Accelerated nucleation of the 2014 Iquique, Chile Mw 8.2 Earthquake

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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

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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 $\mu m s^{-1}$ to 1 $m s^{-1}$ 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 –1 cm/s –and high velocity –1 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

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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

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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 ±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 mWm^{-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 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 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 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 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

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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-

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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 sesimogenic rupture zones.

Seafloor geodetic approach for the Nankai Trough megathrust source region

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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 preforming 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.

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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

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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 as less than the vertical stress defined by the overburden (Shmin = S_3), and define a nearly linear gradient in Shmin 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: Sv' = 33 MPa; SHmax' = 25-36 MPa; and Shmin' = 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

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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

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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 μm/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 (μ_{ss}) has a negative correlation with the content of total clay minerals. μ_{ss} at V_{axial} = 1 μm/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 μ_{ss} when V_{axial} was increased and vice versa, i.e., velocity strengthening, a few deeper samples exhibited a decrease in μ_{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 (≤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

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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 Vp/Vs 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

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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 form 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 examin if similar structural characters are observed.

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

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

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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

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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 x 10^{10} N/m^2, the seismic moment is 1.6 x 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

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The March 2011 Tohoku-oki earthquake was only the second giant (M_w ≥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 ~150-200 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 ≥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 ≥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

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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

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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

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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

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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 positon 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 ~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 (~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 well 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: postseimic 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

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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

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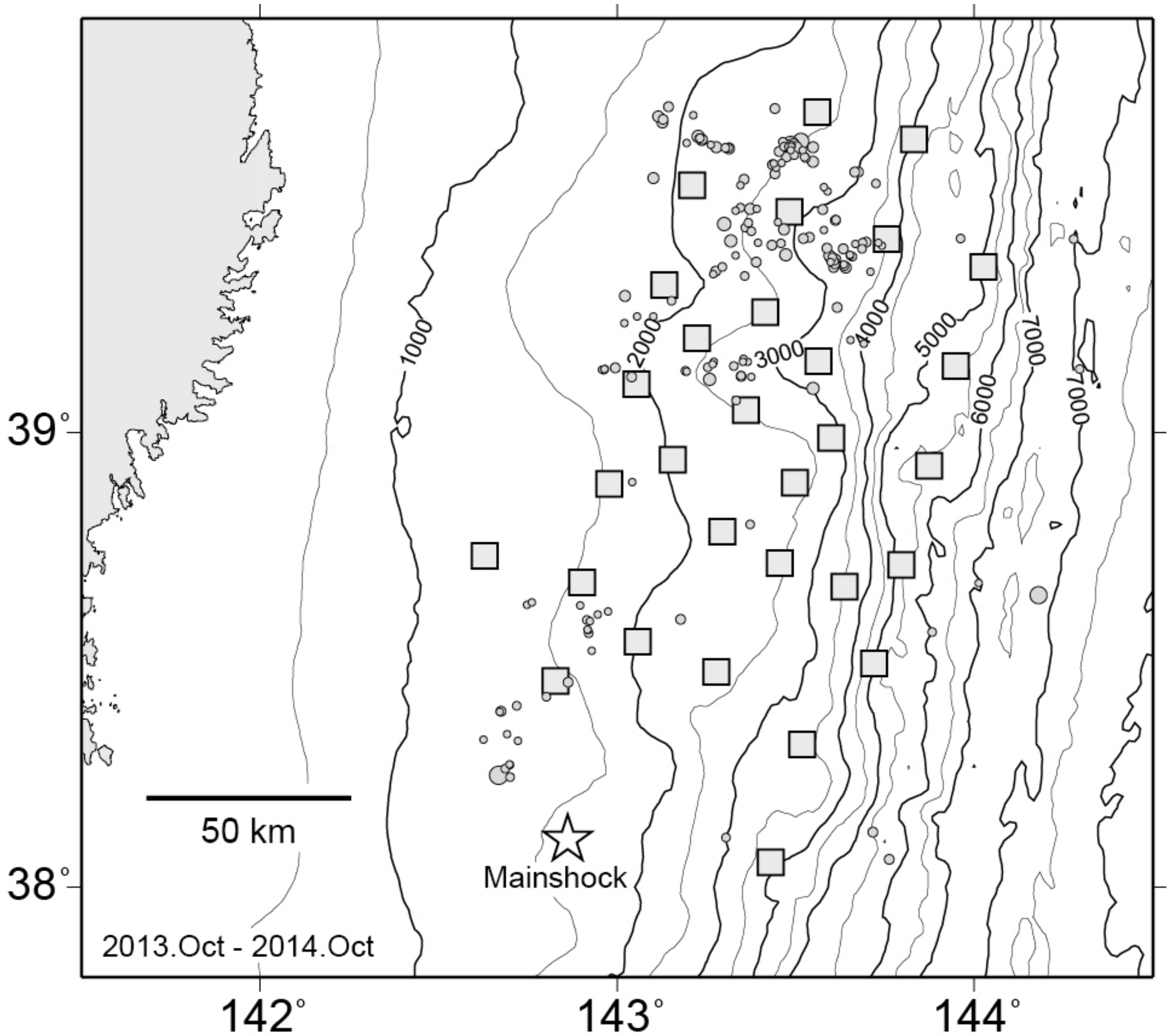
The 2011 off the Pacific coast of Tohoku earthquake occurred at the plate boundary between the Pacific plate and the landward plate on March 11, 2011, and many aftershocks followed the mainshock. To obtain a precise aftershock distribution is important for understanding of mechanism of the earthquake 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

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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