

2014年チリ北部イキケ地震(Mw8.2)発生前に見られた加速的な滑り

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 $10 \mu\text{ms}^{-1}$ to 1ms^{-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

コスタリカ沖前弧ウェッジの固結を支配する隆起過程と沸石沈殿

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 $\sim 10\text{-}30^\circ$, 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 $\sim 1.71\pm 0.24$ 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.

キーワード：沈み込み帯、コスタリカ沖中米海溝、岩石物性

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 $\pm 5\%$.

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 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 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

大時空間スケールから見た地震発生沈み込み帯のテクトニックな枠組み—南海トラフの例

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-NantoproSEIZE 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.

南海トラフ巨大地震震源域への海底地殻変動観測によるアプローチ

Seafloor geodetic approach for the Nankai Trough megathrust source region

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南海トラフ巨大地震の震源域の大部分は海底にあるため、これまでの陸域観測では固着の状態を十分に把握することは困難であった。近年、海上保安庁海洋情報部で実施している海底地殻変動観測によって、 ± 1 cm/year程度の精度で海底の移動速度が決定されることで、固着状態についても理解し得る状況となってきている。南海トラフ海域では、東北沖地震前から配置されている点を含めて、15点の観測点が配置されている。これらの観測点は年2~3回程度の頻度で観測されている。観測データは東北沖地震の本震と余効変動の影響を受けているため、Iinuma et al. [2012, JGR] の震源モデルとSun et al. [2014, Nature] を修正したSun and Wang [2015, JGR] の余効変動モデル（余効すべり+粘弾性緩和）を用いた計算量によって補正を行った。我々は補正されたデータから、ロバスト推定によって移動速度を導出した。結果として2.0~5.5 cm/yearの移動速度が得られた。

これらの結果から想定される固着の強い領域は、沈み込む海山の分布 [Kodaira et al., 2000, Scienceなど] と相補的であった。また、特にその周辺で発生しているVLFEの分布域 [Asano et al., 2008, EPSなど] と弱固着域は高い相関があることが示唆された。ただし、現在の観測網は巨大津波発生域として想定されているトラフ際には観測点がなく、まだ最浅部の議論を行うことはできない。

これらは、過去4~9年間の観測結果であるため、長期的な地殻変動量の変化を考察するにはデータが不足しており、今後も観測を継続する計画である。また、スロースリップ現象による変動量を分離するためには観測頻度・精度が不足している。この発表では、解析的なアプローチや技術開発による精度向上についても紹介する。

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キーワード: 海底地殻変動観測、南海トラフ、海溝型巨大地震

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

南海トラフ地震発生帯の海底孔内観測所で見つけた浅部短期的スロースリップ現象の可能性
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.

キーワード：南海トラフ、スロースリップ、孔内観測

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 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

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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

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 $\mu\text{m/s}$, 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 (μ_{ss}) has a negative correlation with the content of total clay minerals. μ_{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 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.

キーワード : friction, mudstone, accretionary prism, Nankai Trough

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 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

地下構造探査で探る日本海溝アウターライズから海溝軸にかけての断層運動

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 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.

キーワード：日本海溝、地震探査、沈み込み帯、アウターライズ

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

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

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.

キーワード: trench outer-rise, intra-plate normal faulting earthquake

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

日本海溝北部における1896年三陸津波地震と2011年東北地方太平洋沖地震のすべり分布
The slip distributions of the 1896 Sanriku and 2011 Tohoku earthquakes along the northern
Japan Trench

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1896年明治三陸地震は、地震波に比べて異常に大きな津波を発生した、典型的な津波地震である。2011年東北地方太平洋沖地震の際、津波波源は日本海溝沿いに北方へ延び、ここでは地震発生から3分程度遅れて津波が発生した。明治三陸津波地震の波源はさらに北方の海溝軸付近に位置している。1896年と2011年の津波を比較すると、三陸海岸北部・中部での津波高さはほとんど同じであるのに対し、やや離れた検潮所（花咲、鮎川、銚子）で記録された津波波形の振幅は、2011年の方が数倍以上大きい。津波波形から求めた2011年のすべり分布（日本海溝北部のみ）から1896年の津波を計算すると、三陸海岸での津波高さは再現できるが、検潮所での津波波形は1896年の実測に比べてずっと大きくなる。三陸海岸での津波高さ、宮古での津波到達時間、さらに検潮所での津波波形をすべて説明できるのは、長さ200km、幅50kmの断層面（平均すべり量は8 m）で、20 mの大すべり域（100km x 25 km）があるというモデルである。剛性率を20 GPaと仮定すると、地震モーメントは 1.6×10^{21} Nm、モーメントマグニチュードはMw 8.1となる。1896年の大すべり域（深さ 3.5 -7 km）では2011年のすべりは3 -14 mと小さく、その海溝軸側の浅い部分（0 -3.5 km）では、1896年のすべりは3 mだったが、2011年のすべりは20 -36 mと大きかった。すなわち、日本海溝北部では1896年と2011年のすべりは相補的で、1896年津波地震の方がより深い部分に大すべり域があった。

キーワード：1896年明治三陸津波地震、2011年東北地方太平洋沖地震、津波

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 ($M_w \geq 9.0$) 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.

掘削トルクデータから求めた日本海溝沈み込み帯の高速摩擦強度断面

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.

キーワード：摩擦強度、掘削トルク、東北地方太平洋沖地震調査掘削

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

雑微動データにS波スプリッティング解析を適用して推定された2011年東北地方太平洋沖地震における東日本の応力場の時空間変化

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.

キーワード：時間変化、雑微動、S波スプリッティング、東北沖地震、応力状態

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

GPS音響結合観測より示唆される2011年東北沖地震に伴う余効変動の空間的特徴

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 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 ~ 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 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.

キーワード：余効変動、2011年東北沖地震、GPS音響結合方式、海底測地観測

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

海底地震観測データから見る2011年東北沖地震震源域における地震発生前後のb値の時空間変化—地震後—

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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キーワード : b-value、 the 2011 Tohoku earthquake、 OBS data、 back projection

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

長期観測型海底地震計を用いた2011年東北沖地震震源域北部における地震観測

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

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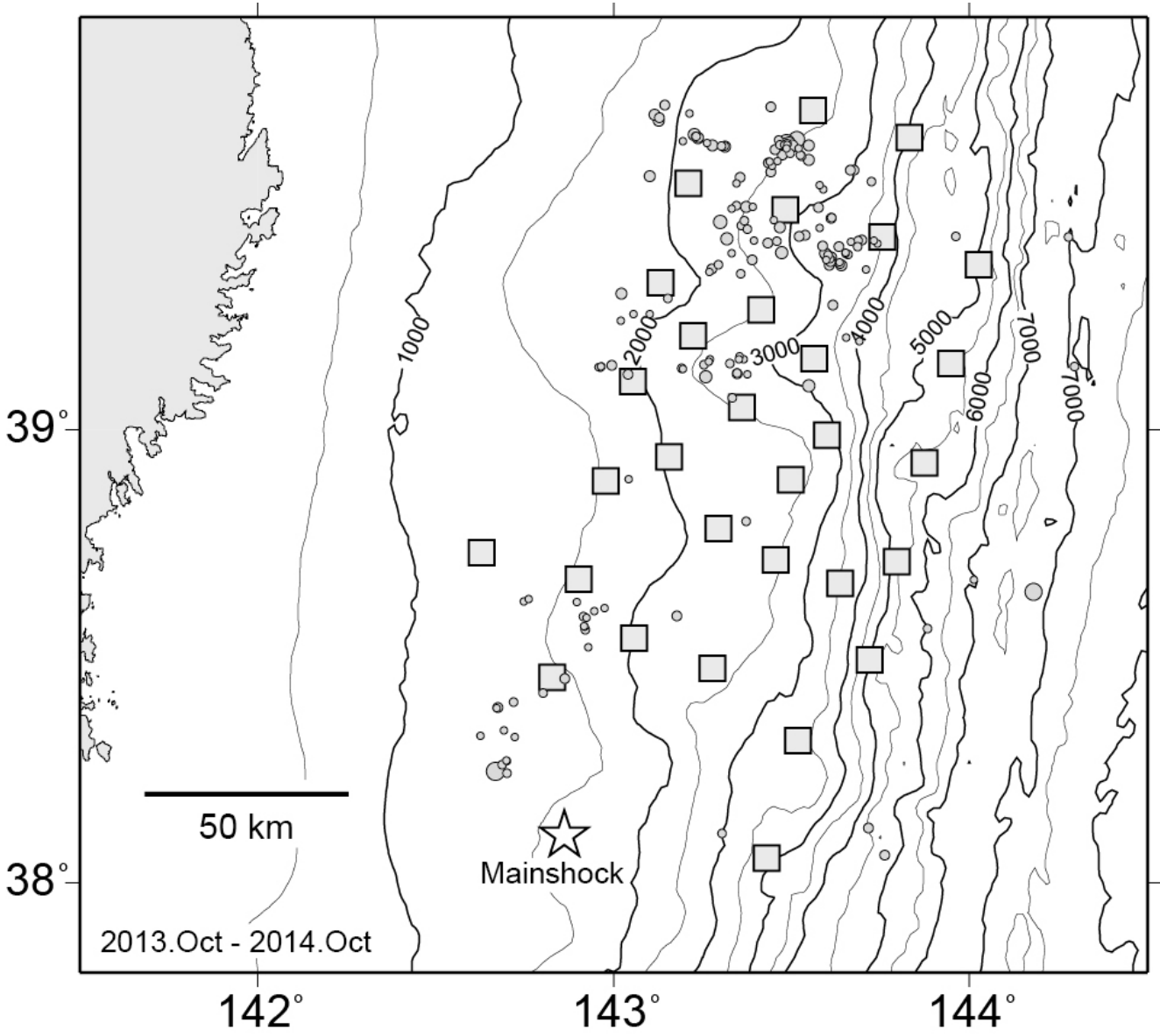
2011年3月11日東北地方太平洋沖地震が、太平洋プレートと陸側プレートのプレート境界で発生し、本震後に多数の余震が発生した。この巨大地震の発生を考える上において、正確な余震分布は重要な情報である。そこで、本震直後から、100台を超える海底地震計を用いた余震観測が開始され、2011年9月まで実施された。海底地震観測網は、震源域全体に渡って、約25km間隔で展開された。その後、気象庁一元化震源カタログから、震源域で発生したと思われる余震を選別して、海底地震計データからP波、S波の到着時刻が読み取られ、1次元構造に基づく震源決定が行われた。その際、海底地震計直下の地震波速度が遅い堆積層の影響を取り除くために、観測点補正值も考慮された。この緊急余震観測の結果、本震後約3ヶ月間の正確な余震の震源分布が求められた (Shinohara et al., 2011, 2012)。過去に行われた構造探査実験の結果と比較したところ、もっとも大きい地震時滑りが推定された宮城沖のプレート境界において、余震がほとんど発生していないことがわかった。震源域上の陸側プレート内では、多数の余震が発生しており、正断層型または横ずれ型の震源解を持つものが多い。海洋プレート内においても、同様の傾向であった。緊急海底地震観測後の2011年9月に、震源域における地震活動のモニタリングのために、長期観測型海底地震計40台が震源域全域にわたって設置され、2012年11月に回収された。この1年間の連続データを用いて、緊急余震観測と同様の手順で、震源決定がなされた。余震数は時間と共に減少していたが、震源域北部では、地震発生位置には、大きな変化がなかった。陸側プレート内での余震活動は引き続き活発であり、震源解は正断層型または横ずれ型を持つものが多い傾向も同様である。本震の前には、北部震源域下のマントル内で地震活動が確認されていたが、本震後はほとんど地震が発生していない。

地震活動の時空間変化を調べるために、2013年10月に、岩手県沖の震源域北部に、30台の長期観測型海底地震計を再度設置した。この海底地震計は、速度型3成分地震計を持ち、1年間の連続観測が可能である。海底地震計は、2014年9月または10月に回収された。データ処理については、これまでの震源決定と同様の方法を用いて、実施した。ここでは、2013年から2014年にかけて得られたデータを用いて、震源域北部における地震活動の時空間変化を報告する。予察的な結果では、岩手県沖の領域では、本震直後と比べて、地震活動様式が変化した可能性が示唆される。

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キーワード：平成23年東北地方太平洋沖地震、長期観測型海底地震計、地震活動の時空間変化

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



人工震源構造調査で明らかとなった、2011年東北地震北限域における地震前後のプレート境界反射波振幅の変化

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.

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キーワード：東北地方太平洋沖地震、反射波振幅、人工震源海域構造調査

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

精密音響測距による日本海溝を挟んだ相対運動の検出

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

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2011年東北地方太平洋沖地震（東北沖地震）では、50 mを超える地震時すべりが発生したと報告されている（例えば、Iinuma et al., 2012, JGR). 東北沖では、東北沖地震後、精力的にGPS/音響結合方式（以下、GPS/A）による地殻変動観測が実施されており、Tomita et al. (2015, GRL) では計測された太平洋プレート加速はSun et al. (2014, Nature) がモデル計算で示した粘弾性緩和の寄与で説明可能としている。一方、GPS/A観測のみではプレート境界の局所的な変形様式の詳細は不明である。そこで、我々は、2014年9月～2015年5月の8ヶ月間、海底間音響測距観測を実施した。海底間音響測距は、プレート間を挟んで機器を設置することにより、連続的かつ精密に地殻変動が検出できる。本観測に先立って行われた予備観測では、1 cm/yrの精度で相対速度を検出できることが示されている（長田・他、2014, JpGU).

本観測では、宮城県沖の日本海溝軸を挟むように3台の機器を設置し、2基線の変位検出を試みた。基線長はそれぞれ約7 kmと10 kmで、4時間毎に音波の送受信を行った。音波の往復走時と精密な音速との積をとることにより、相対距離を検出できる。精密音速は温度、圧力、塩分に依存するため、音波収録と併行して、温度計測も実施した。圧力は理論潮汐NAO.99Jb (Matsumoto et al., 2000, J. Oceanogr.) を使用、塩分濃度は深海底の安定した環境であることから定数とした。なお、精度に関しては、両基線とも2 cm/yr以内であり、予備観測とほぼ同様であった。

約8ヶ月間の測距データを解析したところ、観測精度内の有意な変位は認められず、グローバルモデルによる日本海溝のプレート収束速度（約8 cm/yr）に相当する変形は海溝軸に局在化して存在しないことがわかった。従って、宮城県沖の海溝付近では、少なくとも現在は余効すべりが無く、再固着していると推測される。

2015年9月には、同海域に新たに5台の機器を設置し、約2年間の予定で観測中である。更に、余効すべりが著しいとされる福島県沖（Sun and Wang, 2015, JGR）にも新たに観測点を追加する計画も進行中である。これら新たなデータとも統合し、より精密な日本海溝のプレート相対速度の検出が期待される。

キーワード：海底間音響測距、東北地方太平洋沖地震、日本海溝、余効すべり、海底測地

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

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

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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.

キーワード：日本海溝、反射法探査

Keywords: Japan Trench, reflection seismic survey

日本海溝における単独観測点法を用いた低周波微動の検出

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

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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.

宮城県沖日本海溝浅部における海底地震計アレイ観測

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

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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).

キーワード：日本海溝、スロー地震、微動、海底地震計アレイ

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

2012年12月東北沖スラブ内ダブルット地震 (Mw7.2) の断層モデルから考察した2011年東北沖地震後のスラブ内応力場

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

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2012年12月7日に宮城県沖の海溝軸付近において発生したダブルット地震について、震源直近に設置された海底圧力計が捉えた津波記録から、ダブルットを構成するサブイベントの断層モデルの推定を行った。この地震の震源周辺では、東北沖地震前のスラブ内応力は浅部と深部それぞれで伸長・圧縮応力場であることが知られていたが、まず深部の圧縮応力場で逆断層型イベント (57.8km, サブイベント1) が起こり、その12秒後に浅部の伸長場で正断層型イベント (19.5km, サブイベント2) が起こった (いずれもMw7.2, Global CMT)。2011年東北地方太平洋沖地震が発生した影響でスラブ内応力が変化した可能性が指摘されている (例えばObana et al., 2012, GRL)。伸長応力場と圧縮応力場の間には、応力の中立域があると期待され、その深さはスラブ内応力の変化に伴って変化すると考えられる。そのため、我々はこれまで、2つのサブイベントの破壊の深さ方向の広がりから、東北沖地震後の応力中立域の深さを拘束できると考え、各サブイベントの断層モデルの推定を試みてきた。その結果、2つのサブイベントの破壊域は海面から約40kmの深さを境に棲み分けており、2012年の地震時に応力中立域がこの深さにあると推定した (久保田ほか, 2015, JpGU; 2015, SSJ; Kubota et al., 2015, AGU)。しかし、これまで用いたデータが津波のみだったため断層の広がり深さ方向の制約が十分でない可能性があることから、他の観測記録の情報に基づく拘束を与え、断層モデルに関して再検討を進めている。海底地震計から決定された2012年の地震の余震分布 (Obana et al., 2014, EPS; 2015, AGU) によると、サブイベント2の周辺で多くの余震が発生し、その震源が西に傾斜する分布を示す一方、サブイベント1の周辺ではほとんど余震は起こっていなかった。そこで、余震の情報からサブイベント2の断層に拘束を与え、それによる海底上下変動と津波解析から推定された津波波源分布との整合性を検討した。1枚矩形断層を仮定し、その水平位置、走向、傾斜を余震分布に拘束した。断層の上端、下端はそれぞれスラブの表面 (海面からの深さ約7km) と、余震分布の下限 (~40km) の範囲にあるとし、すべり量はGlobal CMTとスケーリング則に基づいて与えた。この断層モデルから海底上下変動分布を求め、これに水深フィルタ効果 (Saito and Furumura, 2009, GJI) を考慮して得られる海面上下変動分布を、津波波源逆解析から推定した波源分布と比べたところ、波源モデルの沈降域の広がり沈降量をおおむね説明でき、津波波源の沈降部分が基本的にはサブイベント2によって形成されたことがわかった。今後、断層すべりの深さ分布の違いによる海面変動分布パターンに注目して、サブイベント2の断層の深さ方向の広がりについて詳細に検討する。また、地震発生時に設置されていた海底地震計の記録からサブイベント1の破壊開始点の位置を決定することにより、その断層位置を拘束する。さらに、2つのサブイベントの複合破壊による津波の波形計算を行い、各サブイベントの震源断層モデルを改善し、地震活動に基づく先行研究との比較から、応力中立域の深さに着目して、東北沖地震前後でのスラブ内応力場の変化について考察する。

キーワード：津波、ダブルット地震、スラブ内応力、2011年東北地方太平洋沖地震

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

2011年東北地方太平洋沖地震津波の遠地DARTデータに基づく海面変位の津波インバージョン
Tsunami inversion for sea surface displacement from far-field DART data of the 2011 Tohoku tsunami

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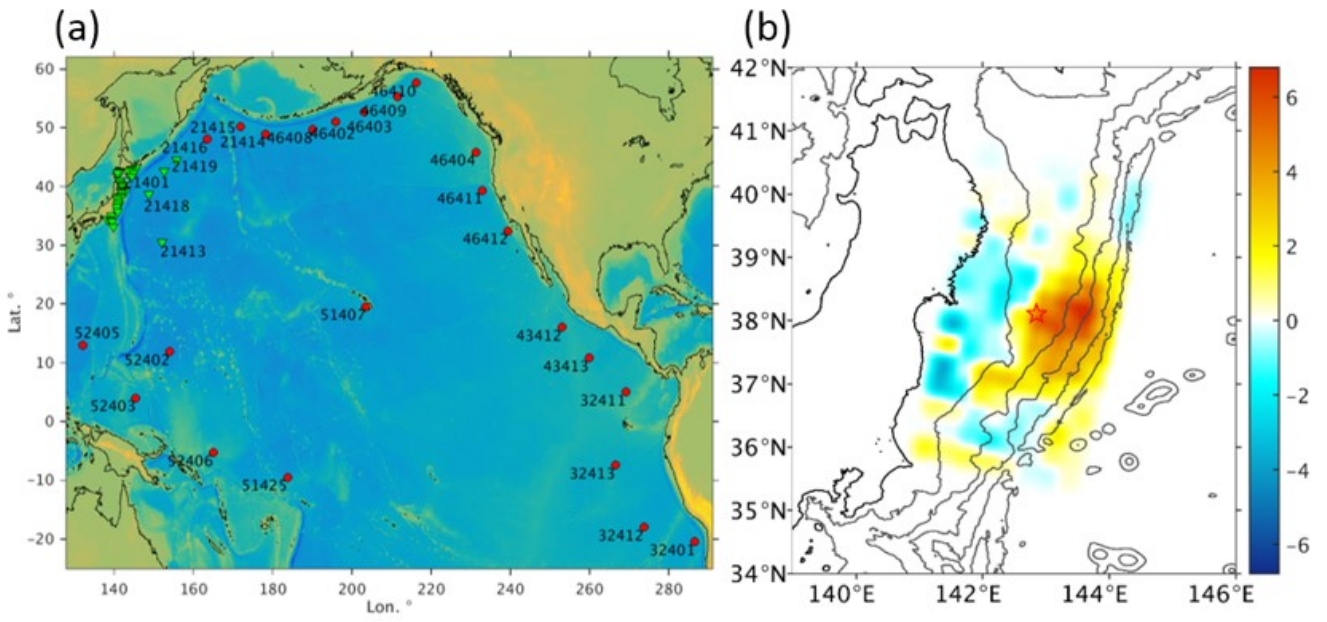
We re-examined the 2011 Tohoku tsunami source using far-field DART data, which was not used in previous waveform inversions. Only near-field stations around Japan were used in most inversion studies of the 2011 tsunami. Although the number of available tsunami gauges such as tidal gauge, ocean-bottom 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.

キーワード：津波、インバージョン、遠地、DART、東北地方太平洋沖地震津波

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



Variation of the subduction structure along the Nansei-Shoto trench

Variation of the subduction structure along the Nansei-Shoto trench

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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 ~ 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.

キーワード: Megathrust earthquakes、Plate subduction、Active-source experiments

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

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

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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.

キーワード：沈み込み帯、レシーバ関数

Keywords: subduction zone, receiver function

地震波動シミュレーションをデジタル岩石に適用して得られた南海トラフ周辺の地震断層の特徴
Characterization of Nankai Seismogenic Fault by Applying Dynamic Wave Propagation
Simulation to Digital Rock Models

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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.

キーワード：震源断層、南海トラフ、動的波動シミュレーション、デジタル岩石

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

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

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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.

キーワード：Nankai trough、3D MCS

Keywords: Nankai trough, 3D MCS

南海掘削Exp. 348で採取されたコア試料に対する三軸剪断試験結果：Geomechanics解析への応用
Result of triaxial shear test on core sample taken in NanTroSEIZE Exp. 348: Implications for geomechanics analysis.

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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.

キーワード：南海掘削、三軸剪断試験、一軸圧縮強度、ジオメカニクス

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

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

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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.

キーワード: Submarine landslide、meag-splay fault、Nanki Trough、Navigable Sampling System

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

南海付加体内部の力学特性：掘削カッタングス試料を用いたインデンテーション試験による解析
Strength and mechanical behavior of the Nankai accretionary prism sediments from
NanTroSEIZE Expedition 348

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岩石の力学特性は、一般に直径・長さ数十mm以上の試料を用いた圧縮・引張実験によって調べられる (e.g., Paterson and Wong, 2005). しかし、海洋底掘削、特にライザーシステムを用いた超深度掘削では、直径数cmの掘削コア試料は限られた深度からしか採取されない可能性が高く、コア試料を用いるだけでは岩石物理特性の連続データを得ることはできない。そこで本研究では、ライザー掘削によって連続採取されるカッタングス試料を用いたインデンテーション試験から、地下深部の圧力条件下での物理特性を調べるための手法開発を試みた。手法開発では、異なるPorosityを呈する4種類の堆積岩 (Carrara marble, Rajasthan砂岩, 白浜砂岩, Berea砂岩) を用いて、インデンテーション試験と一軸圧縮実験を室温・大気圧条件下にておこなった。その結果、インデンテーション試験と一軸圧縮実験から得られるヤング率には指数関数的な相関があり、最大強度は線形相関であることがわかった。これらの相関式を用いると、インデンテーション試験から一軸圧縮条件下における岩石の物理特性を推定することが可能となった。

この手法を応用し、南海付加体を構成する堆積物の力学特性が深度方法約2kmにわたって連続的にどのように変化するかをインデンテーション試験によって調べた。試験には、IODP NanTroSEIZE第348次研究航海で超深度ライザー掘削孔Site C0002の海底面下870m~3058m (以下, mbsf) の間で採取されたカッタングス試料の中から固結したものを取り出したhand-picked intact cuttings試料を用いた。インデンテーション試験は、直径4mmのサファイアの球状圧子を用いて、載荷速度は秒速0.5N, 最大荷重は100Nとした。試験は、室温・大気圧下において、人工海水で飽和させた試料について排水条件下でおこなった。上記で求めた相関関係、および内部摩擦角と間隙率の相関から地下深部での内部摩擦角を推定することによって、現位置におけるヤング率と強度を推定した。その結果、SiteC0002における付加体物質のヤング率は、870mbsf~2000mbsfにかけて0.5GPaから2.2GPa程度まで増加し、その後3000mbsfまで2.2GPa程度とほぼ値が変わらないことが明らかになった。また最大強度は870mbsf~3000mbsfにかけて数MPaから70MPa程度まで増加傾向を示した。これらの結果は、2200mbsfにて採取されたコア試料を用いた三軸圧縮変形実験の結果と調和的であることがわかった。付加体堆積物のような比較的多孔質な物質を用いたインデンテーション試験から、地下深部での物質の力学特性を調べることが可能であることが確認できた。

キーワード：付加体、インデンテーション試験、IODP、第348次研究航海

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

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

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

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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 (Mw=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.

キーワード：沈み込み帯地震、国際深海掘削科学、物性

Keywords: subduction earthquakes, IODP, physical property

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

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

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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 (μ_{ss}) decreases with increasing content of total clay minerals, except for the Nonokawa sandstone with a relatively high μ_{ss} of 0.62 in spite of its moderate content of total clay minerals. μ_{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 μ_{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 μ_{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.

キーワード : friction、Northern Shimanto Belt、seismogenic condition

Keywords: friction, Northern Shimanto Belt, seismogenic condition

南海トラフ巨大分岐断層における断層運動によって促進されたイライト化反応

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

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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.

キーワード：沈み込み帯、断層ガウジ、摩擦発熱

Keywords: Subduction zone, Fault gouge, Frictional heating

炭質物の多角的分析による巨大分岐断層滑りパラメータの推定

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

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プレート沈み込み境界で周期的に発生する地震は、巨大津波を伴い人間社会に大きな被害を及ぼす。地震時のすべりはプレート境界のみならず、プレート境界深部で分岐した逆断層に伝搬し、より大きな津波を引き起こす可能性があるため、巨大分岐断層での地震時の滑り挙動の理解が重要である。

滑り面における摩擦発熱履歴から、地震時の剪断応力などの滑りパラメータを推定することが可能である。その検出方法として、炭質物の熱熟成に伴うビトリナイト反射率の増加やラマンスペクトルのD・Gピーク強度比の変化が提案されている。しかし炭質物の熱熟成過程は、その初期状態や元素組成に強く依存し、また剪断による構造変化等の影響があるという問題があった。そのため、ある炭質物では単一の分析結果からの推定でなく、多角的な分析による確認が不可欠である。

そこで本研究では、南海トラフ巨大分岐断層の滑り挙動を明らかにするため、四国四万十帯久礼メランジ中に発達する過去の巨大分岐断層（アウトオブシーケンス衝上断層）を対象とし、採取試料から抽出した炭質物において、加熱実験・分光測定（IR及びRaman）・CHNSO元素組成分析を行った。その結果、滑り面の最高温度は400-600°Cであると推定された。さらに、一次元熱拡散シミュレーションを用いた滑りパラメータの推定を行った結果、滑り量はいずれの場合でも10 m以下であることがわかった。累積滑り量が2.5-5.5 kmと推定されていることを考慮すると、本断層では少なくとも数百回の地震が繰り返し起こったことが示唆される。

キーワード：炭質物、摩擦発熱、分光分析、元素分析、すべりパラメータ

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

四国西部，明浜地域に分布する四万十帯の被熱構造と断層の形成過程

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

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四万十帯は、海洋プレートの沈み込みに伴い形成された付加コンプレックスを主体としている（平ほか、1980）。九州東部や四国中・東部では、メランジュ帯や、シュードタキライトを伴う脆性断層などの強変形帯の存在が知られており（例えばTaira et al., 1988, Mukoyoshi et al., 2006）、沈み込み帯周辺での長期的・短期的な変形現象を記録していると考えられている。このような断層解析や被熱構造解析は、四国においては主に中・東部を中心に行われ、西部での調査例は多くない。大橋・金川（2014）では、四国西部の四万十帯の一部で東西走向、高角北傾斜の脆性断層が密集する脆性剪断帯があり、地震性断層運動を示唆する炭酸塩鉱物基質の断層角礫を伴うことを確認している。そこで本研究は、大橋・金川（2014）によって見出された四国西部（西予市明浜地域）に発達する断層帯について、岩相・変形マッピング、断層記載、多重逆解法を用いた古応力場解析、およびビトリナイトの反射率測定より被熱構造解析を行った。また、被熱温度より、断層上・下盤の温度差がどの程度あるかを算出し、その温度差をつくるための累積変位量を見積もり、破碎帯の幅と変位量の関係を比較した。そして、これらの調査をもとに、四国西部の四万十帯北帯に発達する断層帯の形成場と形成メカニズムを明らかにしていく。

調査の結果、当地域の断層帯は砂岩、泥岩及び砂泥互層を原岩とし、破碎帯はカタクレーサイトで幅が数cmから数10 cm、東西走向の北傾斜、条線はレイク角が平均32° W、そして右横ずれ成分を含む逆断層センスが多く確認された。調査で得られた断層スリップデータをもとに多重逆解法による古応力場解析を行ったところ、北西-南東方向の最大主応力軸 σ_1 、北東-南西方向の最小主応力軸 σ_3 が求まった。また、断層帯を挟んだビトリナイト反射率(R_m)のギャップは0.18%（温度に換算すると約11°C）以下であり、Mukoyoshi et al. (2006) や北村ほか（2014）で認められているような0.3%を超える明瞭なギャップは存在しない。反射率ギャップ0.18%を生じさせるのに必要な斜め横ずれ変位量を推定したところ、0.04~0.23 kmであり、求められた変位量に比べてトータルの破碎帯の幅（約6 m）は有意に大きい。

以上の被熱構造との関係性から、今回の調査地域の断層帯は最大被熱イベント以前に形成されたものであると考えられる。また、未~半固結時変形の特徴に乏しいため、本研究の断層帯はある程度の固結性を獲得した付加プリズムの前部で形成されたと推測できる。また、今回の調査において斜め横ずれを示す断層が多く確認された。これは、これらの断層がノンアンダーソン型断層であることを示唆する。今後は断層帯の内部構造や微細組織について、より詳細に解析を行う予定である。

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

九州四万十帯延岡衝上断層における断層帯中軸部の変化に富んだ化学組成

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

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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.

キーワード：延岡衝上断層、XRF core scanner

Keywords: Nobeoka thrust, XRF core scanner

遠洋性珪質堆積物中に発達する大規模剪断帯の構造

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

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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} m²) would contribute to fluid pressure fluctuation in large shear zones within pelagic sediments.