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

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Researchers reported that the 2011 Tohoku-oki earthquake accompanied coseismic slip over 50 m (e.g. Iinuma et al., 2012, JGR). In the Tohoku-oki region, GPS/Acoustic (GPS/A) observation is now ongoing after the Tohoku-oki Eq. Tomita et al. (2015, GRL) revealed the observed acceleration of the Pacific plate can be explained by viscoelastic relaxation modeled by Sun et al. (2014, Nature). However precise nature of localized interplate motion is still unknown only using GPS/A observation. Therefore, we conducted direct path acoustic ranging across the Japan Trench from September 2014 to May 2015. Direct path acoustic ranging can continuously and precisely detect relative motion between a pair of instruments across plate boundary or a fault. In our preliminary examination, precision in 1 cm/yr was achieved (Osada et al., 2014, JpGU).
In the observation, three instruments were deployed across the trench axis at the Miyagi-oki region forming two baselines, 7 km and 10 km, respectively. Acoustic ranging was repeated every 4-hours. Relative ranges can be calculated by multiplying a round trip time of acoustic signal and sound velocity. Sound velocity depends on temperature, pressure and salinity. Then, we concurrently measured in-situ temperature. Pressure was taken from NAO.99Jb tide model (Matsumoto et al., 2000, J. Oceanogr.). Salinity was assumed to be constant because of its stability in deep ocean. Precisions of 2 baselines were less than 2 cm/yr, as same as the pre-observation.
In the observation, we obtained data for about 8 months, and found no relative motion, which indicates subducting rate about 8 cm/yr in global model is not compensated at the trench. Thus, near Miyagi-oki region, postseismic slip does not occur at this moment and is already in the interseismic locking state.
Since September 2015, five instruments were newly installed at the same region for two-years continuous observation. Furthermore, we plan to install additional instruments at Fukushima-oki region, where postseismic slip rate is reported strikingly large (Sun and Wang, 2015, JGR). Integrating these data, it is expected in the near future that deformation pattern along the trench axis would be revealed.

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

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

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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.

Keywords: Japan Trench, reflection seismic survey

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.

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).

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

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

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We investigated the intraslab doublet earthquake occurred near the trench off Miyagi Pref. on December 7, 2012, based on near-field tsunami records by ocean bottom pressure gauges. Near the source area, the stress field before the 2011 Tohoku-Oki earthquake (Mw 9.0) was estimated to be tensile and compressional stresses in the upper and lower part of the subducting slab, respectively. The doublet was composed of the first deep (57.8 km) reverse faulting subevent (Mw 7.2, subevent 1) and the second shallow (19.5 km) normal faulting subevent (Mw 7.2. subevent 2) according to the GCMT solution, and the difference in focal mechanisms of the subevents is consistent with the stress state prior to the Tohoku-Oki earthquake. However, it is suggested that the intraslab stress state changed after the 2011 Tohoku-Oki earthquake (e.g., Obana et al., 2012, GRL), and the depth of the stress neutral zone, which exists between the upper tensile region and lower compressive stress region, may also changed. It is expected that the depth of the stress neutral zone after the Tohoku-Oki earthquake is constrained by the vertical extents of the fault ruptured during the two subfaults. The fault model estimated by our preliminary analysis (Kubota et al. (2015, JpGU; 2015, SSJ; 2015, AGU) consists of two planer subfaults, separated at around a depth of ~40 km from sea surface, which would be the depth to the stress neutral zone. However, the fault depths may not be constrained enough because we only used the tsunami waveforms, and we try to improve the fault model taking the other information (e.g., aftershock distribution) into account.
The aftershock distribution deduced from local OBS observation (Obana et al., 2014, EPS; 2015, AGU), the west-dipping aftershock lineation is clearly shown around the subevent 2, and little aftershocks were identified around the subevent 1. Therefore we compared between the tsunami source model derived from inversion analysis of pressure records and the sea surface vertical displacement expected only from the subevent 2 constraining the fault geomotry based on the aftershocks. In the calculation, we assumed a planar fault with uniform slip and constrained the location, strike and dip of the fault plane based on the aftershock distribution. The depth extent of fault plane was set between the slab surface (~7km) and the lower limit of aftershocks (~40km), and slip amount is given by scaling law and CMT solution. The sea surface displacement is obtained by applying depth filter (Saito and Furumura, 2009, GJI) to the seafloor displacement. As a result, the calculated extent and amount of the subsidence area is mostly comparable to the tsunami source model, suggesting that the subsidence area is created basically from the subevent 2. In the presentation, we will constrain the vertical depth extent of the subfault 2 in more detail considering the difference of the pattern of sea surface displacement associated with the vertical location of the fault slip. We will also constrain the hypocenter of the subevent 1 based on the local OBS network and improve the fault geometry of the subevent 1. Finally we will compare the previous studies of seismicity in this region and discuss the intraslab stress change associated with the Tohoku-Oki earthquake.

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

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

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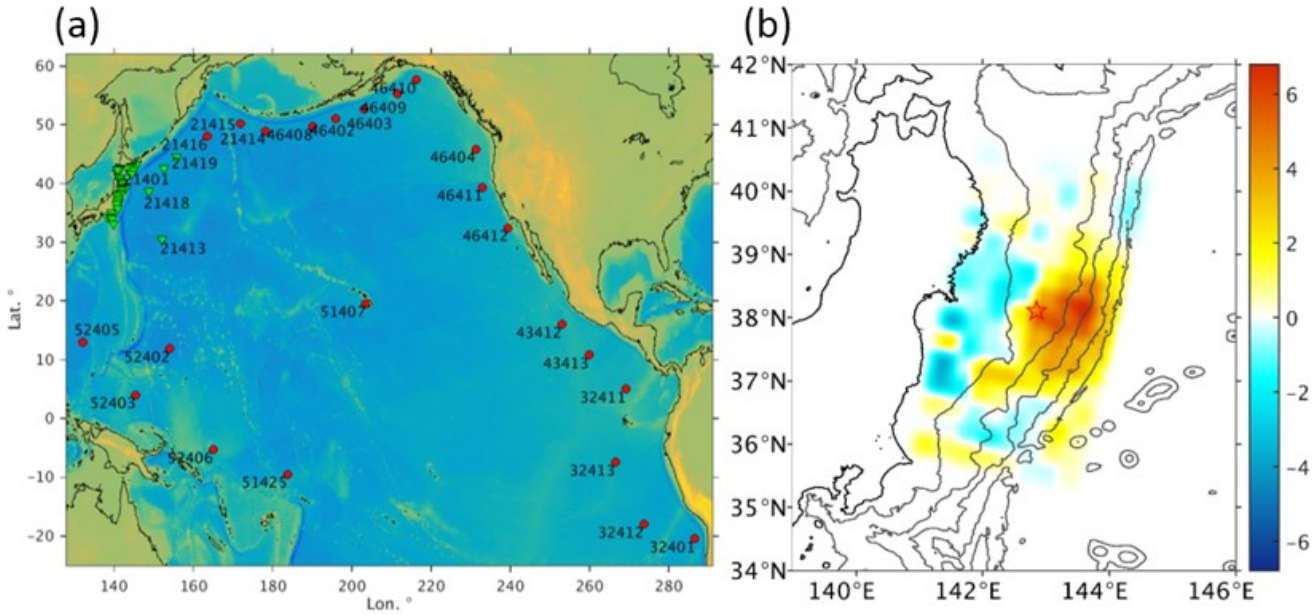
We re-examined the 2011 Tohoku tsunami source using far-field DART data, which was not used in previous waveform inversions. Only near-field stations around Japan were used in most inversion studies of the 2011 tsunami. Although the number of available tsunami gauges such as tidal gauge, ocean-bottom 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 traveltime) data of 2011 Tohoku tsunami, effects of additional far-field stations is limited.
Fig. (a) Far-field stations (red dot) used in this research, reverse triangles are for near-field stations. (b) Inversion result of simultaneous movement after adding far-field stations.

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



Variation of the subduction structure along the Nansei-Shoto trench

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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 (M8.0) in the northern part of the subduction zone at ~29ºN (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.

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

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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.

Keywords: subduction zone, receiver function

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 (Vp, Vs) 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., Vp/Vs) 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 Vp, Vs, and ratio of P-and S-wave velocities (Vp/Vs) 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 Vp and Vs 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 Vp and Vs 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 Vp/Vs ratio of water saturated case (Vp/Vs=~1.84) is higher than dry condition (Vp/Vs=~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 Vp/Vs 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 Vp/Vs at coseismic region observed in the Nankai Trough region could be explained by the mineral filling of cracks.

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

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

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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.

Keywords: Nankai trough, 3D MCS

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.

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

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.

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

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

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

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

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

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

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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.

Keywords: subduction earthquakes, IODP, physical property

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 μm/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 μm/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.

Keywords: friction, Northern Shimanto Belt, seismogenic condition

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.

Keywords: Subduction zone, Fault gouge, Frictional heating

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

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Megasplay faults branching from megathrusts could play an important role in faulting systems in the plate-subduction zone. Because not only subduction megathrust but also megasplay faults could slip during an earthquake, possibly generating gigatic tsunami.
For understanding the slip behavior of these faults, maximum temperature recorded is one of the keys to estimate the slip parameters such as shear stress and displacement of the earthquake. Here we develop new multiple analyses to detect the heat signal recorded in the carbonaceous materials by performing heating experiments, spectroscopic analyses (IR and Raman), and chemical composition analysis (CHNSO element analysis). We targeted the carbonaceous materials retrieved from an ancient megasplay fault developed in the late Cretaceous Shimanto accretionary prism, southwest Japan.
Our results revealed that the fault zone had experienced 400–600 °C. By performing numerical temperature calculation, we found that any case of the earthquake events always accompany a slip displacement of ≤10 m, suggesting that several hundreds of events repeatedly took place.

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

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

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

In the study area, the fault zones are developed in coherent unit comprised of sandstone, mudstone and alternations of sandstone/mudstone. The fault zones typically has a cataclasite zone of a few to tens of cm and fracture zone of a few tens to hundred of cm in width. On the other hand, soft-sediment deformations are rarely found. These faults strike east-west and dip to north, and the average rake angle of the striations are 32 °from west. Kinematic indicators such as composite planar fabrics or slickenside topography show dextral sense of shear with reverse-slip component. Using the fault-slip data obtained in the area, we conducted a stress tensor inversion to estimate paleostress directions. The result indicates NW-SE direction for the maximum principal stress, σ1, and NE-SW direction for the minimum principal stress, σ3. σ1 axes gently to moderately plunge whereas σ3 axes generally shows subhorizontal. Although those faults has reverse-slip component, the vitrinite reflectance does not show significant difference across the fault zones (ΔRm = 0.18% in maximum). The absence of thermal gap across the thrust fault suggests that the faulting proceeded prior to the formation of thermal structure, which may be conducted during subduction. We thus conclude that the fault zones were developed at the relatively early stage of the subduction (frontal to middle part of the accretionary prism). Our results suggest that the oblique-slip fault (non-andersonian fault) was formed during the early to middle stage of the subduction. This finding might become important when we look at ongoing subduction process through ocean drilling programs.

[Acknowledgements]
We thank Arito Sakaguchi (Yamaguchi Univ.) and Makoto Otsubo (AIST) for kind cooperations on the vitrinite reflectance measurement and the paleostress analysis.

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

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

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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.

Keywords: Nobeoka thrust, XRF core scanner

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 hydrofracuring maintained by fluid overpressure. It is speculated that low permeability of lithified chert (10^{-19} to 10^{-21} m^2) would contribute to fluid pressure fluctuation in large shear zones within pelagic sediments.

