

## Accelerated nucleation of the 2014 Iquique, Chile Mw 8.2 Earthquake

\*Aitaro Kato<sup>1</sup>, Jun'ichi Fukuda<sup>2</sup>, Takao Kumazawa<sup>3</sup>, Shigeki Nakagawa<sup>2</sup>

1.Graduate School of Environmental Studies, Nagoya University, 2.Earthquake Research Institute, the University of Tokyo, 3.The Institute of Statistical Mathematics

The earthquake nucleation process has been vigorously investigated based on geophysical observations, laboratory experiments, and theoretical studies; however, a general consensus has yet to be achieved. Here, we detected a nucleation phase for the 2014 Iquique, Chile Mw 8.2 megathrust earthquake located within the current North Chile seismic gap, by analyzing a long-term earthquake catalog constructed from a cross-correlation detector using continuous seismic data. Accelerations in seismicity, the amount of aseismic slip, and the background seismicity, accompanied by an increasing frequency of earthquake migrations, started around 270 days before the mainshock at locations up-dip of the largest coseismic slip patch. These signals indicate that repetitive sequences of fast and slow slip took place on the plate interface at a transition zone between fully locked and creeping portions. These different sliding modes strongly interacted with each other and promoted accelerated unlocking of the plate interface during the nucleation phase.

## Past slip to the trench recorded in Central America and its global significance

\*Paola Vannucchi<sup>1</sup>, Elena Spagnuolo<sup>2</sup>, Kohtaro Ujiie<sup>3</sup>, Akito Tsutsumi<sup>4</sup>, Stefano Aretusini<sup>2</sup>, Yuka Namiki<sup>4</sup>, Giulio di Toro<sup>5</sup>

1.Royal Holloway University of London, 2.INGV, 3.Tsukuba University, 4.Kyoto University, 5.Manchester University

The 2011 Tohoku Earthquake revealed that co-seismic displacement along the plate boundary megathrust can propagate to the sea floor. Co-seismic slip to the trench amplifies hazards at subduction zones and its potential occurrence should be investigated globally also addressing past events. A geologic record of past slip to the trench is preserved offshore SE Costa Rica, where an old, < 1.9 Ma, frontal megathrust detached along biogenic oozes. Low- to high-friction experiments (slip-rates of  $10 \mu\text{m s}^{-1}$  to  $1 \text{ m s}^{-1}$  and normal stresses up to 5 MPa) were performed on sediments representing the megathrust's hangingwall, the biogenic oozes, and its footwall, silty clays, to investigate the velocity dependence of friction and the micromechanical foundation of strain localization within the frontal megathrust. Both silty clays and biogenic oozes are velocity-weakening at low  $\sim 1 \text{ cm/s}$  and high velocity  $\sim 1 \text{ m/s}$ , with the silty clays much weaker than the oozes at low velocity, and similarly weak at high velocity. So, while the silty clays form weak layers at both low and high velocities, especially when in the presence of water, the biogenic oozes only become as weak as silty clays at higher velocity. The implication is that the geological structures found in the forearc to offshore SE Costa Rica were formed by high velocity slip-to-the-trench events, because during aseismic creep, deformation should have always localized in the silty-clays, and not in the oozes as seen in the drilled hole.

Keywords: Megathrust, Costa Rica, IODP

## Sediment consolidation affected by uplift, mass movement, and fluid-interaction in the Costa Rica forearc wedge

\*Mari Hamahashi<sup>1</sup>, Elizabeth Screaton<sup>2</sup>, Wataru Tanikawa<sup>3</sup>, Yoshitaka Hashimoto<sup>4</sup>, Kylara Martin<sup>5</sup>, Saneatsu Saito<sup>6</sup>, Gaku Kimura<sup>1</sup>

1.Department of Earth and Planetary Science, The University of Tokyo, 2.Department of Geological Sciences, University of Florida, 3.Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, 4.Department of Applied Science, Kochi University, 5.Naval Research Laboratory, 6.Research and Development Center for Ocean Drilling Science, Japan Agency for Marine-Earth Science and Technology

At the Middle America Trench offshore Costa Rica, Osa Peninsula, the aseismic Cocos Ridge subduct beneath the Caribbean Plate creating active seismicity. To investigate the geologic processes occurring at the Costa Rica margin, we examined the consolidation process and physical property transitions of sediments across the major unconformity developed in the wedge slope using the sediment cores of the middle slope Site 1380 recovered during Integrated Ocean Drilling Program (IODP) Expedition 344. The major unknowns of this margin which this study aim to investigate are the geologic events that created the major unconformity imaged from seismic surveys, and the lithology and consolidation state of the upper plate material beneath the unconformity. On the basis of sediment microstructural observation, physical property measurement, and geochemical composition analyses, we investigated the effects of burial diagenesis and fluid-sediment interaction towards the porosity-depth transition to extract the initial burial compaction curve and to access the maximum burial conditions beneath the unconformity.

The upper plate material below the unconformity developed in the wedge slope was revealed to be lithified sediments that are characterized by consolidation due primarily to burial compaction and mineral precipitation. Na-type zeolite: analcime exist only below the unconformity indicating precipitation during burial diagenesis whereas Ca-type zeolite: heulandite and laumontite are precipitated more broadly due to interaction with high temperature fluid (~100°C) that has likely localized in the vicinity of the unconformity. The experienced maximum temperature of the sediments below the unconformity based on the formation of analcime during burial diagenesis is estimated to range between 86°±5°C ~ 122°±2°C, which is above the current geothermal gradient. The change in zeolite assemblage indicate that the events of uplift from deeper depth and sediment removal have occurred across the unconformity. Beach deposits consisting of shell fragments and damage zones of normal fault regime were identified from the drilled cores above the unconformity, indicating that the sediments have uplifted to near sea surface involving faulting. By quantifying the weight percent of zeolites (laumontite, heulandite) formed by fluid interaction, the porosity decrease due to zeolite precipitation were estimated to be ~4-5% and the porosity-depth curve eliminating the effect of the fluid-interaction were recalculated. The depth along the approximate curve that corresponds to the porosity of the sediments directly below the unconformity corresponds to the maximum burial depth range: 1000±400 mbsf. After initial burial, the sediments have uplifted by minimum ~500 m to maximum 1500±400 m to near sea level, followed by subsidence of ~1050 m, associated with surface erosion of maximum 1000±400 m and/or normal fault displacement of maximum 450±400 m to reach the current depth range. If assuming a dip angle of the slope and fault plane to be ~10-30°, this thickness of maximum mass movement would correspond to the distance of 4600±3400 m (surface erosion) and 2500±2400 m (normal faulting) parallel to the slope and fault respectively. These events occurred during 2.20±0.25 Ma ~ 1.71±0.24 Ma inferred from nannofossil age, which is likely to be consistent with the onset of Cocos Ridge/seamount subduction.

Uplift events are inferred to have occurred during seamount subduction, initiating mass movement, normal faulting, and subsidence in the Costa Rica margin. These processes resulted in significant exhumation of deeper sediments through surface erosion and/or extension and promoted active fluid interaction in high temperature which precipitated zeolites, contributing to the high consolidation in the forearc wedge. Sediment consolidation in the forearc wedge may consequently lift the updip limit of seismogenic zone to a shallower depth range.

Keywords: subduction zone, Middle America Trench offshore Costa Rica, physical property

## Heat flow at the Cascadia, USA, and the Hikurangi, New Zealand, margins

\*Robert N Harris<sup>1</sup>, Marie Salmi<sup>2</sup>, Anson Antriasian<sup>1</sup>, Anne Trehu<sup>1</sup>, H. Paul Johnson<sup>2</sup>

1.Oregon State University, 2.University of Washington

At subduction zones, temperature influences both aseismic and seismic deformation along the subduction thrust. To better understand these processes we collected a series of heat flow measurements seaward of and continuing across the deformation front at the Cascadia subduction zone, USA, and the Hikurangi margin, New Zealand. All measurements were made using a 3.5 m violin bow probe at relatively close spacing (1-2 km) along seismic reflection profiles that provide environmental context for understanding the measured values. Analytical uncertainties are estimated to be  $\pm 5\%$ .

The Cascadia subduction zone (CSZ) is both a seismic and thermal end member of global subduction zones, having one of the lowest rates of seismicity and among the highest plate boundary temperatures worldwide. The high temperatures on the plate boundary are attributed to the young age of the subducting Juan de Fuca plate (5-11 Ma at the deformation front), its slow convergence rate (30-40 mm/yr), and the presence of a thick blanket of insulating sediment both seaward and landward of the deformation front. Just seaward of the deformation front, heat flow varies between 105 and 115  $\text{mW m}^{-2}$ . Over the outer accretionary wedge, at distances up to 30 km landward from the deformation front, heat flow varies between about 85 and 90  $\text{mW m}^{-2}$ , reflecting the depression of heat flow due to thickening sediment and downward heat advection by the subducting plate. At landward and seaward forearc basin edges heat flow increases by 10 to 25  $\text{mW m}^{-2}$ , suggesting upward fluid flow. We also surveyed heat flow over a buried seamount ~25 km seaward of the deformation front. Heat flow over the seamount varies between 116 and 438  $\text{mW m}^{-2}$  and is inversely proportional to the overlying sediment thickness. These values suggest that the top of the oceanic crust is approximately isothermal, indicating active hydrothermal circulation within the 8 My upper oceanic crust. Modeling results suggest that the temperature at the sediment-basement interface at the deformation front is approximately 200° C. Mineral dehydration reactions that can generate fluid overpressures in impermeable sediments and are often invoked to explain the transition from stable sliding to stick-slip behavior are likely to have been completed before the sediments have reached the deformation front.

At the Hikurangi margin, the 120 Ma Hikurangi Plateau, a large igneous province on the Pacific plate, is subducting beneath the Australian plate. Large along-strike variations in interseismic coupling and slow slip event behavior along this margin offer an important opportunity to address processes affecting slip behavior. In particular, slow slip is observed at much shallower depths (<5-15 km) along the northern Hikurangi margin than in Cascadia, where slow slip is observed in a distinct band along the plate boundary at depths of 30-50 km. The background thermal regime seaward of the deformation front is ~50  $\text{mW m}^{-2}$  for both the northern and southern regions, respectively. These values are consistent with cooling plate models for this age of oceanic lithosphere. However, heat flow transects in the northern Hikurangi trough show evidence for crustal fluid flow associated with basement relief. Heat flow transects in the southern Hikurangi trough do not require crustal fluid flow, but this could be due to a lack of basement relief. The contrast in slow slip depth between the northern and southern Hikurangi margin does not appear to be directly linked to temperature.

Keywords: décollement temperature, heat flow, subduction zone



## Sumatra Seismogenic Zone: IODP Expedition 362 Overview

\*Lisa Clare McNeill<sup>1</sup>, Brandon Dugan<sup>2</sup>, Katerina Petronotis<sup>3</sup>

1.University of Southampton, 2.Rice University, 3.Integrated Ocean Discovery Program, Texas A&M University

The 2004 Mw 9.2 earthquake and tsunami that struck North Sumatra and the Andaman-Nicobar Islands devastated coastal communities around the Indian Ocean and was the first earthquake to be analysed by modern techniques. This earthquake and the Tohoku-Oki Mw 9.0 earthquake and tsunami in 2011 showed unexpectedly shallow megathrust slip. In the case of North Sumatra, this shallow slip was focused beneath a distinctive plateau of the accretionary prism, unusual along this subduction zone and on others. This intriguing seismogenic behavior and forearc structure are not well explained by existing models or by relationships observed at margins where seismogenic slip typically occurs farther landward. The input materials of the North Sumatran subduction zone are a distinctive, thick (up to 4-5 km) sequence of primarily Bengal-Nicobar Fan-related sediments. These are thicker and more slowly accumulated than the input section analysed through drilling at any other global subduction zone, but are not atypical, e.g., the Makran and southern Lesser Antilles have similar input sections and relatively unknown seismogenic potential. The Sumatra input sequence shows strong evidence for induration and dewatering and has probably reached the temperatures required for sediment-strengthening diagenetic reactions before accretion. The correspondence between the 2004 rupture location and the overlying prism plateau, as well as evidence for a strengthened input section, suggests that the input materials are key to driving the distinctive fault slip behaviour and the longer term forearc structure. IODP Expedition 362, August-October 2016, will help us start to understand the nature of seismogenesis in North Sumatra by sampling its input materials and assessing their progressive evolution, as they become buried and incorporated into the subduction zone. Properties of the incoming section affect the strength of the wedge interior and base, likely promoting the observed plateau development. In turn, properties of deeper input sediment control decollement position and properties, and hence hold the key to shallow coseismic slip. During Expedition 362, two primary, riserless sites will be drilled on the oceanic plate to analyse the properties of the input materials. Coring, downhole pressure and temperature measurements and wireline logging at these sites will constrain sediment deposition rates, diagenesis, thermal and physical properties, and fluid composition. Post-expedition experimental analyses and numerical models will then be used to investigate the mechanical and frictional behaviour of the input section sediments/sedimentary rocks as they thicken, accrete, and become involved in plate boundary slip system and prism development. Secondary objectives include analysis of the stress state of the incoming oceanic plate, where one of the largest recorded oceanic plate and strike-slip earthquakes occurred in 2012, and the history of Nicobar fan sedimentation as related to the history of Himalayan uplift and monsoon development.

Keywords: subduction zone, earthquakes, ocean drilling

Long-term and large-scale tectonic framework controlling the seismogenic subduction zone earthquake -A case study in the Nankai Trough-

\*Gaku Kimura<sup>1</sup>, Harold James Tobin<sup>3</sup>, Masataka Kinoshita<sup>2</sup>

1.Department of Earth and Planetary Science of the Graduate School of Science, The University of Tokyo, 2.Earthquake Research Institute, The University of Tokyo, 3.University of Wisconsin-Madison

Recent drilling into the Nankai forearc of the IODP-NanTroSEIZE clarified that the wedge composed of accretion prism and forearc sediments have been formed mainly in Plio-Pleistocene after ~6 Ma and especially rapidly after ~2 Ma. The reasons for those punctuated growths seem the resurgence of subduction of the Philippine Sea Plate (PSP) at ~6Ma and the rapid sediment supply from the mountains in central Japan resulted from the new convergence along the eastern margin of the Amurian Plate at ~3-2.5 Ma.

The ~6 Ma resurgence of subduction of PSP appears to be synchronized with other events in the circum-PSP regions; initiations of the Mariana and Okinawa troughs opening, and subduction initiation of PSP along the Philippine Trench.

Slab pull, trench roll-back and suction forces due to the westward subduction of PSP might have promoted the opening of the both troughs as traditionally suggested by many researchers.

The ~3- 2.5 Ma rapid growth of Nankai accretionary prism off-Kii Peninsula is the same as the prism off Shikoku, which was also documented by ocean drilling about 15 years ago. Provenance analysis of the sediments of accretionary prisms documents that they flew down from the mountains in central Japan. The mountain building in central Japan is due to the collision between the northeast and southwest Japan, which is still going on, as documented in detail by many seismologic, geodetic topographic, and geologic investigations. The collision appears to have started at ~3.5 Ma to 2Ma and linked to the change in tectonic stress field in the fold and thrust belt along the eastern margin of the Japan Sea.

The eastern margin and collisional mountains in central Japan are regarded as the eastern convergent plate boundary region of the Amurian Plate as formulated by recent MORVEL plate tectonic synthesis. Eastward movement of the Amurian Plate appears to have started as suggested from intra-continent rifting due to the enhancement of deformation resulted from Great Himalayan collision.

Taking these recent tectonic events in millions year scale into account, we can explain the strange shape of subducting slab of PSP and its effect on the seismogenic rupture zones.



## Seafloor geodetic approach for the Nankai Trough megathrust source region

\*Yusuke Yokota<sup>1</sup>, Tadashi Ishikawa<sup>1</sup>, Toshiharu Tashiro<sup>1</sup>, Shun-ichi Watanabe<sup>1</sup>

1. Japan Coast Guard, Hydrographic and oceanographic department

Future source region along the Nankai Trough is located mainly under the seafloor. The previous onshore geodetic network could not catch up a coupling condition on this interplate boundary. After 2000, Hydrographic and Oceanographic Department, Japan Coast Guard (JHOD), has been performing a seafloor geodetic observation and is measuring movements of seafloor positions with about 1 cm/year precision. This new data has ability to improve our understanding of the coupling condition in this region.

Along the Nankai Trough, fifteen sites, including original sites set before the 2011 Tohoku-oki earthquake, were set broadly and observed at 2 ~ 3 times a year. These data were affected by coseismic and postseismic deformations following the Tohoku-oki earthquake and corrected using calculations obtained by coseismic model of Iinuma et al. [2012, JGR] and afterslip and viscoelastic model [Sun and Wang, 2015, JGR] modified after Sun et al. [2014, Nature]. We derived deformation velocities by robust regression method for those corrected data. As a result, 2.0 ~ 5.5 cm/year of velocities were obtained.

Our observations indicate low-coupling regions that are consistent with distributions of subducting seamounts. Additionally, VLFE activities around these geological features are much corresponding to low-coupling regions, though we cannot discuss the shallowest regions near the trench axis which were predicted as tsunami generation zones due to a lack of seafloor network.

Our data introduced in this presentation was the last 4 ~ 9 year-results and were deficiency in discussion about a long-term crustal deformation and a temporal change. Our next plan is continuous decadal observation.

In the present methodology, observation frequency and precision are not enough to differentiate deformations due to slow slip events. We introduce new technological developments and analytical approaches for high-precision in this presentation.

Acknowledgements: The coseismic and postseismic deformations of the 2011 Tohoku-oki earthquake were calculated by Dr. T. Iinuma of JAMSTEC and T. Sun of University of Victoria, respectively.

Keywords: Seafloor geodetic observation, Nankai Trough, Subduction zone megathrust earthquake

Possible shallow episodic slowslip in the Nankai Trough seismogenic zone detected by seafloor borehole observatory.

\*Eiichiro Araki<sup>1</sup>, Akiko To<sup>1</sup>, Toshinori Kimura<sup>1</sup>, Yuya Machida<sup>1</sup>, Demian M Saffer<sup>2</sup>

1.Japan Agency for Marine-Earth Science and Technology, 2.Penn State Univ.

Occurrence of very low frequency events (VLFE) have been known in the shallow part of seismogenic zones of oceanic plate subduction. In the Tonankai region of the Nankai Trough, where large earthquakes repeatedly occurred in the history, several observation of VLFE has been reported (Ito et. al, Sugioka et. al, To et. al) in the shallower part of the subducting plate interface or in the shallower accretionary prism. These VLFE were detected by surface waves in 0.01-0.1 Hz on land observation, but seafloor displacement due to the VLFE were observed in the seafloor as well as relatively high frequency P and S waves. On the other hand, no detectable motion in lower frequencies was reported that accompanies with these VLFE in the Nankai Trough.

We report two case of possible episodic slow slip in Tonankai region of the Nankai Trough, which were observed by pore-fluid pressure measurement of seafloor borehole observatory in IODP borehole C0002G. The first case was observed after the Tohoku earthquake of March 11, 2011, where borehole pore-fluid pressure showed gradual decrease of 1.8 kPa for two days, while VLFE swarms were observed locally. The second case was in October, 2015. The borehole pore-fluid pressure again gradually decreased by 1.6 kPa over two weeks. In the later period of the two weeks, local VLFE were also observed for a week period.

The pore-fluid pressure measurement in the borehole was taken at approximately 1 km below the seafloor. The pore-fluid pressure measurement can be regarded as a proxy of strain change in periods shorter than a few months. Observed pore-fluid pressure decrease is accounted by an extension of the crust at the observatory at very slow rate (two days, two weeks in these cases). Simultaneous occurrence of VLFE suggests the slow change were caused by slower fault slip probably in the offshore of the observatory where VLFE were observed. After started observation at C0002G, there have been no observation of local VLFE without slower pore-fluid pressure change. Therefore we also consider that, in the Nankai Trough, such slower fault slip exists and the VLFE is passively excited by the slower fault slip.

Keywords: Nankai Trough, slow slip, borehole observatory

## In situ stress state within the inner accretionary prism in the Nankai Trough: Inferences from drilling observations during IODP Expedition 348

\*Demian M Saffer<sup>1</sup>, Harold Tobin<sup>2</sup>, Takehiro Hirose<sup>3</sup>, David Castillo<sup>4</sup>

1.The Pennsylvania State University, 2.The University of Wisconsin, 3.JAMSTEC, 4.Insight Geomechanics

In November 2013- January 2014, Integrated Ocean Drilling Program (IODP) Expedition 348 drilled into the inner accretionary prism of the Nankai subduction zone offshore SW Japan, to investigate the physical properties, structure and state of stress deep within the hanging wall of a seismogenic subduction plate boundary. Drilling deepened Site C0002 to a depth of >3000 m below the seafloor (mbsf) at holes C0002N/P, and included coring over a limited interval from 2163-2218.5 mbsf, and a suite of logging while drilling (LWD) measurements to collect continuous annular pressure while drilling, gamma ray, azimuthal resistivity, and sonic velocity data over the entire depth of the holes. The hole was drilled in a riser mode, with controlled mud pressure and continuous monitoring of mud gases that, together with observations of mud losses, annular pressures, and/or hole conditions, provide indirect constraints on in situ pore pressure and stress state. Operations also included a leak-off test (LOT) at 1954.5 mbsf, and a stepped-rate injection test at 2920 mbsf that provide measurements of the minimum principal stress ( $S_3$ ). Observations of mud losses during drilling and a previous LOT at 874 mbsf conducted during IODP Expedition 338 both provide an additional indication of  $S_3$  at a shallower depth. Finally, several pack-offs occurred near the base of the borehole (3002 mbsf), but without indications of mud loss, suggesting that the accompanying spikes in annular pressure remained lower than the minimum tangential stresses at the borehole's circumference. Because the tangential stresses around a wellbore are a function of the differential stress in the horizontal plane, these data provide an independent constraint on the maximum horizontal stress (SHmax) magnitude.

As an ensemble, these observations - for the first time - constrain stress state and pore pressure in the deep interior of an accretionary wedge. The LOTs show that the minimum principal stress is less than the vertical stress defined by the overburden ( $Sh_{min} = S_3$ ), and define a nearly linear gradient in  $Sh_{min}$  from the seafloor to the base of the hole. Several observations of mud loss, and the lack of observed gas shows even during pipe connections, indicate that formation pore pressure is not significantly (<~10 MPa) greater than hydrostatic. Our estimate of SHmax is close in magnitude to the vertical stress, and defines either a normal or strike-slip faulting regime. At 3002 mbsf we estimate that the effective stresses are as follows:  $S_v' = 33$  MPa;  $SH_{max}' = 25-36$  MPa; and  $Sh_{min}' = 18.5-21$  MPa. A key implication of our analysis is that, at least to ~3 km depth in the hanging wall of the subduction thrust, differential stresses are low, on the order of 10 MPa or less. On this basis, we posit that: (1) the inner wedge is not critically stressed in horizontal compression, consistent with its flat surface slope and the development of a large forearc basin above; (2) basal traction along the megathrust must be low, in order to permit concurrent sliding along décollement and low differential stresses deep within the upper plate; and (3) although differential stresses may remain low all the way to the plate boundary at ~5.4 km bsf, the maximum horizontal stress SHmax must transition to become greater than the vertical stress below the base of the borehole in order to drive thrust motion along the décollement.

## Clay Mineral Provenance and Clay Diagenesis Deep in the Nankai Accretionary Prism: Results from IODP Riser Drilling, Nankai Trough Seismogenic Zone Experiment

\*Michael Underwood<sup>1</sup>

1. New Mexico Institute of Mining and Technology

IODP Expedition 348 set a new record for sampling depth by scientific ocean drilling. Cores were recovered from the Nankai accretionary prism (Site C0002) at depths of 2163-2218 mbsf; cuttings were recovered continuously to 3058 mbsf. Shallower strata near the top of the accretionary prism are as young as 5.6 Ma, but the deeper intervals have an apparent depositional age of 9.56-10.73 Ma. The steeply dipping Miocene strata lie within the hanging wall of the subduction megathrust and are buried beneath Quaternary turbidites of the Kumano Basin. Quantitative analyses of the clay mineral assemblages (using X-ray diffraction) show that the most abundant clay mineral is smectite, followed by illite, chlorite, and kaolinite. The accreted mudstones at Site C0002, however, contain significantly lower percentages of smectite (<25% of the bulk mudstone) as compared to coeval Miocene strata at Sites C0011 and C0012 (Shikoku Basin); those present-day subduction inputs generally contain >40% smectite in the bulk mudstone. One likely reason for the compositional difference is an overprint of the detrital assemblages by smectite-to-illite diagenesis; that reaction results in a steady down-hole increase in illite within the I/S mixed-layer phase. The extent of I/S reaction progress is consistent with kinetic models in which the peak heating time is limited to about 1 Myr, as might be expected with rapid Quaternary accumulation of sediment within the overlying Kumano Basin. Another possible reason for lower contents of smectite, however, is a spatial shift in the depositional environments and detrital provenance of subduction inputs during the Miocene. The mud-dominant facies of the older accretionary prism is enigmatic (when compared to the frontal prism), and its original depositional setting remains uncertain. The older accreted mudstones might have been deposited in a trench during a time period in which supplies of sandy sediment were restricted. An alternative explanation involves northeastward migration of the triple junction that joins the Japan, Izu-Bonin, and Nankai plate boundaries. The depositional settings prior to accretion may have shifted over time from the NE side of the triple junction (subducting Pacific plate) to the SW side (Shikoku Basin, subducting Philippine Sea plate). Regardless of exactly how and when the paleogeography evolved, smaller initial percentages of detrital smectite, combined with the gradual diagenetic loss of smectite with depth, are important for predicting how material properties change toward the seismogenic plate interface. We should see progressive reductions in the volumetric contribution of pore fluid from I/S dehydration toward the base of the hanging wall. On the other hand, fluids should be more abundant below the plate interface, sourced from thermally immature, smectite-rich, Shikoku Basin sediments.

Keywords: Nankai Trough Seismogenic Zone Experiment, clay minerals, accretionary prism

## Frictional properties of the Nankai Trough accretionary mud samples collected from 1000–3000 mbsf at IODP Site C0002

Koki Hoshino<sup>1</sup>, Kosuke Abe<sup>2</sup>, Michiyo Sawai<sup>1</sup>, \*Kyuichi Kanagawa<sup>1</sup>

1.Graduate School of Science, Chiba University, 2.Faculty of Science, Chiba University

We conducted triaxial friction experiments on the Nankai Trough accretionary mud samples collected from 1000–3000 mbsf (meters below seafloor) at IODP Site C0002 off Kii Peninsula, at confining pressures of 44–83 MPa, pore water pressures of 32–50 MPa and temperatures of 51–98°C equivalent to their in situ conditions, and at axial displacement rates ( $V_{axial}$ ) changed stepwise among 0.1, 1 and 10  $\mu\text{m/s}$ , in order to investigate their frictional properties changing with depth.

XRD analyses of tested mud samples revealed that the content of total clay minerals tends to increase with depth from ~30 to ~60 wt%, while that of smectite tends to decrease with depth from ~30 to ~20 wt%. Thus, the smectite fraction in total clay minerals decreases with depth from ~0.75 to ~0.3. Because the temperature at 3000 mbsf reaches ~100°C, this decrease in smectite fraction with depth is likely due to the progress of smectite dehydration with increasing temperature. Friction experiments of tested mud samples revealed that the steady-state friction coefficient ( $\mu_{ss}$ ) has a negative correlation with the content of total clay minerals.  $\mu_{ss}$  at  $V_{axial} = 1 \mu\text{m/s}$  tends to decrease with depth from ~0.5 to ~0.3, according to the increasing content of total clay minerals with depth. Although shallower samples exhibited a clear increase in  $\mu_{ss}$  when  $V_{axial}$  was increased and vice versa, i.e., velocity strengthening, a few deeper samples exhibited a decrease in  $\mu_{ss}$  when  $V_{axial}$  was increased and vice versa, i.e., velocity weakening. Velocity dependence of steady-state friction ( $d\mu_{ss}/d\ln V_{sliding}$ , where  $V_{sliding}$  is sliding velocity) has a positive correlation with the smectite fraction in total clay minerals. Because the latter decreases with depth,  $d\mu_{ss}/d\ln V_{sliding}$  also tends to decrease with depth.  $d\mu_{ss}/d\ln V_{sliding}$  values are relatively large ( $>0.002$ ) and positive at depths shallower than 2000 mbsf, implying stable faulting at these depths. In contrast,  $d\mu_{ss}/d\ln V_{sliding}$  values are relatively small ( $\leq 0.002$ ) and locally negative at depths deeper than 2000 mbsf, implying conditionally stable faulting including slow slip events at these depths.

Keywords: friction, mudstone, accretionary prism, Nankai Trough

## Hydration and dehydration of oceanic plates at subduction zones

\*Manuele Faccenda<sup>1</sup>

1. Dipartimento di Geoscienze, University of Padova

Hydrated oceanic plates may deliver significant amounts of water to the Earth's interior, which has strong implications for the dynamics of our planet.

Oceanic plate hydration is thought to occur principally by seawater downward percolation along cracks and fault zones and is normally associated with a decrease of the seismic velocities, lower heat fluxes, small magnitude seismicity (high b-values) and relatively high electrical conductivities. Extensive hydrothermal alteration of the oceanic plate has been reported in the trench-rise system of several subduction zones where bending across the trench of the oceanic lithosphere causes brittle extensional (compressional) deformation in the upper (mid-lower) portion of the plate and diffuse intraslab seismicity ranging from microearthquakes of  $M_w < 3$  to large intraplate and tsunamigenetic earthquakes of  $M_w > 8$ . The opening of fractures during brittle deformation provides a natural pathway for seawater percolation, which is aided by the establishment of dynamic sub-hydrostatic pressure gradients along the normal faults and, when an interconnected fracture network is present, by hydrothermal convection.

As the hydrated plate subducts, pressure and temperature conditions increase leading to the dehydration of the slab. Slab dehydration is normally linked to an increase of the pore-pressure, which in turn reduces the effective normal stress sufficiently to bring the system into the brittle regime. Water stored in pore space and loosely bounded water ( $H_2O^-$ ) in clays and zeolites of the upper oceanic crust and sediments is mostly expelled beneath the accretionary prism and the outer forearc, strongly affecting the mechanical behaviour of the megathrust and of the overlying upper plate. On the other hand, structural water ( $H_2O^+$ ) is progressively released at greater depths by metamorphic dehydration reactions during slab unbending. Most dehydration reactions are temperature sensitive and therefore are expected to occur at greater depths for colder slabs, with the dehydration front migrating from the hotter outer portions toward the cold core of the slab. Seismic tremor and intraslab deep seismicity with high b-values together with anomalous  $V_p/V_s$  ratios are often taken as evidence of ongoing metamorphic dehydration reactions of most abundant hydrous minerals such as serpentine, chlorite, amphibole and lawsonite.

In this contribution I will critically review the present-day knowledge relative to the hydration and dehydration of subducting oceanic plates (which is mostly based on geophysical observations and numerical predictions acquired over the last decade), and discuss the implications of these processes for the observed seismicity at subduction zones.

Keywords: subduction, slab hydration/dehydration, fluid-triggered seismicity

## Seismological constraint on fault processes from trench axis to outer-rise in Japan Trench

\*Shuichi Kodaira<sup>1</sup>, Yasuyuki Nakamura<sup>1</sup>, Gou Fujie<sup>1</sup>, Koichiro Obana<sup>1</sup>, Seiichi Miura<sup>1</sup>

1.R&D Center for Earthquake and Tsunami Japan Agency for Marine-Earth Science and Technology

JAMSTEC has been conducting marine seismological studies from the trench axis to the outer-rise of the Japan Trench since the 2011 Tohoku-oki earthquake occurred. The trench-to-outer-rise seismological study consists of two projects: one is a high-resolution seismic reflection survey in the trench axis and the other is a large-scale seismic reflection/refraction survey with earthquake observation in the outer-rise. Previous seismic studies discovered a small-scale fault-and-thrust structure in the incoming/subduction sediment at the trench, where the co-seismic slip reaching to the trench axis is observed. Based on those results, we propose a hypothesis indicating that the small-scale fold-and-thrust structure at the trench can be a structural proxy of a seismic slip reaching to the trench. In order to examine a lateral variation of a slip to the trench along the Japan Trench, seismic studies done by 2014 covered an area from 38 N to 40.5 N, and a further survey carried out at the south from 37 to 38 N in 2015. The seismic images obtained show that, i) the frontal small scale fold-and-thrust structures are generally observed from 38 -40.5 N, except around 39.5 N where thin (less than 50 m thick) incoming sediment to the trench is imaged, ii) width of the fold-and-thrust structure seems to become larger toward the north, iii) the structural character indicating a frontal fold-and-thrust seems to be unclear toward 37 N from 38 N. A purpose of the seismological study in the outer-rise is to obtain a seismological constraint on a distribution of potential fault of an outer-rise normal fault earthquake. Although no clear image of a normal fault from seafloor to the mantle is imaged, seismic reflection images near the trench around 38 N shows i) clear Moho reflection of the incoming plate is observed to the trench from the outer-rise with partially obscure Moho reflections, and ii) clusters of the normal fault aftershocks extending to the mantle in an area where the Moho reflection is obscure. Those structure and seismic activity are interpreted to reflect a distribution of the potential outer-rise normal fault. We will investigate seismic reflection imaged obtained around 39 N to examine if similar structural characters are observed.

Keywords: Japan Trench, Seismic imaging, subduction, outer-rise

## Seismicity observations in the source region of the 1896 Meiji-Sanriku and 1933 Showa-Sanriku Earthquakes

\*Koichiro Obana<sup>1</sup>, Yasuyuki Nakamura<sup>1</sup>, Yuka Kaiho<sup>1</sup>, Yojiro Yamamoto<sup>1</sup>, Shuichi Kodaira<sup>1</sup>, Gou Fujie<sup>1</sup>

1.Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology

Subduction zone megathrust earthquakes have some interaction with intra-plate normal-faulting earthquakes in trench-outer rise region. For example, after the 2011 Tohoku-Oki earthquake (Mw 9.0), many M7-class normal-faulting earthquakes occurred in the trench-outer rise region seaward of the largest co-seismic slip area during the 2011 Tohoku-Oki earthquake. Large outer-trench normal-faulting earthquakes have potential to generate large tsunamis resulting in severe damage in coastal area. Hence, to know the potential source region of the outer-trench normal faulting earthquake is important to assess the relating Tsunami hazard. In northern part of the Japan Trench, the 1933 Showa-Sanriku earthquake, M 8.1 outer-trench normal-faulting earthquake, occurred 37 years after the 1896 Meiji-Sanriku Tsunami earthquake (M ~8.5). Tsunamis generated by both earthquakes caused severe damage in coastal area. The observations using routine land seismic stations suggest the long-lasting aftershock activity in the source region of the 1896 and the 1933 earthquakes. However, due to the large distance from the coast and large water depth beyond the maximum operational depth of conventional ocean bottom seismographs (OBS), precise locations of the earthquakes in the source region of the 1896 and the 1933 earthquakes have not been obtained. Recently, the JAMSTEC has been utilized ultra-deep ocean bottom seismographs (UDOBS), which can be deployed up to 9000 m water depth. We have conducted seismicity observations using OBSs including the UDOBSs from July to September 2015. Based on the preliminary analysis, there are three epicentral lineations in the outer trench region. These lineations are almost parallel to the trench axis. One lineation in the southeastern part of the OBS network is the aftershock activity of the Mw 7.6 outer-trench normal-faulting earthquake occurred 40 minutes after the 2011 Tohoku-Oki earthquake. The other two lineations are located just seaward of the trench axis. These lineations have almost the same length with the fault model of the 1933 Showa-Sanriku earthquake estimated by Kanamori (1971). The seismic activity along these lineations likely corresponds to the aftershock activity of the 1933 earthquake.

Keywords: trench outer-rise, intra-plate normal faulting earthquake



## The slip distributions of the 1896 Sanriku and 2011 Tohoku earthquakes along the northern Japan Trench

\*Kenji Satake<sup>1</sup>, Yushiro Fujii<sup>2</sup>, Shigeru Yamaki<sup>3</sup>

1.Earthquake Research Institute, University of Tokyo, 2.IISEE, Building Research Institute ,  
3.Seamus

The 1896 Sanriku earthquake was a typical "tsunami earthquake" with large tsunami despite its weak ground shaking. The tsunami source of the 2011 Tohoku earthquake extended toward north along Japan Trench with ~3 min delay. The 1896 source is located the north of this slip along the trench axis. Comparison of the two tsunamis shows that the runup heights along the northern and central Sanriku coasts were similar, but the amplitudes of the 1896 tsunami waveforms recorded on tide gauges at regional distances were much smaller than those of the 2011 tsunami. Computed tsunami from the northeastern part of the 2011 slip model roughly reproduces the 1896 heights on Sanriku coast, but much larger than the 1896 waveforms, consistent with the comparison of observed data. The 1896 coastal heights along Sanriku coast, arrival time at Miyako, and waveforms at regional distances are all reproduced by a 200 km long, 50 km wide fault with an average slip of 8 m, with large (20 m) slip on a 100 km x 25 km asperity. Assuming a rigidity of  $2 \times 10^{10}$  N/m<sup>2</sup>, the seismic moment is  $1.6 \times 10^{21}$  Nm and the corresponding moment magnitude is Mw 8.1. The slip at the 1896 asperity (depth 3.5 to 7 km) was 3 to 14 m in 2011, while the shallower (0 -3.5 km) part slipped 3 m in 1896 but 20 to 36 m in 2011. Thus the large slips of the two earthquakes were complementary, and the large slip asperity was deeper in 1896.

Keywords: 1896 Sanriku tsunami earthquake, 2011 Tohoku earthquake, tsunami

## Residual topography and gravity anomalies reveal structural controls on co-seismic slip in the 2011 $M_w$ 9.0 Tohoku-oki earthquake

\*Dan Bassett<sup>1</sup>, David T Sandwell<sup>1</sup>, Yuri Fialko<sup>1</sup>, Anthony B Watts<sup>2</sup>

1.Scripps Institution of Oceanography, 2.University of Oxford

The March 2011 Tohoku-oki earthquake was only the second giant ( $M_w \geq 9.0$ ) earthquake in the last 50 years and is the most recent to be recorded using modern geophysical techniques. Available data place high-resolution constraints on the kinematics of earthquake rupture, which have challenged prior knowledge about how much faults can slip in a single earthquake and the seismic potential of a partially coupled megathrust interface. But it is not clear what physical or structural characteristics have controlled either the rupture extent or the amplitude of slip. Here we use residual topography and gravity anomalies to constrain the geological structure of the overthrusting plate in NE Japan. These data reveal an abrupt SW-NE striking forearc segment boundary, across which gravity modelling indicates a south-to-north increase in the density of rocks overlying the megathrust of  $\sim 150\text{-}200 \text{ kg m}^{-3}$ . We suggest this boundary represents the offshore continuation of the Median Tectonic Line (MTL), which onshore juxtaposes geological terranes composed of granite-batholiths (north) and accretionary complexes (south). The megathrust north of the MTL is strongly coupled, has a history of large earthquakes (18 with  $M_w \geq 7$  since 1896) and produced peak slip exceeding 40 m in the Tohoku-oki earthquake. In contrast, the megathrust south of this boundary is weakly coupled, has not generated an earthquake with  $M_j \geq 7$  since 1923, and experienced relatively minor (if any) co-seismic slip in 2011. We show that forearcs are not passive components of subduction zones and propose that the structure and frictional properties of the overthrusting plate are a key control on megathrust coupling and seismogenic behavior in NE Japan.

## High-velocity frictional strength across the Tohoku-Oki megathrust determined from surface drilling torque

\*Kohtaro Ujiie<sup>1,2</sup>, Tomoya Inoue<sup>3</sup>, Junya Ishiwata<sup>3</sup>

1. Graduate School of Life and Environmental Sciences, University of Tsukuba, 2. Research and Development Center for Ocean Drilling Science, Japan Agency for Marine-Earth Science and Technology, 3. Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology

High-velocity frictional strength is one of the primary factors controlling earthquake faulting. The Japan Trench Fast Drilling Project drilled through the shallow plate-boundary fault, where displacement was ~50 m during the 2011 Tohoku-Oki earthquake. To determine downhole frictional strength, we analyzed the surface drilling torque data acquired at rotation rates equivalent to seismic slip rates (0.8-1.3 m/s). The results show a clear contrast in high-velocity frictional strength across the plate-boundary fault: the apparent friction coefficient of frontal prism sediments (hemipelagic mudstones) in the hanging wall is 0.1-0.3, while that of the underthrust sediments (mudstone, laminar pelagic claystone, and chert) in the footwall increases to 0.2-0.4. The apparent friction coefficient of the smectite-rich pelagic clay in the plate-boundary fault is 0.08-0.19, which is consistent with that determined from high-velocity (1.1-1.3 m/s) friction experiments. This suggests that surface drilling torque is useful in obtaining downhole frictional strength.

Keywords: frictional strength, drilling torque, Japan Trench Fast Drilling Project

## Foreshock activities before the 2011 Tohoku-Oki Earthquake

\*Debebe Kifle Atnafu<sup>1</sup>, Ryota Hino<sup>1</sup>, Ryosuke Azuma<sup>1</sup>, Yusaku Ohta<sup>1</sup>, Masanao Shinohara<sup>2</sup>, Yoshihiro Ito<sup>3</sup>

1. Research Center for Prediction of Earthquake and Volcanic Eruption, Graduate School of Science, Tohoku University, 2. Earthquake Research Institute, University of Tokyo, 3. Disaster Prevention Research Institute, Kyoto University

The 2011 Tohoku-Oki Earthquake (Mw 9.0) was preceded by a series of evident foreshock activity for about a month. Kato et al. (2012) identified more than 1,000 earthquakes by applying a waveform correlation method to land-based seismic records and discussed the spatio-temporal development of the foreshock activity. They interpreted the foreshock migration in terms of the propagation of aseismic slip in the vicinity of the mainshock hypocenter to suggest relatively fast slip immediately after the largest foreshock (Mw 7.3), occurred two days before the mainshock promoted the rupture of M9 mainshock. Since their hypocenters were determined by only the land seismic data, they can be much improved by including the arrival time readings recorded by ocean bottom seismographs (OBSs) deployed around the foreshock activity area. Suzuki et al. (2012) relocated the hypocenters of foreshocks with a magnitude 2.0 or larger using the OBS data and showed the foreshock activity initiated at the trenchward end of the foreshock activity zone, ~ 30 km away from the M 7.3 foreshock epicenter. This demonstrates that the OBS data significantly improve the resolution of epicenter distribution especially in the dip direction of the seismogenic zone. In this study, we relocated the hypocenters of the foreshocks identified by Kato et al. (2012) by using the OBS arrival time data. We picked the arrival times by manual and 1385 hypocenters, out of 1416 events on the list of Kato et al. (2012), were relocated.

Keywords: Foreshock events, Hypocenter relocation, Ocean Bottom Seismograph (OBS), Tohoku-Oki Earthquake

## Spatial and temporal variation of stress state in east Japan during the 2011 Tohoku-oki earthquake: Insights from S-wave splitting analysis from ambient noise records

\*Tatsunori Ikeda<sup>1</sup>, Takeshi Tsuji<sup>1</sup>

1.WPI-I2CNER, Kyushu University

The 2011 Tohoku-oki earthquake induced significant deformation of east Japan. However, the temporal and spatial variations of the regional stress field are poorly known. Here we apply S-wave splitting analysis for continuous ambient noise records to reveal temporal and spatial variations of the stress field during the 2011 Tohoku earthquake. Before the Tohoku earthquake, we observed small temporal variations in fast S-wave oscillation directions (FSODs), indicating high time-stability of our approach. At the Tohoku earthquake, we observed clear change in FSODs. We identified small rotations of FSODs and their gradual return to pre-earthquake values. We suggest that these changes represent temporary rotations of the maximum horizontal stress directions caused by the earthquake. We further identified 90° changes in FSODs in the volcanic region, suggestive of changes in pore pressure conditions due to magmatic activities. We also observed 90° changes in FSODs in the eastern coast of the study area. We interpret the cause of these 90° changes as changes in pore pressure conditions because increase of maximum shear strain or seismicity was observed in this region. From temporal and spatial variations of estimated FSODs, we classified east Japan into three regions with similar stress change associated with the Tohoku earthquake. Since our approach using ambient noise has high temporal resolution, we can identify temporal changes in FSODs and monitor their recover process. As a result, we can possibly distinguish changes in FSODs associated with rotations of maximum horizontal stress directions with those associated with pore pressure conditions. Therefore, our approach may be a new monitoring tool of stress state to identify unstable regions and predict aftershock and volcanic activity.

Keywords: temporal changes, ambient noise, S-wave splitting, Tohoku-oki earthquake, stress state

## Spatial characteristics of postseismic deformation following the 2011 Tohoku-oki earthquake inferred from repeated GPS/Acoustic observations

\*Fumiaki Tomita<sup>1</sup>, Motoyuki Kido<sup>2</sup>, Yusaku Ohta<sup>1</sup>, Ryota Hino<sup>1</sup>, Takeshi Iinuma<sup>3</sup>, Yukihiro Osada<sup>1,4</sup>

1. Graduate School of Science and Faculty of Science, Tohoku University, 2. International Research Institute of Disaster Science, Tohoku University, 3. Japan Agency for Marine-Earth Science and Technology, 4. GNSS Technologies Inc.

On- and off-shore geodetic observation studies have revealed the postseismic deformation process of the 2011 Tohoku-oki earthquake (e.g., Ozawa et al., 2012, JGR; Watanabe et al., 2014, GRL). Using these observation data, Sun et al. (2014, Nature) and Sun and Wang (2015, JGR) modeled viscoelastic relaxation (VE) causing significant landward movement in the main coseismic ruptured area (MCRA) of the Tohoku-oki earthquake and afterslip causing trenchward movement in north and south of the MCRA. However, a broad spatial pattern of the postseismic deformation near the Japan trench has not been revealed because of shortage of the off-shore geodetic observation sites. Therefore, we have newly deployed twenty GPS/acoustic (GPS/A) observation sites near the Japan trench from Aomori-oki to Ibaraki-oki to spatially constrain the postseismic deformation pattern (Kido et al., 2015, IAGS). We have conducted repeated GPS/A surveys at the new sites from September 2012 to November 2015; almost five times of surveys have been conducted at each site. Adopting the method of Kido et al. (2006, EPS), we estimated a horizontal seafloor transponders array position for each survey. Moreover, a postseismic displacement rate at each site was calculated by M-estimation robust linear regression method. The estimation error of the rates is averagely  $\sim 3$  cm/yr. Although we have reported the displacement rates in the new sites (e.g., Tomita et al., 2015, AGU), more reliable results are shown in this presentation using the latest survey data in November 2015. The calculated displacement rates clearly show spatial variation of the postseismic deformation along the trench. In the south region of the MCRA (36-37°N), all of observation sites show high trenchward displacement rates (5-15 cm/yr), which is interpreted as the effect of afterslip. Moreover, we also found out that highest trenchward movement have been occurred in Fukushima-oki near the trench. In the MCRA, most of the observation sites show high landward displacement rates ( $\sim 10$  cm/yr), which are interpreted as the effect of VE. This landward movement is extended to 39.5° N. Meanwhile, some of the nearest observation sites to the trench which are located in the highest coseismic slip area show lower landward displacement rates (-7 cm/yr). In north of 39.5°N, the observation sites show low landward displacement rates (-5 cm/yr). Although the spatial variation in the displacement rates can be roughly explained by the existing postseismic deformation models (Sun et al., 2014; Sun and Wang, 2015), there are two significant local misfits between the observation and the model. The first misfit can be seen in the northern MCRA (39-39.5°N) near the trench. In this region, the observed landward movements are significantly higher than the VE model. We expect that additional coseismic slip in this region to correct the VE model will reproduce further landward movement. The second misfit can be seen in the nearest MCRA region to the trench where the highest coseismic slip was occurred. Although the VE model predicts high landward displacement rates our results show clearly low landward displacement rates. This misfit requires aseismic fault slip and/or a new VE model which can produce moderate deformation in this region. Thus, our GPS/A observation results revealed overall spatial characteristics of the postseismic deformation of the Tohoku-oki earthquake and suggest re-examination of the VE model. We expect that our results contribute to constructing a more reliable postseismic deformation model.

Keywords: postseismic deformation, the 2011 Tohoku-oki earthquake , GPS/Acoustic technique, seafloor geodetic observation

## Spatiotemporal changes in the b-value along the plate interface before and after the 2011 Tohoku earthquake constrained by ocean bottom seismic network: Post-Tohoku

\*Yukihiro Nakatani<sup>1</sup>, Kimihiro Mochizuki<sup>1</sup>, Masanao Shinohara<sup>1</sup>, Tomoaki Yamada<sup>1</sup>, Hajime Shiobara<sup>1</sup>, Ryota Hino<sup>2</sup>, Ryosuke Azuma<sup>2</sup>, Yoshihiro Ito<sup>3</sup>, Yoshio Murai<sup>4</sup>, Toshinori Sato<sup>5</sup>, Kenji Uehira<sup>6</sup>, Takashi Shimbo<sup>6</sup>, Hiroshi Yakiwara<sup>7</sup>, Shuichi Kodaira<sup>8</sup>, Yuya Machida<sup>8</sup>, Kenji Hirata<sup>9</sup>, Hiroaki Tsushima<sup>9</sup>

1.Earthquake Research Institute, University of Tokyo, 2.Graduate School of Science, Tohoku University, 3.Disaster Prevention Research Institute, Kyoto University, 4.Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University, 5.Graduate School of Science, Chiba University, 6.National Research Institute for Earth Science and Disaster Prevention, 7.Nansei-toku Observatory for Earthquakes and Volcanoes, Faculty of Science, Kagoshima University, 8.Japan Agency for Marine-Earth Science and Technology, 9.Meteorological Research Institute, Japan Meteorological Agency

Changes in seismicity before and after the occurrence of megathrust earthquakes provide key information to better understanding the extension of its source area and the rupture propagation. In particular, it has been proposed that spatiotemporal variation of the b-value along the subduction zone megathrust reflects the interplate coupling [e.g., Ghosh et al., 2008, GRL]. In the case of the 2011 Tohoku earthquake, a target of this study, several studies have already reported the spatiotemporal changes of the b-value within its source area. However, it still remains controversial, because of problems with existing catalogs in completeness of magnitude after the first few months of the main shock and accuracy of focal depths for offshore earthquakes. Therefore, in this study, we analyze seismicity including small earthquakes along the plate interface using data from ocean bottom seismometers (OBSs) obtained during extensive seafloor aftershock observations [Shinohara et al., 2011, 2012] and recurrent OBS observations off Miyagi by Tohoku University. In order to automatically detect and locate interplate earthquakes, we applied a back projection method based on semblance analysis [Nakatani et al., 2015, GRL] to the data. In order to inspect validity of our method, we conducted three kinds of tests: synthetic tests, focal mechanism tests, and focal depth tests. We confirmed the validity of our method to evaluate seismicity along the plate interface. Also, we appropriately corrected event magnitudes determined by OBS records, which are, in general, overestimated due to large amplifications caused by seafloor sediments, by comparing with those listed in the JMA (Japan Meteorological Agency) catalog. Finally, we obtained an original earthquake catalog which shows an improvement in completeness of magnitude for interplate earthquakes. The resulted distribution of seismicity for the first three months after the main shock shows mutually complementary relationship between the active area of interplate aftershocks and the large coseismic slip zone. We also observe spatial variation of the b-value during the same observation period.

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Keywords: b-value, the 2011 Tohoku earthquake, OBS data, back projection



## Seismic monitoring in the northern source region of the 2011 Tohoku-oki earthquake by using long-term OBSs

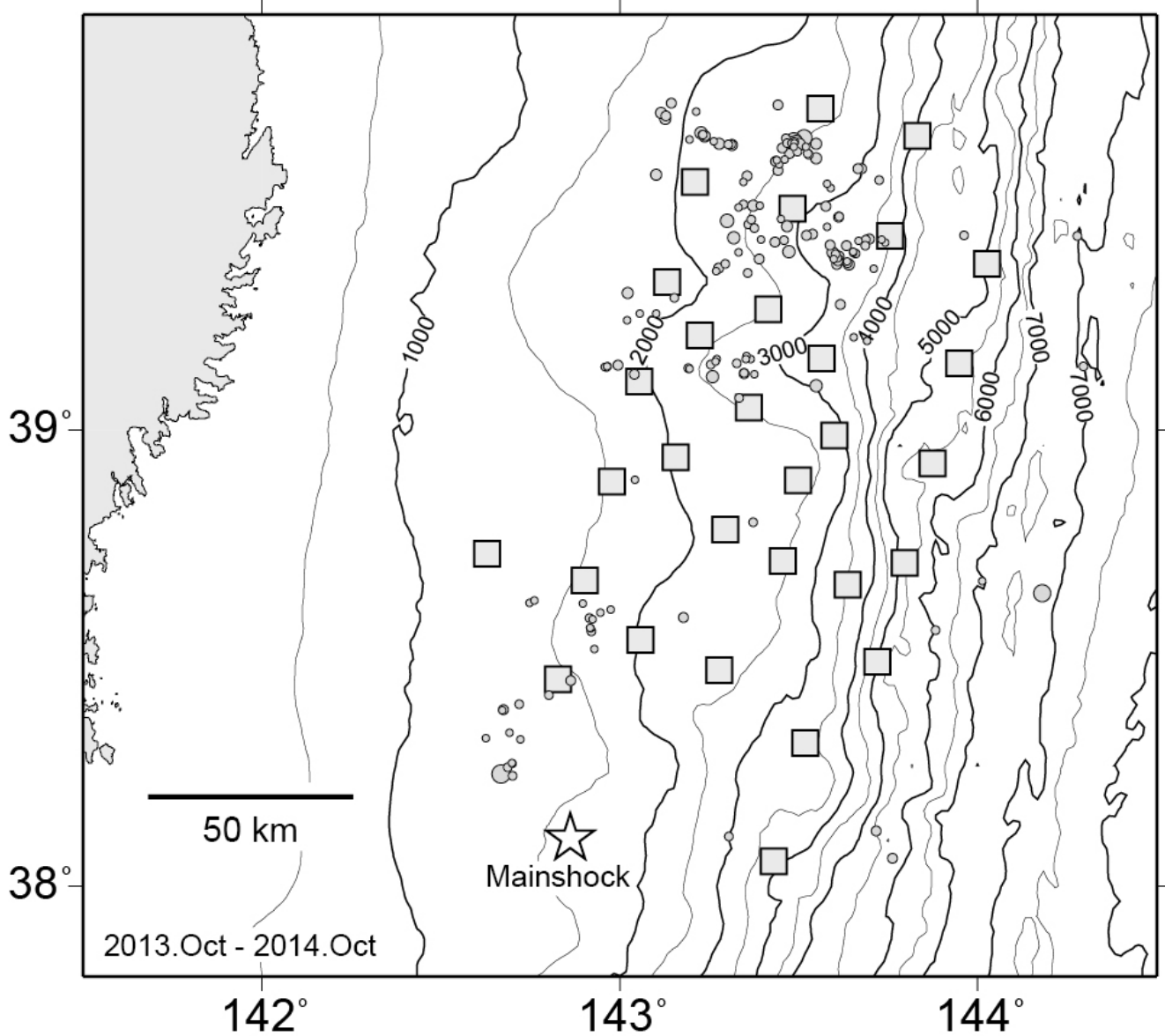
\*Masanao Shinohara<sup>1</sup>, Tomoaki Yamada<sup>1</sup>, Kimihiro Mochizuki<sup>1</sup>, Takeshi Akuhara<sup>1</sup>, Yukihiro Nakatani<sup>1</sup>, Hajime Shiobara<sup>1</sup>, Yoshio Murai<sup>2</sup>, Shinya Hiratsuka<sup>2</sup>, Ryota Hino<sup>3</sup>, Yusaku Ohta<sup>3</sup>, Ryosuke Azuma<sup>3</sup>, Toshinori Sato<sup>4</sup>, Yoshihiro Ito<sup>5</sup>, Yusuke Yamashita<sup>5</sup>, Kazuo Nakahigashi<sup>6</sup>, Takuya Teraoka<sup>6</sup>, Hiroshi Yakiwara<sup>7</sup>

1.Earthquake Research Institute, University of Tokyo, 2.Institute of Seismology and Volcanology, Hokkaido University, 3.Research Center for Prediction of Earthquakes and Volcanic Eruptions, Tohoku University, 4.Faculty of Science, Chiba University, 5.Disaster Prevention Research Institute, Kyoto University, 6.Faculty of Science, Kobe University, 7.Nansei-Toku Observatory for Earthquakes and Volcanoes, Kagoshima University

The 2011 off the Pacific coast of Tohoku earthquake occurred at the plate boundary between the Pacific plate and the landward plate on March 11, 2011, and many aftershocks followed the mainshock. To obtain a precise aftershock distribution is important for understanding of mechanism of the earthquake generation. In order to study the aftershock activity of this event, extensive seafloor aftershock observation using more than 100 ocean bottom seismometers (OBSs) was carried out just after the mainshock to September 2011. The OBS network covered the whole source region of the mainshock with average interval of 25 km. Events whose epicenter is located below the OBS network from the JMA earthquake catalog were selected, and P and S-wave arrival times were picked from the OBS data. Hypocenters were estimated by a maximum-likelihood estimation technique with one dimensional velocity structures. Thickness of sedimentary layer, which changes below each OBS was evaluated and the estimated travel times by the location program were adjusted. As a result of the urgent OBS observation, a precise aftershock distribution for approximately three months was obtained (Shinohara et al., 2011, 2012). Comparing hypocenter distribution to velocity structures by marine seismic surveys, there is few aftershocks along the plate boundary in the region off Miyagi, where a large slip during the mainshock is estimated. Activity of aftershocks within the landward plate above the source region is high and many aftershocks within the landward plate have normal fault type or strike-slip type mechanism. Within the subducting oceanic plate, most of earthquakes also have normal fault type or strike-slip type mechanism. After the urgent aftershock observation using OBSs, the observation using long-term OBSs was continued to monitor seismic activities in the source area. Forty long-term OBSs (LT-OBSs) in the whole source region were deployed in September 2011 and have completed recovery of the LT-OBSs until November, 2012. The 1 year data from September 2011 were processed using the same procedure as the urgent aftershock observation. Although a number of aftershock decreases with a time, there is no large spatial change of seismic activity in the northern source region. Seismic activity in a landward plate was high for the whole observation period, and focal mechanism was similar to that just after the mainshock. Before the mainshock, deep earthquakes under a landward slope were seen. However we obtain little seismic activity in such deep region after the mainshock. We deployed 30 LT-OBSs in the northern source region (off-Iwate region) in October 2013 to investigate spatiotemporal variation of the seismic activity. The LT-OBS has 3 component 1Hz velocity-type seismometers with a recording period of typical 1 year. The OBSs were successfully recovered in September or October 2014. We process the data from the 2013-2014 observation using the same procedure as before. We will report precise seismic activities in the northern source region with spatial and temporal variation. From preliminary analysis, a seismic activity in the off-Iwate region from 2013 to 2014 may be changed from the activity just after the mainshock. This study was supported by the Ministry

of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program.

Keywords: The 2011 off the Pacific coast of Tohoku earthquake, Long-term ocean bottom seismometer, Spatiotemporal variation of seismic activity



Amplitude changes of the seismic reflected phases from the plate interface before and after the 2011 Tohoku earthquake around its northern limit region as revealed by active seismic surveys

Ken Ishihara<sup>1</sup>, \*Kimihiro Mochizuki<sup>1</sup>, Tomoaki Yamada<sup>1</sup>, Masanao Shinohara<sup>2</sup>, Yusuke Yamashita<sup>3</sup>, Ryosuke Azuma<sup>4</sup>, Ryota Hino<sup>4</sup>, Toshinori Sato<sup>5</sup>, Yoshio Murai<sup>6</sup>, Hiroshi Yakiwara<sup>7</sup>

1.Earthquake Prediction Research Center, Earthquake Research Institute, University of Tokyo, 2.Center for Geophysical Observatoin and Instrumentation, Earthquake Research Institute, University of Tokyo, 3.Miyazaki Observatory, Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, 4.Resarch Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, 5.Faculty of Science, Chiba University, 6.Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University, 7.Nansei-Touko Observatory for Earthquakes and Volcanoes, Faculty of Science, Kagoshima University

Seismicity along the Japan Trench off the northeastern part of Japan is not uniformly distributed, but it shows spatial variation. In fact, there have been identified aseismic areas off Miyagi prefecture around 39°N, 143°E. In order to investigate the origin of this variation in seismicity around this region, seismic surveys were conducted in 1996 and 2001. P-wave velocity structures were obtained along along-strike and along-dip profiles using data of the 1996 survey. Fujie et al. (2002) identified amplitude variation in reflected phases from the plate interface along the along-strike profile, and compared their amplitudes with the seismicity. They observed good anti-correlation between the amplitude and the seismicity such that large amplitude reflections were observed within seismically inactive regions. Spatial distribution of large amplitude reflections from the plate interface around the region was then revealed by Mochizuki et al. (2005), and the good anti-correlation between the amplitude and seismicity was confirmed. They also revealed that such reflection amplitudes increase as the plate interface becomes deeper. By qualitatively reproducing reflection amplitudes by numerical simulations, they concluded that there exists a thin low P-wave velocity layer over the subducting oceanic plate. They proposed abundant fluid must exist along the plate interface as the origin of such low P-wave velocity. In 2011, the devastating Tohoku earthquake occurred along the Japan Trench with its fault dimensions reaching 500 km along-strike and 200 km along dip. A number of models for its rupture region have been proposed, and all share the common northern limit of the co-seismic slip at around 39°N where considerable contrast of seismicity exists. In order to investigate if physical properties along the plate interface may have changed in response to the rupture propagation, we conducted a seismic survey in 2013. In order to directly compare the observed waveforms with those obtained in 2001 survey, we deployed ocean bottom seismometers (OBSs) at the same station locations along the same along-strike profiles.

We estimated P-wave velocity structures using data of the 2013 survey. At first, we constructed 1-D V-p structures to about 2km depth beneath the seafloor for each OBS station by applying the analysis method. Then, we conducted forward modeling of 2-D Vp structures by referring to the 1-D V-p structures so that the models explain travel times of shallow P-wave arrivals. Finally we obtained 2-D Vp structures by travel-time inversion. The depth of the plate interface was simultaneously estimated by including arrival-time picks of the plate interface reflected phases. We compared amplitudes of the reflected arrivals from the plate interface between the 2001 and 2013 surveys. Because the type of OBSs are mutually different between the surveys even at the same station sites, and the source signature of the airgun array was also different, we normalized amplitudes of reflected arrivals from the plate interface by the first arrival refracted waves. The

amplitudes of the reflected waves from the plate interface appeared decreased within the seismically quiet region where abundant fluids had existed along the plate interface, whereas they were increased within the seismically active region. We propose a possible explanation that fluids migrated from the aseismic (fluid abundant) region to the other regions in response to the rupture propagation during the Tohoku earthquake.

This study was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program.

Keywords: 2011 off the Pacific coast of Tohoku Earthquake, reflection amplitudes, active source marine seismic surveys

## Detecting a relative motion across the Japan Trench using precise acoustic ranging

\*Ryusuke Yamamoto<sup>1</sup>, Ryota Hino<sup>1</sup>, Motoyuki Kido<sup>2</sup>, Yusaku Ohta<sup>1</sup>, Tatsuya Kubota<sup>1</sup>, Fumiaki Tomita<sup>1</sup>, Kazuaki Ohta<sup>3</sup>, Yukihiro Osada<sup>1,4</sup>

1.Graduate School of Science, Tohoku University, 2.International Research Institute of Disaster Science, Tohoku University, 3.Disaster Prevention Research Institute, Kyoto University, 4.GNSS Technologies, Inc.

Researchers reported that the 2011 Tohoku-oki earthquake accompanied coseismic slip over 50 m (e.g. Iinuma et al., 2012, JGR). In the Tohoku-oki region, GPS/Acoustic (GPS/A) observation is now ongoing after the Tohoku-oki Eq. Tomita et al. (2015, GRL) revealed the observed acceleration of the Pacific plate can be explained by viscoelastic relaxation modeled by Sun et al. (2014, Nature). However precise nature of localized interplate motion is still unknown only using GPS/A observation. Therefore, we conducted direct path acoustic ranging across the Japan Trench from September 2014 to May 2015. Direct path acoustic ranging can continuously and precisely detect relative motion between a pair of instruments across plate boundary or a fault. In our preliminary examination, precision in 1 cm/yr was achieved (Osada et al., 2014, JpGU).

In the observation, three instruments were deployed across the trench axis at the Miyagi-oki region forming two baselines, 7 km and 10 km, respectively. Acoustic ranging was repeated every 4-hours. Relative ranges can be calculated by multiplying a round trip time of acoustic signal and sound velocity. Sound velocity depends on temperature, pressure and salinity. Then, we concurrently measured in-situ temperature. Pressure was taken from NAO.99Jb tide model (Matsumoto et al., 2000, J. Oceanogr.). Salinity was assumed to be constant because of its stability in deep ocean. Precisions of 2 baselines were less than 2 cm/yr, as same as the pre-observation.

In the observation, we obtained data for about 8 months, and found no relative motion, which indicates subducting rate about 8 cm/yr in global model is not compensated at the trench. Thus, near Miyagi-oki region, postseismic slip does not occur at this moment and is already in the interseismic locking state.

Since September 2015, five instruments were newly installed at the same region for two-years continuous observation. Furthermore, we plan to install additional instruments at Fukushima-oki region, where postseismic slip rate is reported strikingly large (Sun and Wang, 2015, JGR). Integrating these data, it is expected in the near future that deformation pattern along the trench axis would be revealed.

Keywords: direct path acoustic ranging, the 2011 Tohoku-oki earthquake, the Japan Trench, postseismic slip, seafloor geodesy

## Along strike structural variation in the central to northern part of the Japan Trench axis region

\*Yasuyuki Nakamura<sup>1</sup>, Shuichi Kodaira<sup>1</sup>, Mikiya Yamashita<sup>1</sup>, Seiichi Miura<sup>1</sup>, Gou Fujie<sup>1</sup>, Koichiro Obana<sup>1</sup>

### 1. Japan Agency for Marine Earth Science and Technology

Great earthquakes have occurred along the Japan Trench subduction zone, and some of them, e.g. Meiji Sanriku earthquake in 1896, could have ruptured the shallow portion of the plate boundary fault similar to the 2011 Tohoku earthquake. Geological/geophysical structure in the vicinity of the trench axis is one of the keys to understand the nature of shallow mega thrust events and tsunamigenesis. We have conducted high resolution seismic surveys in the northern part of the Japan Trench axis region in 38 -40.5 N to investigate the detailed structure in the trench axis area. Thrust faults and possible slope failures are observed landward of the trench axis, beneath the lowermost landward trench slope. The deformation and evolution styles of the lowermost landward slope show variation along the trench strike. To the south of the survey area in 38 -39 N, imbricate thrust-and-fold packages is observed but limited within the vicinity of the trench axis. Thickness of the hanging wall sediment is relatively thinner in the lowermost landward slope. These observation could suggest that the lowermost slope has not been well developed in this area. To the north around 40 -40.5 N, frontal thrusts and imbricate structure are clearly observed on the seismic profiles through ~ 10 -15 km landward of the trench axis. Thickness of the hanging wall sediment is thicker in this area. The bending-related faults on the subducted plate are generally not located beneath the lowermost slope up to ~ 10 km landward of the trench. These observations suggest that the imbricate structure has been well developed in the last ~ 10 kyr in this area. Around 39.5 N, it is suggested that slope failures have occurred. The trench axis is filled by slump deposits and debris with chaotic acoustic characteristics. Above mentioned variations in the deformation and evolution style in the lowermost landward slope could affect the mechanism of tsunami generation in the northern Japan Trench. The variation on the thickness of the incoming sediments is also identified along the trench strike. The variation of the sediment thickness on the incoming plate and its relation with the throw of the bending-related normal fault could also be an important factor for the tsunami generation caused by the shallow mega slip events in the northern Japan Trench. In 2015, another high resolution seismic survey was conducted in the Japan Trench off Miyagi-Fukushima region. We acquired 20 seismic profiles and will introduce initial results in this presentation.

Keywords: Japan Trench, reflection seismic survey

## Detecting tectonic tremor through frequency scanning at a single station in the Japan Trench subduction zone

\*Satoshi Katakami<sup>1</sup>, Yoshihiro Ito<sup>2</sup>, Kazuaki Ohta<sup>2</sup>, Ryota Hino<sup>3</sup>, Syuichi Suzuki<sup>3</sup>, Masanao Shinohara<sup>4</sup>

1.Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto university,  
2.Research Center for Earthquake Prediction, Kyoto university, 3.Graduate School of Science, Tohoku University, 4.Earthquake Research Institute, University of Tokyo

Slow earthquakes, such as tectonic tremors and slow slip events (SSE), are the most distinctive geophysical phenomena on the subducting plate interface and occur at both ends of updip and downdip of coseismic slip areas. Tremors and SSEs have been observed in the subduction zone at the updip portion near the Japan Trench [Kato et al., 2012; Ito et al., 2013, 2015].

Ito et al. (2015) showed three possible tectonic tremor sequences from the excitation of amplitude of ambient noise accompanying SSE. The tremor signals in these sequences with very weak amplitudes were observed at only one station. Here, we apply the frequency scanning analysis to detect and validate tectonic tremors near the Japan Trench; we re-examine the tremor activities from ocean bottom seismometer (OBS) data.

Sit et al. (2012) proposed "the frequency scanning analysis" to detect tectonic tremors by calculating ratios of the envelope waveforms through different bandpass filters of broadband data at a single station in the Cascadia margin. We apply this analysis to the seismic data recorded at 17 short-period OBS network stations deployed in the Japan Trench axis area off Miyagi, northeast Japan. Three types of bandpass filters with frequencies of 2-4 Hz, 10-20 Hz, and 0.5-1.0 Hz, corresponding to the predominant frequency band of tectonic tremors, local earthquakes, and ocean noises, respectively, are adopted.

The results show three major tremor sequences, which correspond to the tremor sequences reported in Ito et al. (2015), suggesting the occurrence of tremors in the subduction zone. Furthermore, we have successfully detected tremor signals at another two sites, especially from the second tremor sequences. We conclude that the second tremor sequence probably occurred in a slightly far area from the Japan Trench, or with larger magnitude than the other two tremor sequences. We have also estimated the release energy of tremors occurring Japan Trench before the largest foreshock of Tohoku-Oki earthquake.

## Seismic observations using ocean bottom seismometer arrays off-shore Miyagi, northeast Japan

\*Kazuaki Ohta<sup>1</sup>, Yoshihiro Ito<sup>1</sup>, Ryota Hino<sup>2</sup>, Yusaku Ohta<sup>3</sup>, Ryosuke Azuma<sup>3</sup>, Masanao Shinohara<sup>4</sup>, Kimihiro Mochizuki<sup>4</sup>, Toshinori Sato<sup>5</sup>, Yoshio Murai<sup>6</sup>

1.Disaster Prevention Research Institute, Kyoto University, 2.Graduate School of Science, Tohoku University, 3.Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, 4.Earthquake Research Institute, University of Tokyo, 5.Graduate School of Science, Chiba University, 6.Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University

Japan Trench is one of the most important subduction zones when discussing the occurrence condition of slow earthquakes. Although recent studies have identified some slow slip events (SSEs) and tectonic tremors in the shallow part of the Japan Trench subduction zone (Kato et al., 2012; Ito et al., 2013; Ito et al., 2015), the existing observation is still very limited because of the sparse seismic network. For the aim of examining detailed activities of shallow seismicity including tectonic tremors, we deployed ocean bottom seismometer (OBS) arrays near the trench. In this study, we analyze 6 months observed array data to show the fundamental performances of installed arrays. We installed three OBS arrays (AoA1-3) at interval of about 20km near the trench where the anticipated slip area of SSEs and the high coseismic slip area are overlapped. Each array consists of 5 stations spacing about 500m. The station at the center of array has a broad-band OBS and other 4 stations have a short-period OBS, respectively. While the observation is now going on with replacing of the OBSs, the first observation of AoA has been performed for 6 months from the 28 October 2014. Data from all stations have been successfully recovered on May 2015.

For each array data, we conduct a coherence analysis using the moving-window correlation technique to detect coherent signals and estimate their incoming directions (e.g. Fletcher et al., 2006). For every 4s time window, the optimum azimuth and apparent velocity are measured by maximizing the average cross correlation of all pairs of seismograms within an array with an assumption of plane waves.

We successfully detect many coherent signals. The number of signals detected simultaneously by all arrays is about 2,500 in the entire observation period, which includes regional and distant earthquakes or artificial signals like airgun shooting. About 1,000 signals correspond to the regional events in the earthquake catalog of the Japan Meteorological Agency (JMA). For corresponding events the azimuths estimated by two arrays (AoA2, AoA3) are almost consistent with azimuths from JMA epicenters, whereas the azimuths estimated by AoA1 are inconsistent and strongly biased to the specific direction of about 90 degrees, which is probably due to site effects. We also show detected tremor-like signals, though their origins are still uncertain at this time.

Acknowledgements: This study is supported by JSPS KAKENHI (26000002).

Keywords: Japan Trench, slow earthquake, tremor, OBS array



## Improved fault model of the Tohoku intraslab earthquake on Dec. 2012 (Mw 7.2) and its implication for the post-2011 stress state

\*Tatsuya Kubota<sup>1</sup>, Ryota Hino<sup>1</sup>, Syuichi Suzuki<sup>1</sup>, Yusaku Ohta<sup>1</sup>, Daisuke Inazu<sup>2</sup>

1.Graduate School of Science, Tohoku University, 2.Ocean Alliance, The University of Tokyo

We investigated the intraslab doublet earthquake occurred near the trench off Miyagi Pref. on December 7, 2012, based on near-field tsunami records by ocean bottom pressure gauges. Near the source area, the stress field before the 2011 Tohoku-Oki earthquake (Mw 9.0) was estimated to be tensile and compressional stresses in the upper and lower part of the subducting slab, respectively. The doublet was composed of the first deep (57.8 km) reverse faulting subevent (Mw 7.2, subevent 1) and the second shallow (19.5 km) normal faulting subevent (Mw 7.2, subevent 2) according to the GCMT solution, and the difference in focal mechanisms of the subevents is consistent with the stress state prior to the Tohoku-Oki earthquake. However, it is suggested that the intraslab stress state changed after the 2011 Tohoku-Oki earthquake (e.g., Obana et al., 2012, GRL), and the depth of the stress neutral zone, which exists between the upper tensile region and lower compressive stress region, may also changed. It is expected that the depth of the stress neutral zone after the Tohoku-Oki earthquake is constrained by the vertical extents of the fault ruptured during the two subfaults. The fault model estimated by our preliminary analysis (Kubota et al. (2015, JpGU; 2015, SSJ; 2015, AGU) consists of two planar subfaults, separated at around a depth of ~40 km from sea surface, which would be the depth to the stress neutral zone. However, the fault depths may not be constrained enough because we only used the tsunami waveforms, and we try to improve the fault model taking the other information (e.g., aftershock distribution) into account.

The aftershock distribution deduced from local OBS observation (Obana et al., 2014, EPS; 2015, AGU), the west-dipping aftershock lineation is clearly shown around the subevent 2, and little aftershocks were identified around the subevent 1. Therefore we compared between the tsunami source model derived from inversion analysis of pressure records and the sea surface vertical displacement expected only from the subevent 2 constraining the fault geometry based on the aftershocks. In the calculation, we assumed a planar fault with uniform slip and constrained the location, strike and dip of the fault plane based on the aftershock distribution. The depth extent of fault plane was set between the slab surface (~7km) and the lower limit of aftershocks (~40km), and slip amount is given by scaling law and CMT solution. The sea surface displacement is obtained by applying depth filter (Saito and Furumura, 2009, GJI) to the seafloor displacement. As a result, the calculated extent and amount of the subsidence area is mostly comparable to the tsunami source model, suggesting that the subsidence area is created basically from the subevent 2. In the presentation, we will constrain the vertical depth extent of the subfault 2 in more detail considering the difference of the pattern of sea surface displacement associated with the vertical location of the fault slip. We will also constrain the hypocenter of the subevent 1 based on the local OBS network and improve the fault geometry of the subevent 1. Finally we will compare the previous studies of seismicity in this region and discuss the intraslab stress change associated with the Tohoku-Oki earthquake.

Keywords: Tsunami, Doublet earthquake, Intraslab stress state, 2011 Tohoku-Oki earthquake

## Tsunami inversion for sea surface displacement from far-field DART data of the 2011 Tohoku tsunami

\*Tungcheng Ho<sup>1</sup>, Kenji Satake<sup>1</sup>

1.Earthquake Research Institute,The University of Tokyo

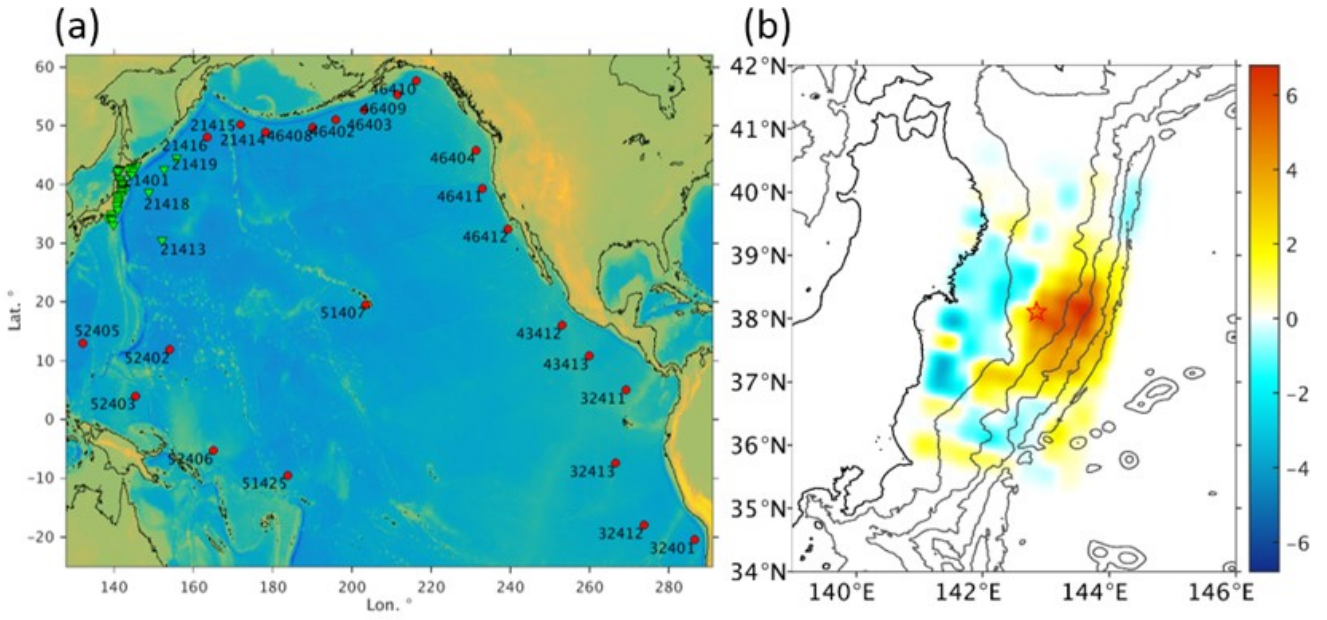
We re-examined the 2011 Tohoku tsunami source using far-field DART data, which was not used in previous waveform inversions. Only near-field stations around Japan were used in most inversion studies of the 2011 tsunami. Although the number of available tsunami gauges such as tidal gauge, ocean-bottom pressure gauge and DART increased after the 2004 Indian Ocean tsunami, most tsunami gauges are coastal gauges and DART gauges in the deep ocean are still fewer. For an accurate and reliable tsunami waveform inversion, the azimuthal coverage of stations is important. For a better station coverage, tsunami waveforms recorded at far-field stations must be utilized.

Problems that prevented to use far-field tsunami data in inversion were travel time-delay and polarity reversal of tsunami waveforms recorded at far-field stations. However, Watada et al. (2014, JGR) proposed a phase correction method, which corrects the tsunami waveforms simulated by solving the linear shallow water equations into a dispersive waveform which accounts for the effects of elastic tsunami loadings on the Earth, compression of seawater, and gravitational potential change associated with tsunami propagation. With the phase correction method, we are able to use the waveforms recorded at far-field stations and attain more azimuthally complete result in waveform inversion.

We apply the phase correction method to synthetic linear long waves and use those phase-corrected far-field waveforms together with near-field waveforms in the inversion. We re-examined the result of 2011 Tohoku earthquake tsunami. Both single time window and multiple time window inversion are performed. The poor azimuthal coverage of near-field stations are replenished by far-field stations. Because the previous studies used abundant near-field (< 2 hour travelttime) data of 2011 Tohoku tsunami, effects of additional far-field stations is limited.

Fig. (a) Far-field stations (red dot) used in this research, reverse triangles are for near-field stations. (b) Inversion result of simultaneous movement after adding far-field stations.

Keywords: tsunami, inversion, far-field, DART, Tohoku tsunami



## Variation of the subduction structure along the Nansei-Shoto trench

\*Ryuta Arai<sup>1</sup>, Tsutomu Takahashi<sup>1</sup>, Shuichi Kodaira<sup>1</sup>, Seiichi Miura<sup>1</sup>, Yoshiyuki Kaneda<sup>2</sup>, Azusa Nishizawa<sup>3</sup>, Mitsuhiro Oikawa<sup>3</sup>

1.Japan Agency Marine-Earth Science and Technology, 2.Nagoya University, 3.Japan Coast Guard

The Nansei-Shoto subduction zone, extending 1,200 km from Kyushu to Taiwan, has been intensively examined in terms of seismic coupling along the plate boundary and tsunami potentials. On the contrary to other subduction zones nearby, the Nansei-Shoto subduction zone has lacked clear evidence of great megathrust earthquakes ( $M > 8$ ) for the last few hundred years and thus the overall interplate coupling is thought to be weak (Peterson and Seno, 1984). Correspondingly, slow slip events and very low frequency earthquakes are ubiquitously distributed in the forearc region (Nishimura, 2014; Nakamura and Sunagawa, 2015), supporting the idea that the plate interface is "weakly" coupled. One of the exceptional great earthquakes known in the history is the 1911 Kikai-jima earthquake ( $M 8.0$ ) in the northern part of the subduction zone at  $\sim 29^{\circ}\text{N}$  (Usami, 1996). Recent studies suggest that this earthquake may have been a shallow interplate event that accompanied a large tsunami (Goto, 2013). However, background subduction structure generating such an event in a weakly-coupled condition remains enigmatic.

In order to improve our understanding of the seismic potentials and the controlling factors of the seismogenic process in the Nansei-Shoto subduction zone, JAMSTEC has been working on the integrated seismic project that consists of two-dimensional active-source experiments and extensive passive observations. In 2015, multichannel seismic reflection data were collected along two lines that cross the potential source region of the 1911 Kikai-jima earthquake. Together with refraction/wide-angle reflection data obtained by Japan Coast Guard in the same area, we succeeded in imaging the structure of the subducting slab and the frontal wedge.

The most prominent structural feature we found is a  $\sim 100$ -km-wide low-velocity zone at the seaward edge of the overriding plate within which multiple landward-dipping reflectors are imaged. This structure is very similar to the accretionary prisms in the Nankai subduction zone and is in a great contrast with the non-accretionary frontal wedge (with less than 40 km width) in the southernmost part of the Nansei-Shoto subduction zone. This difference probably comes from the structural variation of the incoming plate and the amount of sediment supply into the trench: To the north lie a series of volcanic ridges of late Cretaceous to early Eocene ages (Amami Plateau, Daito Ridge and Oki-Daito Ridge), while the West Philippine basin to the south exhibits a deep seafloor with little amount of sediments on its top. Large bathymetric highs and volcanic products on the incoming plate may have contributed to produce the accretionary frontal wedge and anomalous earthquakes in the northern part of the Nansei-Shoto subduction zone.

Keywords: Megathrust earthquakes, Plate subduction, Active-source experiments

## Evidence for a fluid-rich layer beneath the Nankai Trough megathrust fault off the Kii Peninsula inferred from receiver function inversion

\*Takeshi Akuhara<sup>1</sup>, Kimihiro Mochizuki<sup>1</sup>

1. Earthquake Research Institute, the University of Tokyo

Exploring fluid distribution on megathrust faults is an important issue, since the fluid affects frictional property and thus slip behaviors on the faults. Scattered teleseismic phases, or receiver functions (RFs), have made significant contributions to understand the fluid content of the subducting plates. Most recently, we developed a technique to compute RFs using data from ocean-bottom seismometers (OBSs) with the removal of the water reverberations and produced RF image beneath the offshore region around the Kii Peninsula [Akuhara and Mochizuki, 2015, JGR]. The image roughly suggests that a low-velocity zone (LVZ) exists along the plate interface beneath the offshore region, at seismogenic zone depth.

In this study, we conducted RF inversion analysis to assess the property of the LVZ quantitatively. We employed relatively high-frequency range (<4 Hz) for the analysis to separate P-to-S conversion phases (our targets) from sediment-related reverberations. The inversion analysis aimed to determine 1-D velocity structures beneath each OBS deployed around the Kii Peninsula which can well explain observed RFs. This optimization was realized by neighborhood algorithm [Sambridge, 1999]. The results elucidate the presence of thin low-velocity zone (LVZ) beneath, or along, the plate interface. Its average thickness among the sites is 2 km, and the P- and S-wave velocities are 3 and 2 km/s, respectively. We consider that this LVZ reflects incoming sediment layer, the upper part of the oceanic crust, or the combination of the both. In any case, fluid-rich property is strongly expected from the extremely low velocities. So far, we conducted the inversion analysis at only 5 sites out of whole 32 sites within our OBS network. We still see, however, the systematic spatial change in the LVZ properties: both thickness and velocities of the LVZ tend to decrease toward the rupture area boundary between the 1944 Tonankai and 1946 Nankai earthquake. Further investigation into the other sites may offer more insight into how fluid controls slip behavior of megathrust earthquakes.

Keywords: subduction zone, receiver function

## Characterization of Nankai Seismogenic Fault by Applying Dynamic Wave Propagation Simulation to Digital Rock Models

\*Chandoeun ENG<sup>1</sup>, Tatsunori Ikeda<sup>1</sup>, Takeshi Tsuji<sup>1</sup>

1.Kyushu Univ.

In the Nankai Trough, the Philippine Sea plate is subducting beneath the Japanese Island at 4-6.5cm/s. The plate interface in the Nankai Trough is active seismogenic fault and causes massive earthquakes and tsunamis. However, the active seismogenic fault is too deep to drill through it. Thus, it is difficult to investigate its characteristic. To understand the characteristics of the deep active fault (i.e., plate interface), we use P- and S-wave velocities ( $V_p$ ,  $V_s$ ) of the digital rocks extracted from outcrop of ancient plate boundary fault at Nobeoka in Kyushu, southwest Japan. By comparing the elastic properties derived from digital rock with seismic velocity (e.g.,  $V_p/V_s$ ) acquired around the in situ seismogenic fault, we characterize the deep seismogenic fault. We extract 3D digital rock models with the size of 5mm x 5mm x 5mm from 3D micro-CT images. By using Finite Difference Method (FDM), we perform the dynamic wave propagation simulation and measure the effective  $V_p$ ,  $V_s$ , and ratio of P- and S-wave velocities ( $V_p/V_s$ ) of 3D digital rock models. Moreover, using this approach, we can identify the heterogeneity, which strongly influences to the seismic velocity. Here, we investigate the sensitivity of  $V_p$  and  $V_s$  to crack-filling materials. The heterogeneous texture, such as fracture or pore space was identified based on comparison of the density and porosity from digital rock model with the average of porosity from laboratory measurement. We can measure  $V_p$  and  $V_s$  for heterogeneity texture with any fracture-filling materials by replacing the pore space with dry, water saturated and mineral filling (quartz and calcite) conditions. The results demonstrated that the pore space in the dry and water saturated conditions significantly decreases velocity. The  $V_p/V_s$  ratio of water saturated case ( $V_p/V_s \sim 1.84$ ) is higher than dry condition ( $V_p/V_s \sim 1.75$ ). In the mineral-filling model (quartz and calcite), the P and S-waves travel faster than dry and water saturated conditions. This is because the bulk and shear modulus are increased in these mineral filling condition. The  $V_p/V_s$  of mineral-filling cases is lower than water saturated case, because S-wave cannot travel through the fluid which highly decreased in water fill pore case. Therefore, low  $V_p/V_s$  at coseismic region observed in the Nankai Trough region could be explained by the mineral filling of cracks.

Keywords: seismogenic fault, Nankai Trough, dynamic wave simulation, digital rock

## Improvement of 3D MCS data processing by advanced technology in Nankai trough

\*Kazuya Shiraishi<sup>1</sup>, Masataka Kinoshita<sup>2</sup>, Gregory Moore<sup>3</sup>, Yoshinori Sanada<sup>1</sup>, Yasuhiro Yamada<sup>1</sup>, Gaku Kimura<sup>4</sup>

1.Japan Agency for Marine-Earth Science and Technology, 2.Earthquake Research Institute,The University of Tokyo, 3.Department of Geology and Geophysics, University of Hawaii , 4.Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo

For the next stage of the deep scientific drilling in Nankai trough seismogenic zone, it is essential to know exactly shapes and depths of the mega-splay and the subducting oceanic plate, and fine structures in accreted sediments around the drilling site. Three dimensional multi-channel seismic (3D MCS) survey data were acquired in Kumano nada, and original data processing were also carried out in 2006. The 3D geometry of megasplay fault system in the Nankai trough subduction zone and detail structures in the frontal accretionary prism were revealed. However, any detail structures are not clear in the old accretionary prism between Kumano forearc basin and the megasplay fault, which are essential information for the successful deep drilling. The most difficult problem of the 3D seismic data is strong water-period surface related multiples which highly decrease the image quality. Especially in the deeper part than about 5 km, the resolution of the reflection image is very low with bandlimited signals by applying the specific processing to eliminate the multiples and noise with the technology of the day.

In order to obtain the clearer depth image for the next deep drilling target, reprocessing of the 3D data is highly required with advanced technology in a decade after the original data processing. There are three major scientific goals on the reprocessing of the 3D MCS data. First, 3D geometry and relationship between megasplay and plate interface beneath outer ridge, where multiples obscure clear imaging, to reveal whether decollement steps down to the plate interface or connects to the megasplay. Second, the fine scale imaging is required in the old accretionary prism beneath Kumano Basin. Distribution of faults, folds, or fractures, should be revealed to compare the seismic scale dipping structures to the nearly vertical fractures obtained at C0002 hole drilled by D/V Chikyu. Third, the reliability and the resolution of the velocity model should be improved to prove whether the low velocity zone (LVZ) in the outer wedge continue to that beneath the megasplay beneath Kumano Basin, and how much this velocity contrast contributes to the negative polarity in the megasplay fault.

The combination of the recent surface-related multiple elimination (SRME) and other noise attenuation techniques for better multiple attenuation, and broadband processing will contribute to enhancement of the deep reflection signals. Then, the sophisticated velocity model building to improve resolution and reliability, and the recent pre-stack migration method in depth domain with the updated data improve the depth image for mega-splay fault and the subducting plate. The advanced beam migration technique beyond the conventional Kirchhoff migration helps to image the steep dip fold and fault structures inside the old accretionary prism beneath the Kumano basin.

Keywords: Nankai trough, 3D MCS

Result of triaxial shear test on core sample taken in NanTroSEIZE Exp. 348: Implications for geomechanics analysis.

\*Takamitsu Sugihara<sup>1</sup>, Kan Aoike<sup>1</sup>, Takahiro Kawahara<sup>2</sup>, Koichi Hosoda<sup>2</sup>, Humihiro Mochida<sup>2</sup>, Yotsuo Kamidozono<sup>2</sup>

1.Center for deep earth exploration, Japan Agency for Marine-Science and Technology, 2.Core-Lab Testing Institute, OYO Corp.

In order to determine shear failure parameters of the Nankai accretionary prism sediments, triaxial shear test was conducted for core sample taken in the IODP Expedition 348. Core sample for the test was taken at 2183 mbsf in Hole C0002P and ~30 cm whole-round core sample was dedicated to the test. 5 plugs (~25 mm diameter and ~50 mm length) were sampled from the whole-round core. One plug (3R1-0) was used for test experiment to set up triaxial apparatus and 4 plugs (3R1-1, 3R1-2, 3R1-3 and 3R1-4) were applied to triaxial tests under different confining pressures. The triaxial test was conducted by using a triaxial test apparatus installed in Core Lab of OYO Corp. Effective confining pressures were 1 MPa (3R1-1), 2 MPa (3R1-2), 4 MPa (3R1-3), and 7 MPa (3R1-4). As the result, rock strength parameters (Cohesion, Internal friction angle and Unconfined compressional strength (UCS)) were determined as follows:

Cohesion: 1.8 MPa, Internal friction angle: 32.08 deg., UCS: 6.5 MPa.

The obtained UCS is obviously lower than those of the Kumano Basin sediments and typical basin formations. This observation indicates that rock strength of the Nankai accretionary prism would be weakened by deformation during accretion process. In this presentation, UCS-log Vp curve of the Nankai accretionary prism are presented and discussed its implication to geomechanical analysis for future NanTroSEIZE expedition.

Keywords: NanTroSEIZE, Triaxial shear test, Unconfined Compressional Strength, Geomechanics



## Submarine landslide on the hanging wall of mega-splay fault, Kumano-nada, Nankai Trough

\*Toshiya Kanamatsu<sup>1</sup>, Juichiro Ashi<sup>2</sup>, Ken Ikehara<sup>3</sup>, KH-15-2 Leg3 scientific party

1.Japan Agency for Marine-Earth Science and Technology, 2.Atmosphere and Ocean Research Institute, The University of Tokyo, 3.Institute of Geology and Geoinformation, National Institute of Advanced Industrial Science and Technology

Submarine landslide in the Kumanonada splay fault, Nankai Trough, southwest Japan were explored by Navigable Sampling System (NSS), Atmosphere and Ocean Research Institute, the University of Tokyo. A sedimentary sequence in the area was cored by IODP Expedition 333 in advance as the "Nankai Trough Submarine Landslides History". The Pleistocene to Holocene sequence of stacked mass-transport deposits was recovered at Site C0018, located within a slope basin on the footwall of the mega-splay fault. Six mass-transport deposit (MTD) units intercalated with coherent intervals were recovered within 1Ma. Although the MTD occurrences were regarded to have been induced by the past Nankai earthquake events, the found frequency of MTDs is absolutely lower than that of To-nankai and Nankai earthquake as every 100-200 year intervals during the historical times. This discrepancy indicates that our understanding on the collapsing induced by the mega-splay faulting is not enough. In order to have well documentations on the relationship between the mega-splay fault and MTDs, we implemented a sub-bottom imaging around the mega-splay fault using NSS. We recovered the image which shows that a 20-m thick sediment layer slid down about 50-m high on the hanging wall of mega-splay fault. Also the image shows that the small depression formed by this sliding was aggraded by fill deposits after the event. If those events were corresponding to a mega-splay faulting in a time, the record will be a proxy to shows the timing of mega-splay faulting in past. And the dimension interpreted from obtained image is useful to assess the risk of hazard induced by mega-splay faulting. We will discuss the scenario of this collapse using data acquired during the cruise.

Keywords: Submarine landslide, meag-splay fault, Nanki Trough, Navigable Sampling System

## Strength and mechanical behavior of the Nankai accretionary prism sediments from NanTroSEIZE Expedition 348

\*Manami Kitamura<sup>1</sup>, Takehiro Hirose<sup>2</sup>

1.Hiroshima University, 2.Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology

Physical properties of rocks are generally examined by compression or extension experiments in laboratory (e.g., Paterson and Wong, 2005). For these laboratory experiments, cylindrical rock specimens with diameter and length >20 mm are commonly used. However, in ocean drilling, in particular deep riser drilling, core samples that can be used for the experiments are often collected from limited depth. Thus it is quite difficult to know continuous physical property along the drilling hole from geological materials. Hence, we have developed a potential method using an indentation test for the estimation of strength and Young's modulus of rocks from drilling cuttings recovered during riser drilling operation. In this study we conducted the spherical indentation tests as well as conventional uniaxial compression tests on four rocks types with different porosities under room temperature and pressure conditions. As a result, we found an exponential correlation between the Young's modulus obtained by uniaxial test and indentation test, and a linear correlation between strength obtained by those tests.

We adapted this method to investigate the depth profile of mechanical property along Holes C0002N and C0002P, the Nankai accretionary prism. We conducted spherical indentation experiments on the hand-picked intact cuttings retrieved from 870 to 3058 meters below seafloor (mbsf) at Site C0002. We used a spherical sapphire indenter with a diameter of 4 mm to deform the cuttings sample of >2mm thickness saturated with brine at room temperature and pressure conditions with a constant loading/unloading rate of 0.5 N/sec and maximum load of 100 N. Using the correlations mentioned above and assuming internal friction value that may be correlated with porosity, we estimated in-situ Young's modulus and strength of the sediments at Site C0002. The Young's modulus increases from ~0.5 GPa at 870 mbsf to ~2.2 GPa at 2000 mbsf, then it becomes nearly constant at ~2.2 GPa below 2000 mbsf. The failure strength under in-situ pressure condition increases with depth from a few MPa at 870 mbsf to ~70 MPa at 3000 mbsf. The results of the failure strength are consistent with that obtained by triaxial compression tests on discrete core samples collected from ~2200 mbsf under in-situ pressure and temperature conditions. The result indicates the possibility that strength of sediments which is commonly determined by triaxial experiment can be reasonably estimated from drill cuttings using a spherical indentation test.

Keywords: Accretionary prism, Indentation test, IODP, Expedition 348

## Tectonic stress of the upper-plate crust above the Tonankai seismogenic zone

\*Arito Sakaguchi<sup>1,2</sup>, Miki Inoue<sup>1</sup>, Yuya Komine<sup>1</sup>, Weiren Lin<sup>2</sup>, Osamu Tadai<sup>3</sup>, Kentaro Hatakeda<sup>3</sup>, Asuka Yamaguchi<sup>4</sup>

1.Yamaguchi Univ., 2.JAMSTEC, 3.Marine Works Japan LTD., 4.AORI, Univ. of Tokyo

The crustal physical property is necessary information to understand the seismogenic mechanism. Soft sediment changes to hard rock to be the seismogenic material during plate subduction. In this process, strength is the most developing property than the other of the porosity, bulk density, elastic wave velocity and etc. The sediment lithification depends on the stress due to strain hardening, and the strength of the sediment products us the stress condition in the plate subduction zone.

IODP Exp.338 took samples from 1000 mbsf to 2000 mbsf above the seismogenic zone of the Tonankai earthquake of 1944 ( $M_w=8.0$ ) during Nankai Trough Seismogenic Zone Drilling Project (Moore et al., 2013). Because the riser-drilling, the cutting-sample were taken in all section differ from the core samples. These cutting-samples have the potential to make the strength profile of upper plate in the subduction zone. We develop new method to estimate the rock strength using the needle penetrator that applicable for small cuttings-sample. Since the needle penetration makes the Mode I crack, the obtained strength concerns with cohesion of the rock. This needle-penetration strength was compared with uniaxial compression strength using various strength samples of mortar and natural sandstones.

In the result, higher cohesive samples were obtained at deeper section at site C0002. The cohesion gradient increases suddenly at the boundary between the Kumano basin and the accretionary prism. The accretionary sediment may suffer tectonic stress, and high cohesion gradient can be explained by increasing tectonic stress with depth. In case of frictional sliding, shear stress within upper plate increases with depth above the asperity. The cohesion curve may show upper plate stress field in the seismogenic zone.

Keywords: subduction earthquakes, IODP, physical property

## Frictional properties of the Northern Shimanto Belt rocks at a seismogenic pressure and temperature condition

\*Kosuke Abe<sup>2</sup>, Koki Hoshino<sup>1</sup>, Michiyo Sawai<sup>1</sup>, Kyuichi Kanagawa<sup>1</sup>

1.Graduate School of Science, Chiba University, 2.Faculty of Science, Chiba University

We conducted triaxial friction experiments on the Northern Shimanto Belt rocks exhumed from the seismogenic zone, at an effective confining pressure of 75 MPa and a temperature of 150°C, and at axial displacement rates ( $V_{axial}$ ) changed stepwise among 0.1, 1 and 10  $\mu\text{m/s}$ , in order to investigate their frictional properties at a seismogenic condition. Tested samples are sandstone, mudstone and chert from the Yokonami *mélange*, basalt from the Kure *mélange*, and sandstone and mudstone from the Nonokawa Formation, all collected in central Shikoku Island. XRD analyses of tested samples revealed that the content of total clay minerals is 15.1 wt%, 11.8 wt% and 0 wt%, respectively in the Yokonami *mélange* sandstone, mudstone and chert, 1.9 wt% in the Kure *mélange* basalt, 16.3 wt% and 32.9 wt%, respectively in the Nonokawa sandstone and mudstone.

Friction experiments of tested samples revealed that the steady-state friction coefficient ( $\mu_{ss}$ ) decreases with increasing content of total clay minerals, except for the Nonokawa sandstone with a relatively high  $\mu_{ss}$  of 0.62 in spite of its moderate content of total clay minerals.  $\mu_{ss}$  at  $V_{axial} = 1 \mu\text{m/s}$  is 0.65 for the Yokonami *mélange* chert, 0.63 for the Kure *mélange* basalt, 0.52 for the Yokonami *mélange* mudstone, 0.50 for the Nonokawa sandstone, and 0.37 for the Nonokawa mudstone. The Yokonami *mélange* chert without clay minerals and the Nonokawa mudstone with 32.9 wt% clay minerals exhibited an increase in  $\mu_{ss}$  when  $V_{axial}$  was increased and vice versa, i.e., velocity strengthening. Microstructures of these samples after experiments show that deformation is distributed within the gouge layer. In contrast, other samples with 1.9-16.3 wt% clay minerals exhibited a decrease in  $\mu_{ss}$  when  $V_{axial}$  was increased and vice versa, i.e., velocity weakening. Microstructures of these samples after experiments show that deformation is localized along a continuous slip surface. Experimental conditions suggest that dissolution-precipitation processes are possibly responsible for such change in velocity dependence of friction according to the content of clay minerals.

Our results suggest that seismogenic faulting would occur in rocks with 2-20 wt% clay minerals, but not in rocks without or rich in clay minerals, provided that other conditions are the same.

Keywords: friction, Northern Shimanto Belt, seismogenic condition

## Faulting-promoted illitization along the megasplay fault in the Nankai Trough

\*Hirokazu Masumoto<sup>1</sup>, Jun Kameda<sup>1</sup>, Yohei Hamada<sup>2</sup>, Yujin Kitamura<sup>3</sup>

1.Graduate School of Science, Hokkaido University, 2.Japan Agency for Marine-Earth Science and Technology Kochi Institute for Core Sample Research, 3.Department of Earth and Environmental Sciences, Graduate School of Science and Engineering, Kagoshima University

The transformation of smectite to illite is thought to have important role on faulting because illitization can change friction strength and produce fluid overpressure by dehydration reaction. We performed X-ray diffraction analyses of sediment samples around the megasplay fault in the Nankai accretionary prism, recovered from Integrated Ocean Drilling Program (IODP) Expedition 316 Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE). Quantitative analysis of the illite fraction in illite-smectite mixed layers (I-S) crystallites shows that the dark gouge has ~10% more illite content than that in the host rock. If applying a kinetic expression obtained under a static condition from the previous works, the observed mineralogical anomaly requires an event of frictional heating that have caused temperature rise to an extraordinarily high level around the dark gouge. We combined data from XRD analyses with modified kinetic simulations of illitization to quantify effect of mechanochemical processes. As a result, if we applied an activation energy ~30% lower than the value from the previous works, illitization can be reasonably explained by frictional heating. These results suggest that seismic slip helped to overcome kinetic barrier due to mechanochemical processes in the fault zone.

Keywords: Subduction zone, Fault gouge, Frictional heating

## Determination of slip parameters of subduction earthquake by using multiple analyses of carbonaceous materials

\*Shunya Kaneki<sup>1</sup>, Tetsuro Hirono<sup>1</sup>, Hideki Mukoyoshi<sup>2</sup>, Yoshikazu Sampei<sup>2</sup>, Minoru Ikehara<sup>3</sup>

1. Graduate School of Science, Osaka University, 2. Interdisciplinary Graduate School of Science and Engineering, Shimane University, 3. Center for Advanced Marine Core Research, Kochi University

Megasplay faults branching from megathrusts could play an important role in faulting systems in the plate-subduction zone. Because not only subduction megathrust but also megasplay faults could slip during an earthquake, possibly generating gigatic tsunami.

For understanding the slip behavior of these faults, maximum temperature recorded is one of the keys to estimate the slip parameters such as shear stress and displacement of the earthquake. Here we develop new multiple analyses to detect the heat signal recorded in the carbonaceous materials by performing heating experiments, spectroscopic analyses (IR and Raman), and chemical composition analysis (CHNSO element analysis). We targeted the carbonaceous materials retrieved from an ancient megasplay fault developed in the late Cretaceous Shimanto accretionary prism, southwest Japan.

Our results revealed that the fault zone had experienced 400-600 °C. By performing numerical temperature calculation, we found that any case of the earthquake events always accompany a slip displacement of  $\leq 10$  m, suggesting that several hundreds of events repeatedly took place.

Keywords: carbonaceous materials, frictional heat, spectrometry, elemental analysis, slip parameters

## The thermal structure and formation process of faults in Akehama area of the Northern Shimanto Belt, western Shikoku, Japan

Moe Kuroki<sup>2</sup>, \*Kiyokazu Oohashi<sup>1</sup>

1.Graduate School of Science and Engineering, Yamaguchi University, 2.Faculty of Science, Yamaguchi University

The Shimanto Belt is composed mainly of accretionary complexes, which is formed due to the subduction of the oceanic plate (Taira et al., 1980). In the eastern Kyushu and central to eastern part of Shikoku, melange zones and accompanying strong deformation zones, such as brittle faults with pseudotachylyte are documented (e.g., Taira et al., 1988, Mukoyoshi et al., 2006). These brittle deformation zones are considered to record the long-term and short-term deformation processes in subduction zone. Such a fault analysis and a thermal structure analysis are mainly carried out in the above areas, and seldom in western Shikoku. Oohashi and Kanagawa (2014) reported a distribution of brittle fault zones and mélangé zones, regional geologic structure, and paleothermal structure of the Shimanto belt along the western coastline of Shikoku Island. Here we report the results of deformation mapping, paleostress analysis, and vitrinite reflectance measurement on and around the brittle fault zones developed in Akehama area of the Northern Shimanto Belt.

In the study area, the fault zones are developed in coherent unit comprised of sandstone, mudstone and alternations of sandstone/mudstone. The fault zones typically has a cataclasite zone of a few to tens of cm and fracture zone of a few tens to hundred of cm in width. On the other hand, soft-sediment deformations are rarely found. These faults strike east-west and dip to north, and the average rake angle of the striations are 32 °from west. Kinematic indicators such as composite planar fabrics or slickenside topography show dextral sense of shear with reverse-slip component. Using the fault-slip data obtained in the area, we conducted a stress tensor inversion to estimate paleostress directions. The result indicates NW-SE direction for the maximum principal stress,  $\sigma_1$ , and NE-SW direction for the minimum principal stress,  $\sigma_3$ .  $\sigma_1$  axes gently to moderately plunge whereas  $\sigma_3$  axes generally shows subhorizontal. Although those faults has reverse-slip component, the vitrinite reflectance does not show significant difference across the fault zones ( $\Delta R_m = 0.18\%$  in maximum). The absence of thermal gap across the thrust fault suggests that the faulting proceeded prior to the formation of thermal structure, which may be conducted during subduction. We thus conclude that the fault zones were developed at the relatively early stage of the subduction (frontal to middle part of the accretionary prism). Our results suggest that the oblique-slip fault (non-andersonian fault) was formed during the early to middle stage of the subduction. This finding might become important when we look at ongoing subduction process through ocean drilling programs. [Acknowledgements]

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Keywords: Subduction zone, Northern Shimanto Belt, Vitrinite reflectance, Paleostress analysis, Oblique-slip faults

## Variable chemical composition of the Nobeoka thrust fault core in Shimanto Belt, Kyusyu

\*Rina Fukuchi<sup>1,2</sup>, Asuka Yamaguchi<sup>1</sup>, Jun Kameda<sup>4</sup>, Gaku Kimura<sup>3</sup>, Juichiro Ashi<sup>1,2</sup>

1.Atmosphere and Ocean Research Institute, The University of Tokyo, 2.Graduate School of Frontier Sciences, The University of Tokyo, 3.Department of Earth and Planetary Science of the Graduate School of Science, The University of Tokyo, 4.Earth and Planetary System Science Department of Natural History Sciences, Graduate School of Science, Hokkaido University

The Nobeoka thrust in Kyushu is a tectonic boundary thrust in the Shimanto Belt, Cretaceous–Miocene accretionary complex in Southwest Japan. The Nobeoka thrust is presumed to be a fossilized megasplay fault which was branched from plate boundary fault (Kondo et al., 2005), and represents multiple deformations at seismogenic depths (~ 10 km below sea floor) (Kondo et al., 2005). Kondo et al. (2005) described lithology and macroscopic/microscopic structure of hanging wall, footwall, and the fault core. Fukuchi et al. (2014) showed mineralogical features across the fault zone based on X-ray Diffraction (XRD) analysis. However, Fukuchi et al. (2014) mainly focused on the illite crystallinity of the hanging wall side, and detail description on mineralogical/geochemical features of the fault core is still to be investigated. Therefore, this study was designed to determine chemical/mineralogical features of the fault core of the Nobeoka thrust. For this purpose, we performed elemental mapping on polished slab-shape samples retrieved the outcrop of the fault core of the Nobeoka thrust by using X-ray fluorescence (XRF) core scanner installed at Kochi Core Center (KCC).

Analyzed sample contains hanging wall, footwall, and ~15 cm-thick fault core. The fault core is bounded from both hanging- and footwall by ~3 mm-thick dark zones. Compared with the wall rocks, the dark boundaries and matrix of the fault core are enriched in Al, K, Ti, Mn, Fe and Mg, and depleted in Si, P, and S. My observation implies the following: (1) matrix of the fault core and the dark boundaries between the fault core and hanging-/footwall correspond with the enrichment of white mica and/or chlorite; (2) Depletion of S would reflect dissolution of pyrite and/or gypsum, suggesting the existence of oxidative fluid within the fault core.

Keywords: Nobeoka thrust, XRF core scanner



## Mesoscale structures of a large shear zone developed within pelagic siliceous sediments

\*Asuka Yamaguchi<sup>1</sup>, Rina Fukuchi<sup>1</sup>, Mari Hamahashi<sup>2</sup>, Mayuko Shimizu<sup>3</sup>, Taiga Eguchi<sup>4</sup>, Kyuichi Kanagawa<sup>4</sup>

1.Atmosphere and Ocean Research Institute, The University of Tokyo, 2.Department of Earth and Planetary Science, Graduate School of Science, the University of Tokyo, 3.Tono Geoscience Center, Japan Atomic Energy Agency, 4.Department of Earth Sciences, Faculty of Science, Chiba University

Subduction zones where old oceanic plate underthrust are characterized by thick pelagic incoming sediments originating from diatomaceous/radiolarian oozes. For a better understanding of deformations along plate boundary megathrust in such a setting, we investigate the Ohwaki outcrop in the Mino Belt, which represents a shear zone of a master floor thrust of imbricated thrust sheets composed of cherts and clastic rocks.

The occurrence of the shear zone was presented by geologic mapping based on aerial photographs taken by an unmanned aerial vehicle (UAV). A ~50-m-thick cataclastic shear zone composed of early Triassic carbonaceous black shale matrix including angular blocks of bedded/massive chert, siliceous mudstone, and shale with sandstone blocks bounds early-middle Triassic pelagic rocks and middle Jurassic terrigenous rocks. In contrast to the disrupted and cataclastic deformation of carbonaceous black shale within the shear zone, hanging wall strata of thick bedded/massive chert only exhibits early-stage ductile asymmetric folds.

Stratigraphically controlled occurrence of the shear zone is analogous to the plate boundary fault in the Japan Trench drilled by IODP Expedition 343 and in-sequence thrusts of imbricated chert-clastics sequence in the Inuyama area, in terms of shear localization to weak horizon within pelagic sediments. However, total thickness of the shear zone observed in the Ohwaki outcrop is one order larger than other strata-bound fault zones. Occurrence of a thick shear zone with angular blocks of host rocks would be likely to reflect shear zone thickening caused by strain hardening due to post-failure fluid discharge and hydrofracturing maintained by fluid overpressure. It is speculated that low permeability of lithified chert ( $10^{-19}$  to  $10^{-21}$  m<sup>2</sup>) would contribute to fluid pressure fluctuation in large shear zones within pelagic sediments.