Furthermore, we estimated $\mu$ of several rocks from previous studies (Birch, 1960, Zimmer et al., 2002). Although $\mu$ depends on rock type at low pressure, it converges to values smaller than 1/2 at high pressure. This indicates that all microcracks are completely closed at high pressure and this result conforms to our experiment. If fluid exists in rocks, the value of $\mu$ is less than 1/2 even at low pressure. Therefore the microcrack with fluid acts as having plastic contact. We revealed the process of closing microcracks with the increasing confining pressure from the elastic wave velocity measurement.

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# Frictional properties of the shallow Nankai Trough accretionary sediments

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We have conducted friction experiments on sandstone, tuff, silty mudstone and clayey mudstone samples cored from the shallow Nankai Trough accretionary prism, using a triaxial apparatus recently installed at Chiba University, at a confining pressure of 37 MPa, a pore pressure of 29 MPa, a temperature of 42 degrees C, and an axial displacement rate of 1 micrometer/s. These pressure, pore pressure and temperature correspond to those supposed at the depth of 1 km below seafloor at IODP Site C0002. The results reveal that frictional properties of these samples change systematically according to the content of clay minerals, in particular of smectite. The content of clay minerals is 6.0 wt% in the sandstone sample, 17.2 wt% in the tuff sample, 34.1 wt% in the silty mudstone sample, and 42.0 wt% in the clayey mudstone sample. Except for the sandstone sample in which smectite is absent, smectite is the most abundant clay mineral in all the other samples, occupying 68-76 wt% of total clay minerals.

Steady-state friction coefficient decreases with increasing content of clay minerals, from 0.83 of the sandstone sample, through 0.74 of the tuff sample and 0.34 of the silty mudstone sample, to 0.27 of the clayey mudstone sample. Slip-dependent frictional behavior also changes according to the content of clay minerals; the sandstone sample exhibits slip hardening, while the other samples exhibit slip softening, which becomes more pronounced with increasing amount of clay minerals.

We will also report the velocity dependence of steady-state frictional strength at this condition as well as how frictional properties of these samples change at deeper conditions up to 5 km below seafloor.

Keywords: Nankai Trough, accretionary sediments, frictional properties

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# Effects of shear displacement and fault zone structure on the frictional be havior of montmorillonite-quartz gouge

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Recent observation of the low frequency earthquakes in the shallow part of the Nankai subduction zone has demonstrated that faulting there is slow yet seismic; suggesting that frictional velocity dependence along the fault would be negative. However, in a widely accepted model, sediments there is expected to exhibit velocity-strengthening frictional behavior. We have reported that the fault material along the megasplay fault in the Nankai Trough exhibited both velocity-strengthening and velocity-weakening frictional behavior [Tsutsumi et al., 2011]. Fault zone structures may be important to understand why the samples exhibited different velocity dependence. In this study, we have conducted frictional experiments on artificial gouges composed of montmorillonite and quartz mixtures, in order to understand the relationship between the fault zone structures and velocity dependent frictional behavior.

We examined frictional behavior and fault zone structure of the artificial gouge samples composed of montmorillonite/quartz mixtures. All of the experiments were conducted under water-saturated conditions at 1 to 5MPa of normal stress, with shear displacement of 30 mm to 14 m, using a rotary-shear friction testing machine. Velocity step tests were conducted in a range of velocities from 0.003mm/s to 30 mm/s, in order to examine velocity dependent frictional behavior.

Results of these experiments reveal influences of normal stress and displacements on frictional behavior. Velocity weakening behavior was observed for the mixtures of montmorillonite/quartz = 20/80 and 40/60 wt%, respectively, at large displacement. In velocity-weakening samples, montmorillonite becomes to be finer-grained and is well mixed with quartz in the gouge layer after long shear displacements and at high normal stresses. These observation demonstrates that frictional behavior of the montmorillonite/quartz gouge changes with the development of the deformation structures. It is suggested that fault zone structure is one of the important factors of describing the frictional behavior along faults at the Nankai Trough.

Keywords: montmorillonite, frictional experiment, fault zone structure

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# Friction constitutive properties of shallow subduction zone material as estimated from rotary shear friction experiments

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In order to understand the dependence of constitutive parameters, $a$, $b$, and $D$c, on slip velocity, $V$, we conducted experiments by using a rotary shear high velocity friction apparatus. Samples used in this work were collected from the Nankai accretionary prism, offshore from Kii Peninsula, Japan, at Site C0004 during Integrated Ocean Drilling Program (IODP) Expedition 316 [Expedition 316 Scientists, 2009; Tsutsumi *et al*., 2011], and from the Costa Rica subduction zone, Cocos Ridge, at Site U1381 during IODP Expedition 334 [Expedition 334 Scientists, 2012 ]. All of the samples from the Nankai accretionary prism are clayey silt, whereas those from Costa Rica can be divided into 2 groups with respect to their composition: one is clayey silt (hereinafter referred to as ”Costa Rica Unit I”), the other is silicic to calcareous ooze (”Costa Rica Unit II”). All experiments were carried out at 5 MPa normal stress and 0.0028-2.8 mm/sec slip velocity under wet condition (0.5 g samples with 0.5-0.9 ml distilled water). Moreover, we created a simulation program, which can estimate the values of constitutive parameters and system stiffness, $k$, with Levenberg-Marquardt method, supposing the spring-block model.

The results are summarized as the following: (1) $a$, $b$ and/or $D$c increase with slip velocity; (2) the values are the highest at $V$ = 0.028-0.28 mm/sec; (3) the values are the lowest at $V$ = 0.028-0.28 mm/sec. The reason is not clarified yet, but it is remarkable that, despite the composition, the result of the clayey megasplay fault material from the Nankai accretionary prism resembles the result of Costa Rica Unit II. This implies that, as expected, constitutive parameters depend on not only material but also other conditions. Another remarkable point to be noted is that the values of system stiffness of Costa Rica Unit I decrease by a factor of 10 when compared with the measured apparatus stiffness value. This implies that the mechanical property of the material of Costa Rica Unit I may be more flow-dominated than others. This implies that the mechanical property of the material of Costa Rica Unit I may be more flow-dominated than others. Considering that the samples of the Nankai accretionary prism and Costa Rica contain 20-30 wt%, 60-70 wt% clay, respectively, it is possible that total clay content reflects the gouge behaviour.

Keywords: friction, subduction zone, rate- and state- friction constitutive law, Nankai Trough, Costa Rica

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# Physical properties of sediments in reference sites and Frontal prism off Costa Rica: IODP Expedition 344

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Comparing physical properties in reference and frontal prism sites is key to understand dewatering and lithification processes in subduction zone. Furthermore, it can be evidence for identifying the location of decollement and the underthrusting materials into seismogenic depth. In this study, we examined the physical properties of sediments in reference sites and frontal prism site both from on-board data and from laboratory experiments for velocity and porosity measurements with variation of effective pressure. Finally, we converted on-board porosity to fluid pressure using laboratory experimental data for reference sites and frontal prism site.

We focused on reference sites, U1381 and U1414, and frontal prism site, U1412 in the Integrate Ocean Drilling Program Expedition 344 off Costarica. Laboratory experiments for velocity and porosity measurements were conducted with variation of effective pressure. We kept 1MPa of pore pressure and changed confining pressure stepwise to control effective pressure. We calculated in-situ effective pressure using sample depth, bulk density and assumption of hydrostatic pressure of pore pressure. We obtained velocity and porosity data by 5 steps up to the in-situ effective pressure and 5 steps more up to 10 times of the in-situ effective pressure. Porosity change during experiments was calculated using volume change in pore water volume. We assumed on-board porosity under atmospheric pressure condition. 4 samples from sites U1381 and U1414 were measured so far.

Porosity ranges from about 77% to about 53% during experiments. P-wave velocity ranges from about 1.4 to 1.6 km/s. Velocity-porosity relationships from on-board data and from laboratory experiments are comparable nicely and also represents a good agreement with global empirical model. Because both laboratory data and on-board data shows a similar trend in the velocity-porosity relationship except for data from U1381 Unit II, the physical properties of sediment except for sediments from U1381 Unit II is similar in velocity-porosity-effective pressure relationships. Therefore, the porosity-effective pressure can be applied on most of sediments, implying that we can convert the porosity to effective pressure using laboratory results. We estimated fluid pressure from on-board porosity with depth using porosity-effective pressure relationship obtained from laboratory experiments.

For U1381 Unit I, hydrostatic fluid pressure was estimated although the error was large. Because U1381 is located in reference site, the hydrostatic pressure is expected in U1381. On the other hand, for U1414, lower fluid pressure than hydrostatic pressure was estimated in ˜10m intervals in the upper part of Unit II. Hydrostatic pressure was estimated in other interval in U1414. Therefore, fluid pressure was recovered to hydrostatic pressure below the over-consolidated layer. In the over-consolidated layer, porosity decreases quickly with constant grain density, which is comparable with the over-consolidation state. Below the over-consolidated layer, porosity increases with decrease of grain density, although the hydrostatic pressure is estimated. In the interval with increase of porosity, because sediments possibly have different physical property, further laboratory experiments on the sediments are needed. Finally, for U1412, over-consolidated sediments were estimated, which may be due to quick dehydration by frontal accretion.

Keywords: IODP, subduction zone, physical property of sediment, elastic wave velocity, pore pressure

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# A structural traverse across the Shimanto belt in western Shikoku, Japan

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The Cretaceous and Tertiary Shimanto accretionary complex is largely characterized by imbricated thrust slices of trench-fill and ocean-floor sediments, and is thought as an ancient analog of the Nankai accretionary prism. Recent studies on a thermal structure and fault rock analysis for the Shimanto accretionary complex in the central and eastern Shikoku revealed that it has suffered earthquake faulting along the out-of-sequence thrusts associated with tectonic uplift. However, special distributions of thermal and tectonic structures are remaining unclear since those in the western part of Shikoku are poorly understood. In the presentation, we demonstrate the distributions and details of deformed rocks (e.g. melange and brittle faults), geological structure, and vitrinite reflectance across the Shimanto belt in western Shikoku.

Keywords: Shimanto accretionary complex, Out of sequence thrust, Melange, Vitrinite reflectance, Fault rocks

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# Stress estimation of Kure OSTs, Shimanto accretionary complex

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Stress must be concentrated at front of seismogenic fault during rupture propagation. The level of this stress concentration depends on rupture propagation velocity, fault length, thickness of process zone and strength of host rock. However, few quantitative analysis was reported in natural fault due to difficulty of stress estimation. The calcite-twin piezometer, enables stress estimation from elastic rebounded rock, was proposed based on discrete element method simulation and tri-axial rock experiments (Sakaguchi et al., 2011).

The Shimanto accretionary complex is ancient subduction zone and some fossil seismogenic faults were reported.

Among them, pseudotachylyte bearing Kure OSTs cuts Cretaceous Shimotsui, Nonokawa Formation and Kure Melange. This Kure OSTs is composed of echelon formed small faults with thin damaged zone, and burial depth of the host rock is estimated as below 3 km in depth. We obtained three rock samples, applicable for calcite-twin piezometer. The highest value of estimated stress was approximately 420MPa. This is much higher value than the other seismogenic fault in Shimanto accretionary. The Okitsu Fault, formed deeper depth of approximately 4 km, have suffered lower stress of 350 MPa at fault center (Sakaguchi et al., 2011). This indicates that much higher stress was concentrated at shallow Kure OST than deep Okitsu Fault. We propose two models to make high stress at shallow portion. Long crack length from deep to surface causes high stress concentration at shallow portion. Other model causes high stress due to narrower fault zone than the Okitsu Fault. Stress may tend to concentrate at narrower process zone of Kure OSTs than wide process zone of Okitsu Fault.

Keywords: subduction zone, ancient seismogenic, calcite, twin density

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# Paleostress analysis of a subduction zone megasplay fault - An example from the Nobeoka Thrust, Japan

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The megasplay faults in subduction zones, branching from plate boundary thrusts, are thought to have a potential to generate earthquakes and accompanying tsunamis. It is therefore important to understand the fault mechanism of megasplay faults for earthquakes and tsunamis occuring in subduction zones. Paleo-splay faults exposed on land often preserve clear deformation features of the seismogenic zone and provide information on the fault mechanisms at depth. One of the important informations that can be obtained from exhumed faults is paleo-stress field. Here we investigated the Nobeoka Thrust, a fossilized megasplay fault in the Shimanto Belt in Kyushu. The hanging wall is Eocene Kitagawa Group, composed of phyllitic shales. The footwall is Eocene to early Oligocene Hyuga Group, composed of foliated cataclasite originated from sandstone-shale melanges. The thrust has been active during the period of 48-40 Ma [Hara and Kimura, 2008]. The hanging- and the footwall have experienced maximum burial temperatures of approximately 320$^o$C and 250$^o$C, respectively [Kondo et al., 2005]. The existence of klippes apart from the Nobeoka Thrust shows that the Nobeoka Thrust is nearly horizontal in regional scale [Murata, 1991, 1995]. Kondo et al. (2005) described two orientations of slickensides from the outcrop, suggesting the existence of flexural gentle fold in kilometer scale. In addition to the previous studies focusing on outcrops, scientific drilling has performed in 2011 penetrated through the Nobeoka Thrust, and core samples and geophysical logging data are obtained. The cores provide important information for investigating geological features under the ground and have an advantage without surface weathering.

In this study, we analyzed paleo-stress from slip vectors on small faults observed in the cores. Small faults are expected to be less-reactivated. The number of small faults is much larger than that of large faults, accordingly, high statistical reliability is expected. Multiple inverse method (MIM; Yamaji, 2000; Otsubo and Yamaji, 2006) was applied to the small faults. K-means clustering (Otsubo et al. , 2006) was applied to stress tensors detected by the MIM for estimating optimal solutions. Preliminary results indicate the presence of solutions with three maximum horizontal stress axes: N85.24$^o$E, N30.07$^o$W and N65.47$^o$E. We examined the formation process of the Nobeoka Thrust based on the results and slickensides on the outcrop. Our results would provide potential insights to the fault evolution of a megasplay fault in subduction zone.

Keywords: Nobeoka Thrust Drilling Project, Subduction zone, Shimanto Belt, paleo-stress, Multiple inverse method

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# 3D micro structural observation of pseudotachylyte

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Pseudotachylyte, molten fault rock due to dynamic frictional heating, is a strong evidence of seismic fault slip [Sibson 1975]. Recent research reveals pseudotachylytes can be related with dynamic weakening mechanism such as melt lubrication [DiToro et al., 2006]. However, observations of internal structure of pseudotachylyte have been confined to 2D observations with optical-electron microscope. Here we performed X-ray 3D structural observation of natural pseudotachylyte developed close to the Nobeoka thrust which is a major Out of sequence thrust in fossil accretionary prism (Shimanto-belt).

The Nobeoka thrust located in Kyusyu Island, south west Japan, bounding northern and southern Shimanto belt of Cretaceous-Tertiary accretionary complex. The thrust is considered to have been active during 40-48Ma at seismogenic depth of ˜11kmbsf, experienced maximum temperature of which is 320 Cin the hanging wall and 250 C in the footwall. Thus, the Nobeoka thrust is examined that it was major OST in seismogenic zone of accretionary prism (Kondo et al., 2005; Hara and Kimura, 2008; Raimbourg et al., 2009). The pseudotachylyte bearing fault develops in the hanging wall of the Nobeoka thrust with 1 mm of width. Okamoto et al. (2007) reported that carbonate-matrix implosion breccia fill tensile cracks and inner periphery of the fault, interposing pseudotachylyte, based on optical microscopic observation. Though pseudotachylyte cut the implosion breccia, the fault jog consists only of the carbonate-matrix breccia. It may show the fault experienced dynamic pore water pressurizing accompanied by pseudotachylyte generation at its first frictional slip. Therefore, the fault is appropriate to structural investigation of dynamic fault weakening mechanism.

We performed structural observation of this pseudotachylyte with scanning electron-microscope and 3D X-ray microscope. In the electron microscopic observation, we found that fragments of host rock unevenly distributed in the pseudotachylyte. The number of fragments is larger at lower part (footwall-side) than within the center of the pseudotachylyte. We also found open cracks along the fragments arrangement. It is considered to be cooling crack generated due to rapid cooling of molten rock. The 3D x-ray microscopic observation was performed with cylinder sample of 8 mm diameter. The spatial resolution of the x-ray microscope is 1 micro meter, and detailed 3D fault structure was imaged. We focused four planes, A: lower plane of lower fault filling vein, A': lower plane of pseudotachylyte, B: upper plane of upper vein, B': upper plane of pseudotachylyte. The surfaces configurations were extracted and its roughness was evaluated as calculated average roughness, Ra (theta), in each direction. We found that Ra has minimum value in the same direction in each plane, and the lineation strongly develops at the lower planes (A, A').

From the above results, we discussed the faulting process as:

1) Start faulting. strain concentrated in the footwall side and pore pressure was raised at the part.
2) Hydraulic fracturing by high pore pressure, tensile cracks formation and fluid migration.
3) Strength (friction) recovery by draining and formation of pseudotachylyte.

Keywords: pseudotachylyte, 3D micro structure, surface roughness