Meaning and prospect for science of slow earthquakes

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Slow earthquake is a general term for low-speed fault slip phenomena compared to the ones of ordinary earthquakes. Since around the end of the 20th century, slow earthquakes with wide range of characteristic times have been discovered by densely distributed seismic and GNSS observation networks in Japan then detected in many subduction zones along the circum-Pacific. They are distributed around the seismogenic zone. Because different types of slow earthquakes occurring simultaneously at the same or neighboring regions indicate strong interaction, we expect that frequent occurrence of slow earthquakes might gradually change the physical conditions of the surrounding region, potentially connected to the occurrence of ordinary earthquakes. During the last two decades we have recognized that the slow earthquakes were not special events at each region but common phenomena. Deep low frequency tremor and short-term slow slip event (SSE) were independently discovered at Nankai and Cascadia subduction zones, respectively, after that the coupling phenomena of episodic tremor and slip (ETS) were detected in both regions. Deep very-low frequency (VLF) earthquake associated with ETS was firstly detected in Nankai, after a while also detected in Cascadia. Based on recent marine temporal observation at the western Nankai trough region, shallow tremor has been discovered in association with already-known shallow VLF event like as deep ETS. Therefore, one of our next research targets is to find shallow SSE which is expected to host shallow tremor and VLF. Detailed comparison between shallow and deep slow earthquakes will bring new geological and physical constraints for the similar frictional property at the different thermal and pressure regimes. In future, understanding activity mode, environment, and mechanism of slow earthquakes will contribute to development of Earth science in the following three viewpoints. One is to reconstruct the new comparative subductology based on quantitative comparison study of slow earthquakes at different subduction zones. Second is to reconstruct the approach of earthquake science based on a unified understanding of slow deformations and fast slips. Third is to contribute to advanced evaluation for the occurrence of megathrust earthquake based on understanding mutual interaction between slow and huge earthquakes.

Keywords: Slow earthquake, subduction zone, Nankai trough

Illuminating deep tremors along the Nankai subduction zone, Japan, by matched filter technique

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Deep no-volcanic tremors along the Nanakai subduction zone, SW Japan, can be explained as a swarm of sequential ruptures of low-frequency earthquakes (LFEs) [e.g., Shelly et al., 2007]. Therefore, it is very important to investigate spatio-temporal evolution of each LFE. A matched filter technique is a one of the most powerful tool to detect earthquakes buried in intensive seismic sequence [e.g., Shelly et al., 2007; Kato et al., 2012]. However, there is little constraint on long-term behavior and regional scale properties of LFEs along Nankai Trough throughout the MFT analysis.

To more precisely characterize the evolution of tremors, here, we applied the matched filter technique to continuous seismograms during around 11 years, using template LFEs determined by JMA along the tremor belt from the western Shikoku to Tokai regions, SW Japan. We used continuous three-component velocity seismograms obtained by Hi-net seismic stations located near the tremor belt, which has been operated and archived by NIED. Both continuous data and template waveforms were bandpass filtered from 1 to 6 Hz and decimated to 20 Hz. We divided the tremor belt-like zone over a length of 600 km into ten regions which overlap each other. We selected ~4000 LFEs from the JMA catalog as template waveforms based on the signal-to-noise ratio. We newly detected about 20 times the number of LFE events determined by JMA, which is larger than ones obtained by conventional envelope cross correlation method.

Based on the newly constructed catalog, we find out clear down-dip variations along the tremor belt-like zone. From deep to shallow depths, tremor activity is getting to be more episodic than continuous manner, which well matches with previous studies [e.g., Obara et al., 2010; Wech and Creager, 2011]. But, the transition along-dip direction is more continuous than previously thought. In addition, b-value, which regulate a slope between frequency vs magnitude distribution, gradually decreases with an increasing depth. These depth dependences might be explained by localization of tremor patches and expansion of slow slip area toward shallow depths.

Seismic quiescence of deep very low frequency earthquakes from later 2014 in western Ehime prefecture, southwest Japan

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Deep very low frequency earthquakes (VLFEs) are frequently associated with episodic tremor and slip (ETS) at the downdip region of the megathrust seismogenic zone along the subducting plate interface (Ito et al., 2007; 2009). As a member of slow earthquake family associated with slow slip, VLFE activity is expected to be a proxy of interplate slipping. However, the time change of the deep VLFE seismicity has not been investigated well compared to deep low frequency tremor (e.g., Obara et al., 2010). In this study, we investigated long-term changes of the activity of deep VLFEs in western Shikoku where ETS and long-term slow slip event (SSE) frequently occurred.

We used continuous seismograms of 13 F-net broadband seismometers operated by National Research Institute for Earth Science and Disaster Resilience (NIED) from 2nd April 2004 to 29th September 2016. After applying the band-pass filter with a frequency range of 0.02—0.05 Hz, we adopted the matched-filter technique (Shelly et al., 2007) in detecting VLFEs. The synthetic waveforms calculated by the wavenumber integration method (Takeo, 1987) with the fault mechanisms obtained by Ide and Yabe (2014) at multiple grid points in the Bungo channel and its neighboring inland region are used for templates. The velocity structure for calculating synthetic waves is a one-dimensional model in Japan by Kubo et al. (2002). The time window of each template is 150 seconds. We defined the detection threshold as eight times as large as the median absolute deviation (MAD) of the distribution.

We detected 700—1000 VLFEs at each grid point for 12 years. In inland region, the cumulative number of detected VLFEs increases steeply every half a year. This stepwise change is caused by ETS. In the Bungo channel, the cumulative number of detected VLFEs increases gradually in 2010 and 2014 influenced by long-term SSEs. Interestingly, the activity of deep VLFEs has been low since the latter half of the year 2014 in this region. To investigate the effects of detection rates to the seismic quiescence, we estimated detection rates for events with moment magnitudes of 3.1 by synthetic tests using real seismograms as noise. The detection rate is around 0.7 constantly during the period of analysis. Therefore, we concluded that the seismic quiescence of VLFEs in western Shikoku was not the influence of detection rates. The long-term SSEs in 2014 may influence the seismic quiescence of VLFEs.

Keywords: Slow earthquake, Deep very low frequency earthquake, Seismic quiescence

Slow earthquakes in microseism frequency band (0.1-2 Hz) off Kii peninsula

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Slow earthquakes are divided into deep tectonic tremors, very low frequency (VLF) events, short-term slow slip events (SSE), and long-term SSE, each of which is observed in a different frequency band. Tremors are observed above 2 Hz, and VLF signals are visible mainly in 0.01-0.05 Hz. It was very difficult to find signals of slow underground deformation at frequencies between them, i.e., 0.1-2Hz, where microseism noise is dominant. However, after a Mw 6.5 earthquake off Kii peninsula on April 1st, 2016, sufficiently large signals have been detected in the microseism band, accompanied with signals from active tremors and VLF events, by the ocean bottom seismometer network DONET, maintained by Japan Agency for Marine-Earth Science and Technology. Signals were well observed especially when the microseism noise was low, at a broadband frequency band from 0.01 to 10 Hz. This is the first observation of slow earthquakes in the microseism frequency band, which have no popular name, yet. Then, regarding these “events” as extensions of tremor signals, we determine the hypocenter locations in the same manner as tremor analysis, and compare them with the spatial and temporal distributions of ordinary tectonic tremors above 2 Hz and VLF events.

The data are broadband seismograms recorded at 20 stations of DONET, from April 1st to April 17th. We detected hypocenters by calculating arrival time differences between stations using an envelope correlation method of Ide (2010). Unlike ordinary applications, we repeated analyses for seismograms bandpass-filtered in four separated frequency bands, 0.1-1, 1-2, 2-4, and 4-8 Hz. For each band, we successfully detected events and determined their hypocenter locations. The number of detected events were 32, 44, 177, and 643 in 0.1-1, 1-2, 2-4, and 4-8 Hz, respectively. During the study period, tremors determined in the three high-frequency bands, 1-2, 2-4, and 4-8 Hz, migrated from a small spot near the source of Mw 6.5 event to a broader region in the south-east direction. In the 0.1-1 Hz microseism band, the hypocenters were determined mainly on April 10th, when microseism noises are exceptionally small. On this day, the numbers of evets in the highest frequency band, 4-8 Hz, decreased, while that in lower frequency bands increased.

Many VLF events have been detected in this region in the frequency band of 0.03-0.05 Hz, with location and focal mechanism using a method of Nakano et al. (2008). These VLF events and tremors detected in this study appear to have occurred at the almost same time and locations.

Keywords: slow earthquake, microseism, hypocenter determination, tremor, VLF

Rupture on the megasplay fault along the Nankai trough during the off-Mie earthquake (Mw=6.0) on 1 April 2016

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On 1 April 2016, a moderate-sized off-Mie earthquake (Mw=6.0), occurred off the Kii Peninsula, southwest of Japan. The epicenter is located updip of hypocenter of the 1944 Tonankai earthquake (Mw=8.2 after Ichinose et al., 2003). Wallace et al. (2016) determined the hypocenter distribution of the 2016 earthquake and concluded that this earthquake occurred along the plate boundary. Their hypocenter determination was based on a 1D velocity structure, while horizontal heterogeneity along the dip direction is not negligible in subduction zones.
In this study, we determined the hypocenters of the 2016 earthquake by using a velocity structure reflecting the horizontal heterogeneity. We used a 2D velocity structure obtained by a wide-angle seismic survey on a line that passes through the hypocenter region. We manually picked P-wave onset at each DONET station deployed immediately above the source region (Kaneda et al., 2015; Kawaguchi et al., 2015). S-wave arrival was not used because of the uncertainty in the S-wave velocity structure (Wallace et al., 2016). We used the method of Lomax et al. (2000) for the hypocenter determinations.
We obtained hypocenter distributions very similar to that obtained by Wallace et al. (2016), but shallower mainshock depth at 9.7 km compared to that at 11.4 km of their result. The aftershock distribution was very similar to their result including the source depths.
We compared the hypocenter distribution with a reflection profile obtained from multichannel seismic survey (MCS) along a line where the 2D velocity structure was obtained. The source depths were converted to the two-way travel-time (TWT) by integrating the slowness picked from the 2D velocity structure from the sea level to the source depth. The mainshock was located at slightly shallower than, but very close to, the megasplay fault imaged on the MCS profile, rather than the plate boundary. Aftershocks were distributed beneath the deeper extension of this plane, although the reflection phase is not clear there.
Considering the errors in the hypocenter determinations and velocity structure estimations, two possibilities are available for the mainshock fault. One is a fault in the inner wedge such as an ancient splay fault. The other is the megasplay fault. Ancient splay faults in this region are considered to be inactive after ~2 Ma because of a lack of a dislocation plane due to fault activities in the shallow sediments (Tsuji et al., 2014). The megasplay fault is considered to be active at present (Sakaguchi et al., 2011) to which we attribute the mainshock.
In the transition zone of the accretionary wedge between the megasplay fault and the plate boundary is characterized by a zone of low seismic-wave velocity (Park et al., 2010; Kamei et al., 2012; Tsuji et al., 2014). This zone is considered to consist of fluid-rich sediments, which could not support strong shear stress to cause large earthquakes (Bangs et al., 2009; Kitajima and Saffer, 2012; Tsuji et al., 2014). Accordingly, it is difficult to cause large earthquakes along the megasplay fault or the plate boundary in the source region of the 2016 earthquake. Wallace et al. (2016) attributed this earthquake to a slip along an unstable patch in conditionally stable zone of the plate boundary, but its geological meaning has not been clarified yet.
In MCS profiles we can recognize a portion that the reflection phase is locally very weak along the

megasplay fault or the plate boundary around the mainshock source. Weak reflection phase can be interpreted as a difference in lithology or pore-fluid pressure from the surroundings and the material is locally strong (e.g. Moore et al., 2009; Bangs et al., 2004). This portion would be an “unstable patch”, where large earthquakes can occur. We hypothesize that remnant of fragments of seamounts, of which the main body would have been subducted to deeper part, form the strong patch in the sediments.

Keywords: DONET, Subduction zone, Splay fault

Numerical modeling of slow slip events in a seismic cycle considering the effect of earth tides and the configuration of subducting plate in the Shikoku region

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It has been reported that earth tides affect the activity of episodic tremor and short-term slow slip events (hereinafter, short-term SSEs) in Nankai and Cascadia (e.g., Nakata et al., 2008; Rubinstein et al., 2008; Ide and Tanaka, 2014; Yabe et al., 2015). The tidal effect on the SSEs is also examined by numerical studies (e.g., Hawthorne and Rubin, 2013). In our previous study, we suggested the recurrence intervals of SSEs become shorter in the late stage in seismic cycles of megathrust earthquakes (Matsuzawa et al., 2010). In addition, short-term SSEs recurring in the Shikoku region, Japan, were numerically reproduced in our previous study, incorporating the actual plate configuration and SSE region (Matsuzawa et al., 2013). In this study, we examined the behavior of short-term SSEs in the Shikoku region in a seismic cycle of megathrust earthquakes, considering stress perturbation by earth tides.
Our numerical model is similar to our previous study (Matsuzawa et al., 2013). The interface of the subducting Philippine Sea plate is expressed by 93,144 small triangular elements. A rate- and state-dependent friction law (RS-law) with cutoff velocities is adopted as the friction law on each element. We assumed that (a-b) value in the RS-law is negative within the short-term SSE region, and positive outside the region. The short-term SSE region is based on the actual distribution of deep low-frequency tremor. Low effective normal stress is assumed at the depth of short-term SSEs. We assume that the stress change by earth tides is represented by periods of 10 major tides, calculating stress change as in Yabe et al. (2015). Incorporating this stress perturbation, we calculate the evolution of slip on the plate interface.
In the numerical result with the effect of earth tides, recurrent intervals of SSEs at the relatively isolated SSE region in the eastern Shikoku have smaller fluctuation than the case without tidal effect. For example, standard deviation of recurrence intervals between 5 and 20 years after the first megathrust earthquake are 0.00037 years and 0.00062 years in the isolated SSE region at the northeastern Shikoku, with and without the case of earth tides, respectively. In addition, we also examined the case only with the Mf tide which has the period of about half months. In this case, the fluctuation is slightly smaller than the case without tides, while the fluctuation is larger than the case with 10 major tides. This shows that long-period tides can also affect the recurrence of SSE, even though the amplitude of stress change by the Mf tides is about 10 Pa and about 10^{-1}-10^{-2} times smaller than the amplitudes of major semidiurnal and diurnal tides (i.e., M2, S2, O1, and K1 tides).. Introduction of tidal effect also makes peak velocity faster than that in the case without tidal effect. For example, peak slip velocity averaged between 5 and 20 years increases 3.5% and 8.5% in the northeastern region and the western Shikoku region where SSE regions are largely connected, respectively.
At the later stage in a seismic cycle, the recurrence interval tends to show larger fluctuation even in the relatively isolated SSE region. This may be caused by the long-term SSEs occurring in the updip of the short-term SSE region, as long-term SSEs are more frequently occur at the later stage in a seismic cycle in our numerical simulation. In the case with earth tides, averaged recurrence intervals still becomes slightly shorter in these SSE regions at the later stage in a seismic cycle, as suggested in Matsuzawa et al. (2010).

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Keywords: Slow Slip Event, Earth Tides, Numerical Simulation

Interplate coupling and slow slip events along the northern margin of the Philippine Sea plate estimated from GNSS data

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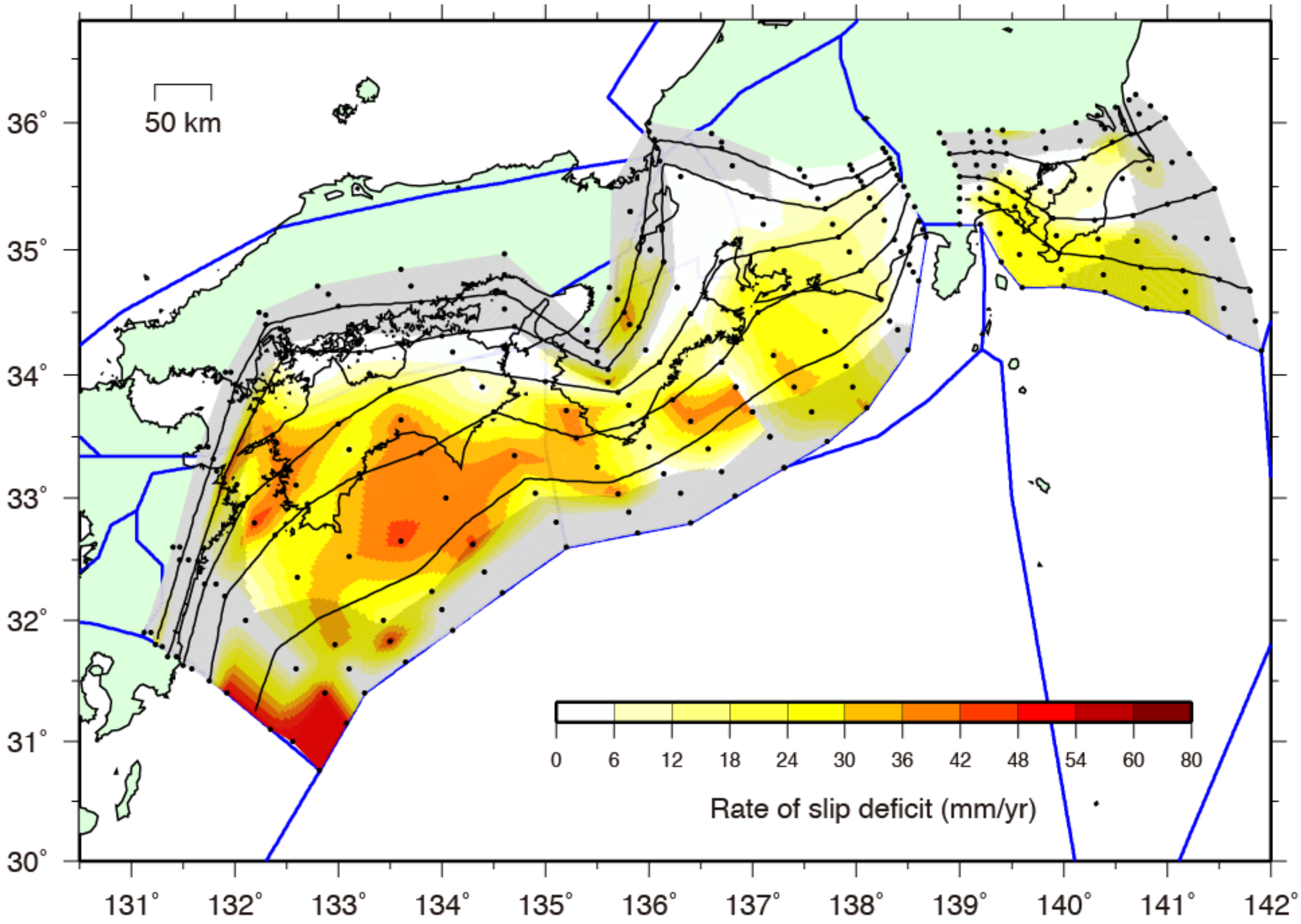
Southwest Japan is situated along the northern margin of the Philippine Sea plate. In the subduction zone along the Nankai trough, megathrust earthquakes historically hit southwest Japan with an interval of 100-200 years. Various slow earthquakes including slow slip events (SSEs) and low-frequency tremors have been observed there. A dense geodetic network including onshore GNSS and offshore GPS-A provides a key observation to clarify slow and fast slip and coupling of the Nankai megathrust zone. This presentation focuses on our recent studies of short-term SSEs (S-SSEs, Nishimura et al., 2013; Nishimura, 2014) and interplate coupling (Nishimura, in prep) estimated from the geodetic data.
In order to detect S-SSEs, we analyzed the data of ˜800 GEONET GNSS stations along the Nankai Trough and the Ryukyu Trench. More than 390 possible short-term SSEs with M_w 5.6 for 19 years were detected by our analysis and they have a variety of characteristic recurrence intervals, magnitudes, durations and coincidental seismic activities. The detected SSEs concentrate in a depth range of 25-40 km and form the ETS (Episodic Tremor and Slip) zone along the Nankai Trough. The detected S-SSEs extend from the ETS zone toward southwest, and then fade away around the subducted Kyushu-Palau Ridge. Although few shallow (depth 20 km) S-SSEs have been detected along the Nankai Trough, S-SSEs often occur on the shallow plate interface along the Ryukyu Trench. This may be related to the incomplete interplate coupling.
We also estimate back-slip rates expressing interplate coupling as well as inland block rotations from GNSS and GPS-A velocities for a quiet period of crustal activity. Land GNSS data from April 2005 to December 2009 are used to estimate interseismic velocities. GPS-A data from 2004-2012 to 2016 are used after correcting co- and post-seismic displacement of the 2011 M_w 9.0 Tohoku-oki earthquake. The estimated coupling distribution (Figure) shows large heterogeneity in both strike and dip directions. Estimated back-slip rates are the highest off Shikoku and in the Bungo Channel at a depth of 10-30 km and decreases toward east. Back-slip rates off Kii Peninsula show heterogeneous distribution. Epicenters of the 1944 M_w8.0 Tonankai and the 1946 M_w8.3 Nankai earthquakes locate in an area of relatively low back-slip rates. Most S-SSEs occur at the down-dip edge of the transition zone from partial coupling to no coupling except in the Bungo Channel where a high coupling zone extends in a down-dip direction.

Keywords: Slow Slip Events, Interplate coupling, GNSS, Crustal deformation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30
36
42
48
54
60
80
Rate of slip deficit (mm/yr)

Structures of the subducted Philippine Sea plate and the overriding SW Japan arc from reprocessing of seismic wide-angle reflection data in Kii Peninsula, SW Japan

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Our recent reprocessing and reinterpretation for seismic refraction/wide-angle reflection data in eastern Kii Peninsula, SW Japan, provided new structural information on the uppermost part of the subducted Philippine Sea (PHS) plate and overriding the SW Japan arc, including the landward reflectivity variation in the vicinity of the plate boundary and the large scale structural change within the SW Japan arc.

The Kii peninsula is located in the eastern part of the well-known seismogenic zone developed along the Nankai trough. The plate boundary beneath this peninsula is in the stable or conditionally stable regime except for its southernmost tip, the northwestern end of the rupture area at the last event (1944 Tonankai earthquake (M7.9)). The surface geology of the overriding SW Japan arc is divided to two parts by the E-W trending Median Tectonic Line (MTL), the most prominent tectonic boundary in SW Japan. South of the MTL, Cretaceous-Jurassic accretionary complexes are exposed, whose northernmost unit consists of high P-T metamorphic rocks (the Sanbagawa metamorphic belt (SMB)). The region north of the MTL, on the other hand, is occupied by older accretionary complexes, partly suffered from the Cretaceous magmatic intrusions.

Our seismic data from five dynamite shots were acquired in 2006 along 80-km line almost perpendicular to the Nankai trough. The structure of the SW Japan arc was obtained both from intensive wide-angle reflection analysis and advanced reflection processing by seismic interferometry technique. The former analysis delineated clear structural change in the uppermost crust across the MTL. In the latter processing, we retrieved virtual shot records at 512 receiver points from free-surface backscattered waves by the deconvolution interferometry. The subsequent CRS (Common Reflection Surface)/MDRS (Multi-Dip Reflection Surfaces) methods provided an enhanced image within the island arc, including a northward dipping reflector band just south of the MTL. This reflection band, about 10-15 km thick, includes the SMB, extending from 2-10 km to 25-35 km depth. The MTL itself is recognized as the uppermost part of this band inclining northward to a depth of nearly 25 km.

In the reflection processing, the PHS plate is well imaged as northward dipping reflectors in a depth range of 20-35 km beneath the southern half of our profile. The wide-angle reflection analysis delineated lateral reflectivity change along the plate boundary. A thin (less than 1 km) low velocity (3.5~5km/s) layer is situated at the top of the PHS plate under the southernmost part of the profile, namely, the trenchward half of the conditionally stable zone. In the central part of the profile (the landward half of the conditionally stable zone), strong reflectors with 2-3 km/s velocity contrast are distributed in a diffused manner at 30-35 km depths, around which low frequency earthquakes are occurring. Such reflective signature fades out to the north, approaching to stable regime region. The obtained lateral structural change are well correlated with the frictional properties of the plate boundary, probably controlled by the dehydration process within the PHS plate.

Keywords: plate subduction, Philippine sea plate, wide-angle reflection data, plate boundary, low frequency earthquake, frictional property

Renovated 3D image of Nankai accretionary wedge and shallow seismogenic zone off Kumano through reprocessing of 3D seismic data

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For the next stage of the deep scientific drilling in Nankai Trough seismogenic zone off Kumano, it is essential to obtain precise structural image and depth estimation around the mega-splay and the plate boundary fault, as well as fine structures in accreted sediments around the drilling site. In 2006, three dimensional multi-channel seismic data acquisition and processing were carried out as a cooperative project between the center for deep earth exploration (CDEX) of JAMSTEC and US (NSF). However, obtained data could not necessarily resolve deep structures due to relatively short (4.5 km) streamers and due to the strong Kuroshio current.
In order to obtain the clearer depth image for the next deep drilling target, we decided to reprocess a part of the 3D volume with today’ s advanced technology. First, preprocessing with recent technologies of multiple elimination and broadband processing was applied in order to clarify reflection signals. Second, the pre-stack time migration for time domain imaging, the sophisticated velocity model building in depth domain, and the pre-stack depth migration were carried out to obtain the fine depth image.
Although the reprocessed 3D volume will be carefully inspected onward, so far we noticed the following preliminary points. Improved images in the shallow accretionary wedge reveal dynamic deformation features (e.g. branching of splay faults, thrusting of the lower Shikoku Basin formation, BSRs). Lower Shikoku Basin formation below the forearc slope area show anomalously low Vp, consistent with estimation by Park et al. (2010 Geology). Additional reflectors above decollements are identified in the formation.
Low Vp zone (<4km/s) spreads beneath the splay fault and above the top of oceanic crust, consistent with Kamei et al. (2012) estimated from the full-wave inversion analysis of MCS-OBS data.
3D geometry of the megasplay fault below the southeastern Kumano Basin indicates a bending downward feature in its southeastern rim of reprocessed area. This bent area is overlain by an anomalously high-Vp volume (>5 km/s) with ~1km thickness on the hanging wall side. We also identify a couple of landward-dipping reflectors in this high-Vp region, in a good contrast with a region of no remarkable reflectors shallower than 3000m below seafloor (i.e. above the high-Vp region). Careful inspection will modify or add these preliminary interpretations.

Keywords: Nankai Trough seismogenic zone, IODP, 3D seismic survey

The NanTroSEIZE Project After Ten Years: Drilling to the Megathrust is More Important Now Than When We Started

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The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is the largest undertaking in the history of scientific ocean drilling. Conceived in the early 2000s, operations began with Expeditions 314 –316 in 2007. Between that year and 2016, there have been 11 IODP expeditions drilling at 13 main sites, with multiple holes to depths from 100s of meters to more than 3000 meters below the seafloor (the deepest scientific borehole in the ocean floor). More than 195 scientists have participated and close to 100 results papers have been published. The transect of boreholes, in concert with three-dimensional seismic reflection imaging and other geophysical studies, has sampled the inner and outer wedge extensively, and two state-of-the-art real-time downhole monitoring systems are now streaming data. This is now the best-known subduction zone forearc and plate boundary complex in the world.

However, the primary objective of drilling –to access, sample, log, and instrument the main plate interface at depth –has still not been achieved. The rapid scientific advance in understanding of the mechanics of faulting in general and subduction zone megathrust processes in particular of the past decade demands renewed efforts to complete this project. Discovery in NanTroSEIZE Stage 1 by 2011 suggested that rapid, seismic slip all the way to the frontal thrust must have occurred in the past, contrary to most accepted concepts at the time, and then the Tohoku-oki M9 earthquake demonstrated that does occur, causing devastating tsunamigenic displacements. The Kumano-nada area was the location where shallow plate boundary VLFE, tremor, and transient slow slip all have been discovered, just up-dip of the 2016 M6 normal earthquake region, dramatically showing the diverse strain accumulation and release activity of the region formerly though to be aseismic. Despite this wealth of geophysical information, we still do not have a clear understanding of the thickness, material properties, or state of stress in a megathrust fault system and surrounding wallrock, and what controls the presence or absence of slip to the trench. For all these reasons, drilling, sampling, and near-field measurements in the 5000 m deep fault at Site C0002 is even more justified than when it was first proposed and approved for drilling.

Keywords: megathrust, Nankai Trough, fault zone processes, ocean drilling, subduction

Seafloor observation network in the Nankai Trough to model dynamics in seismically coupled plate interface.

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Recent development of DONET seafloor observation networks in the Nankai Trough enabled us to capture crustal activities occurring in seismogenic plate interface, which is considered to be in prior phase of large earthquake occurrence. Since the deployment of DONET seafloor observatories, occurrence of low frequency earthquakes has been documented, both in low frequency range as very low frequency earthquake (VLFE) and in relatively high frequency as low frequency tremors (LFT). Deployment of broadband and wide dynamic range seismic sensors in quiet environment in relatively dense configuration (15-30 km) was key technical points to enable detection and analysis of such low frequency earthquakes. Further expansion of our eyes on these slow earthquakes in the seafloor were achieved by instrumentation in deep seafloor boreholes. In deep seafloor borehole where sensors are coupled to cohesive crust, detection of slow change of strain is possible. We identified families of slow slip events (SSE) from pore-fluid pressure records obtained in two seafloor borehole observatories (C0002G and C0010A) deployed in Integrated Ocean Drilling Program (IODP). Now these borehole observatories are linked to DONET network delivering data together with dense seafloor observatories enabling us to study nature of these families of slow earthquakes (VLFE, LFT, SSE), although current number of borehole (=2) is insufficient to model extent of each SSE event in space. Moreover, our ability of seafloor observation is still limited in longer period than a month period. Therefore, we propose further expanding our ability to observe crustal strain in longer period so as to model these slow slip events and effect of these events to the status of coupled plate interface. This would be achieved either by deployment of number of borehole observatories or by improvement of seafloor observatories (already existing in more than 50 locations) to be able to instrument seafloor strain change.

Keywords: borehole observatory, seismogenic zone, seafloor observation network

Borehole strain observations of very low frequency earthquakes in Cascadia

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We identify and examine strain signals associated with very low frequency earthquakes (VLFEs) in central Cascadia. The several hundred M 3.3 - 4.7 VLFEs considered were identified by cross-correlation with the templates of Ghosh et al. (2015) and are located beneath southern Vancouver Island and the Olympic Pensinsula. In the seismic records, the events appear to have most of their energy at periods of 20 to 50 seconds. Here we use nearby PBO borehole strainmeters to examine how deformation accumulates on timescales of 2 minutes to 2 hours. The strain signals produced by VLFEs are small, so we focus on the closest stations: B005, B007, B003, and B004, and we isolate components of strain that have small atmospheric and hydrologic noise. Then we compute moment rates averaged over the 600 VLFE times. First, we estimate the average moment rate within 1 minute of the VLFEs. We estimate that the strain rate in the 2 minutes centered on the VLFEs is about 1.5 times the average strain rate in the surrounding 12 hours. We interpret this increased strain rate as a factor of 1.5 increase in moment rate, which implies an average moment per VLFE equivalent to that of a M 3.4 earthquake, within the range of seismic moment estimates for the VLFEs. Next, we examine the strain rate in the time intervals around the VLFEs. The estimated strain rates decrease only gradually before and after the VLFEs, suggesting that, on average, the slow slip moment rate is higher closer in time to the events. For instance, the strain rate---and by inference the moment rate---in the 2 hours centered on the VLFE times is about 1.2 times larger than the average rate in the 12 hours centered on the VLFEs. Similar strain rates are estimated before and after the VLFEs. The high moment rates in the surrounding intervals may help constrain how VLFEs interact with the larger slow slip event. VLFEs may be more likely to occur when the slip rate in the surrounding slow slip event is higher.

Keywords: slow slip, very low frequency earthquakes, borehole strain

Frontal thrust activity of the Nankai accretionary prism off the Kii Peninsula

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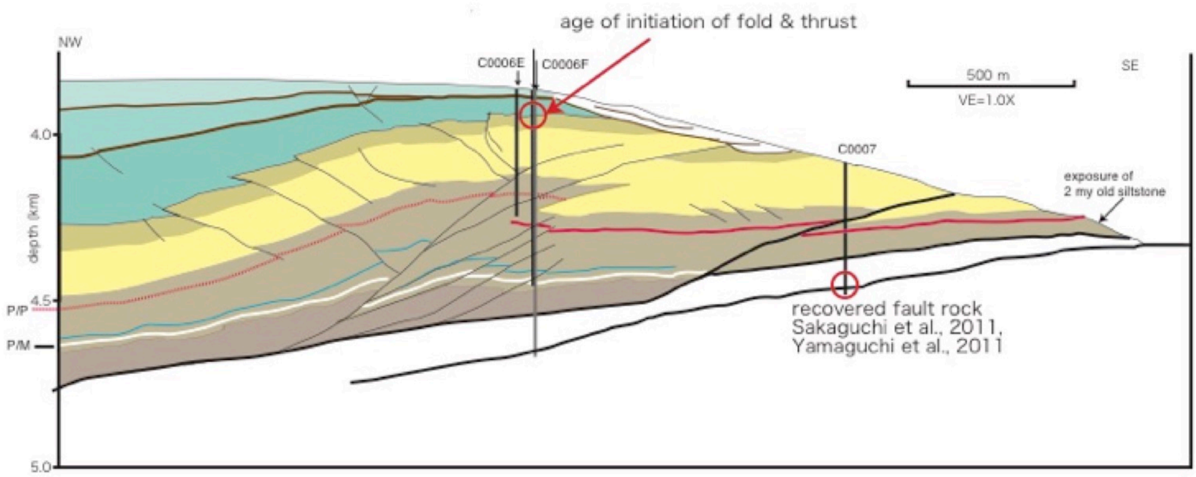
The Nankai accretionary prism was developed since ˜6Ma and the growth has been accelerated after ˜2Ma. Seismic reflection profiles at the toe of the prism clearly present frontal thrust ramping up and making an axial thrust of the anticline (Figure). The fault analyses recovered from the basal decollement document that the slip along the fault was seismo-tsunamigenic high velocity because the frictional heating is clear although the specific age of the slip is unclear. The evidence of the fast slip is similar to that of the rupture and the slip propagation of the plate boundary megathrust and resulted in the disastrous tsunami in the 2011 Tohoku earthquake.
The drilling into the prism and a core-log-seismic integration study of axial thrust of the anticline document that the frontal thrusting would have started within several hundred thousand year ago because the anticline controlled sedimentation appears to have started concurrently with the start of frontal anticline. The balanced cross section profiling presents horizontal shortening of frontal prism is about ˜380m. Historical record of the Nankai Earthquake since seventh century presents at least ten times with mean recurrence time is ˜150 years. The largest earthquake and tsunami was M8.4 earthquake 1707. Geological records from the sediments in the ponds near the coast facing to the Pacific ocean show the tsunami deposits for about 3,000 years and suggests 300˜700 recurrence of large tsunami like the1707 earthquake.
˜500 m horizontal shortening of the frontal prism is cleared. Assuming the shortening took place since 500,000 years ago as inferred from the drilling data, and the shortening was concentrated along the slip on the frontal thrust dipping at 20 degree recurring at ˜500 years interval, each slip is estimated to be ˜0.54 m, which would have been partitioned with the plate convergence along the basal decollement. This amount would be larger if the slip recurrence intervals are longer. Vertical uplift from the anticlinal geometry requires the same amount as the slip.
Seismo-tsunamigenic slip along the decollement is already documented but fault mechanism along the branched frontal thrust is not cleared yet. This hypothetical slip estimation and fault mechanism have to be checked by fault analysis in more detail.


age of initiation of fold & thrust
NW
SE
C0006E
C0006F
500 m
VE=1.0X
C0007
exposure of
2 my old siltstone
4.0
depth (km)
4.5
P/P
P/M
5.0
recovered fault rock
Sakaguchi et al., 2011,
Yamaguchi et al., 2011

Estimates of the geothermal gradient in the deep Nankai accretionary prism, Site C0002, Expedition 348

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Knowing the rate of temperature increase in deep accretionary prisms is critical for understanding changes in physical properties related to clay diagenesis and modes of stress release at the megasplay. We present data constraining temperature at depths of 2000-3000 mbsf in Site C0002. The sediments comprise steeply tilted, hemipelagic mudstone. Direct temperature measurements are only available in the Kumano forearc basin to depths of 900 mbsf. Thermal models of the prism suggest temperatures anywhere from 100˚C to 150˚C on the megasplay (Harris et al., 2011; Spinelli and Harris, 2011; Sugihara et al., 2014). We sampled carbonates from cuttings and cores with the objective of determining temperatures of carbonate formation. Most are calcite veins from 1-8 mm thick. Cements from the cored interval were also sampled. Traditional IRMS d values of oxygen and carbon isotopes (-12 to 0‰ VPDB) are consistent with carbonate formation at variable times during burial. Matrix cements in the cored interval have high $d^{18}O$ values relative to a $d^{18}O$ minimum in the fault zone at 2205 mbsf. Carbon isotopes are only slightly ^{13}C-depleted until the bottom 200 m of the section. The lightest $d^{13}C$ value was measured in the fault-zone sample with the lowest $d^{18}O$ value, suggesting the fault was a conduit for deeper, warmer fluid. The variation in $d^{13}C$ is narrow compared with Nankai input sites and other accretionary prisms. The dominant carbon source may have been recrystallization of biogenic marine carbonate in the sediment. For clumped isotope analysis we focused on samples with the greatest ^{18}O depletions, which are most likely to record maximum temperatures during burial. The amount of "clumping" of the rare isotopes ^{13}C and ^{18}O in carbonate bonds varies inversely with temperature. U-series ages from carbonate veins are at least as young as 108 ka suggesting that the clumped isotope temperatures likely reflect a contemporary geothermal gradient. The clumped isotope data define steadily increasing temperature (44˚C to 70˚C) with depth from 2106 to 2996 mbsf. These results will be used in combination with new thermal models to provide improved estimates for temperatures on the megasplay.

Keywords: IODP Expedition 348, accretionary prism, geothermal gradient, carbonate isotopes, geochronology, megasplay

Frictional properties of the Nankai Trough accretionary mud samples collected and cored from 944.6–3030.5 mbsf at IODP Site C0002

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Friction experiments on the Nankai Trough accretionary mud samples collected and cored from 944.6–3030.5 mbsf (meters below seafloor) at IODP Site C0002 at pressures and temperatures equivalent to their *in situ* conditions, and displacement rates changed stepwise among 0.1155, 1.155 and 11.55 μm/s, revealed frictional properties of accretionary mud samples as well as how they change with depth. The results show that the steady-state friction coefficient decreases with depth from ≈0.52 at ≈1000 mbsf to ≈0.28 at ≈3000 mbsf according to increasing content of total clay minerals in samples, and also that ($a-b$) value, i.e., an indicator of the rate dependence of steady-state friction, decreases with depth from ≈0.005 at ≈1000 mbsf to ≈0 at ≈3000 mbsf according to increasing temperature up to ≈100°C. The latter suggests that the transition from stable aseismic faulting above and potentially unstable, seismic faulting below occurs there around 3000 mbsf.
We also report frictional properties of the Shimanto belt accretionary mudstone samples exhumed from seismogenic depths at pressures and temperatures supposed there, and how they change from those of the Nankai Trough accretionary mud samples.

Keywords: friction, mudstone, accretionary prism, Nankai Trough, Shimanto belt

Transition of frictional velocity dependence of subduction zone fault material as a function of effective normal stress

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Frictional experiments of gouge material in the presence of pore fluid pressure should provide valuable information for the stability of slip in the shallow parts of subduction zone faults. However, most of the previous experiments are limited by the amount of displacement that can be achieved and the frictional behavior at large displacements remains poorly understood. In this study, we have conducted large displacement friction experiments on subduction zone fault materials with a fluid pressure-controlled testing system.
We have performed a series of rotary-shear large displacement (>150 mm) friction experiments on the following two types of shallow fault-simulated material; one is the clayey fault material form the shallow megasplay fault zone within the Nankai accretionary prism (Site C0004, IODP Expedition 316) and the other one is from the input pelagic siliceous to calcareous sediments (ooze) to the Costa Rica subduction zone (Site U1318, IODP Expedition 334). In the experiments, a sequence of velocity stepping by a factor of 10 was imposed to examine the velocity dependence of friction, for loading velocities of 0.0028–0.028 mm/s. In this study, the velocity stepping was imposed to the sample continuously while changing effective normal stress in a range from 1 to 5 MPa by changing pore fluid pressure slowly at a constant increasing or decreasing rate at 500 Pa/s.
Experimental results reveal that frictional velocity dependence changes as a function of pore pressure. For both the clayey fault material and the siliceous to calcareous ooze samples, frictional velocity dependence was slightly negative or almost neutral at a range of relatively higher effective normal stresses (>2.5 MPa). When the level of pore fluid pressures was increased further to reduce the effective normal stress, frictional velocity dependence changed into velocity strengthening behavior.
The SSEs are often described as conditionally stable sliding of faults [e.g., Shelly et al., 2006]. Pore pressure increase will make weakly velocity-weakening fault conditionally stable [Scholz, 1998]. Our experimental results show that velocity-weakening behavior changes into velocity-strengthening behavior when pore fluid pressure is increased. This could be an alternative role of pore fluid to stabilize otherwise unstable (velocity weakening) faults.

Keywords: rock friction, frictional velocity dependence, pore fluid pressure

Excess fluid pressure development beneath the décollement at the Nankai subduction zone

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Pore fluid pressure in subduction zones is very important for understanding earthquake generation processes. However, quantitative constraints on the pore pressure are quite limited. Here we report two estimates of the pore pressure developed within the underthrust sediments in the Nankai Trough off Cape Muroto, Japan, using the shipboard data obtained at Site C0023 during IODP Expedition 370 (T-Limit) (Heuer et al., 2017).

First estimates are based on the depth trend of porosity data in the lower Shikoku Basin (LSB) facies, in which the décollement zone has propagated. Porosities in the LSB facies generally decrease with depth, but turn to increase by 5-7% below the décollement zone at ~760 mbsf. Deeper than ~830 mbsf, porosities resume a general compaction trend. The characteristic downward porosity trend across the dé collement is consistent with those reported from Sites 808 and 1174, ~4 km SW of Site C0023 (Shipboard Scientific Party, 1991, 2001). Screaton et al. (2002) compared a reference site (Site 1173) porosity versus depth curve to data from Sites 808 and 1174 within the protothrust zone and concluded that the downward increase in porosity beneath the décollement is reflected by an excess pore pressure (overpressure ration λ of ~0.42). By applying the same method, we estimated the highest excess pore pressure of ~4.2 MPa (λ = ~0.45) at ~1020 mbsf within the underthrust sediments.

Another estimate is based on the analysis of upwelling drilling-mud flow from the borehole. After installation of a casing at 850 mbsf for the protection of the fragile décollement zone and having drilled down to nearly the bottom of the LSB facies at ~1100 mbsf, the drilling pipes were pulled out from the borehole. At this time, the continuous mud flow from the head of the casing pipe was confirmed by an underwater TV. The evidence directly indicates the development of overpressure somewhere in the depth interval between 850 and 1100 mbsf. The pore pressure which is necessary to flow the drilling mud through the casing pipe out of the hole can be calculated by solving an energy balance Bernoulli equation. Parameters such as density and viscosity of the drilling mud for the calculation were known. The flow rate that was estimated from mud particle movement shown in the TV video. The calculation yields that pore pressure reaches more than lithostatic pressure by 1~3 MPa ($\lambda > 1$).

The pore pressure estimate from the depth porosity trend could yield a minimum value of excess pore pressure because porosity change is only partially reversible (Screaton et al., 2002), while the estimate from the upwelling mud-flow could reflect the current pore pressure state. Our analysis indicates a significant development of excess pore pressure (nearly lithostatic) beneath the décollement zone, most likely at the depth of ~1020 mbsf where the highest overpressure was estimated from the downhole porosity trend and also an anomaly in relative hydrocarbon gas concentrations was observed (Heuer et al., 2017). Friction experiments by Sawai et al. (2016) show that a transition from stable to unstable slip behavior appears with increasing pore fluid pressure that is a prerequisite for the generation of slow earthquakes. Thus, slow earthquakes that occurred off Cape Muroto (Ito and Obara, 2005) can be attributed with the observed significant overpressure beneath the décollement.

Keywords: Nankai trough, Pore pressure, Slow earthquake, IODP Expedition 370

The role of input materials in shallow seismogenic slip at subduction zones: Initial results from IODP Expedition 362, North Sumatra

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In 2004, a Mw 9.2 earthquake ruptured the Sunda subduction zone from North Sumatra to the Andaman Islands, a length of ~1500 km, and triggered a devastating ocean-wide tsunami. This earthquake and the 2011 Tohoku-Oki Mw 9.0 earthquake showed unexpectedly shallow megathrust slip, i.e. extending further beneath the forearc than expected. In the case of North Sumatra, this shallow slip was focused beneath a distinctive plateau of the accretionary prism. This intriguing seismogenic behavior and forearc structure are not explained by existing models or by observations at many other margins where seismogenic slip typically occurs farther landward. The oceanic plate input sequence is thick and geophysically shows strong evidence for induration and dewatering and has probably reached the temperatures required for sediment-strengthening diagenetic reactions. The input materials may be key to driving the distinctive slip behavior and long-term forearc structure. IODP Expedition 362 (conducted in 2016) drilled two boreholes within the input section of the Indian oceanic plate entering the North Sumatran subduction zone. The section reaches 4-5 km at the trench, therefore the more distal and deeper part of this section was targeted where it is only ~1.5 km thick and drilling is feasible. The Expedition successfully cored the entire sedimentary sequence to, and including, the Late Cretaceous oceanic basement. This sequence includes a significant section of Nicobar Fan sediments underlain by a series of pelagic and igneous units. At U1480 coring to 1430 mbsf was completed and to 1500 mbsf at Site U1481 (both in water depths > 4100 m). In addition, a full suite of logs were collected through the entire sedimentary sequence at Site U1481. The two boreholes, U1480 and U1481, together provide a composite cored and logged section and indicate the degree of local variability of the sequence. Initial results will be presented on the lithological composition, geochemistry and physical properties of the deeper input materials where the plate boundary décollement forms. These indicate the current state and potential for diagenesis and fluid generation. Post-expedition research will include experimental work on core samples to test how frictional and physical properties will evolve with increasing burial as the section thickens towards the subduction zone. Details of depositional history of the sequence are relevant to the plate boundary fault properties and evolution of the North Sumatran forearc. They also provide information on the significance of the Nicobar Fan as part of the Indian Ocean sedimentary record, related to Indo-Eurasian collision, Himalayan-Tibetan Plateau uplift and regional climatic conditions. Ultimately post-expedition research integrating core, log and seismic data with experimental and numerical methods will aim to predict the physical, thermal, fluid, and mechanical properties and diagenetic evolution of the sediments as stresses and temperatures increase due to burial and subduction.

Keywords: subduction, megathrust properties, input materials, ocean drilling, shallow slip

Controls on faulting, earthquakes and water cycling in the Alaska subduction zone

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Subduction zones worldwide exhibit remarkable variations in seismic activity and slip behavior along strike and down dip, and many factors have been invoked to explain this variability. Here we will review constraints on plate boundary properties and the incoming oceanic plate off the Alaska Peninsula from marine seismic reflection/refraction data and their relationship to pronounced variations in earthquake behavior in this subduction zone. We observe remarkable along-strike changes in incoming sediment thickness and plate structure and along-strike and downdip variations in megathrust reflection character that correlate with changes in seismicity, locking and earthquake rupture history.

MCS reflection and wide-angle seismic data were collected off the Alaska Peninsula in July-August 2011 on the R/V *Langseth* during the Alaska Langseth Experiment to Understand the megaThrust (ALEUT) program. This region encompasses the full spectrum of coupling: 1) the weakly coupled Shumagin Gap; 2) the Semidi segment, which last ruptured in the 1938 M8.2 event, appears to be locked at present, and 3) the Kodiak asperity, the western part of the 1964 M9.2 rupture. It also exhibits substantial variations in seismicity.

Remarkable variations in bend faulting and hydration of the subducting oceanic plate are observed along strike, which may be controlled by the relationship between the orientations of pre-existing structures in the incoming oceanic plate and the subduction zone. Significantly more bending faulting is observed in MCS profiles and bathymetry data from the Shumagin Gap, where pre-existing structures are favorably aligned, than the Semidi segment where they are oblique to the trench. Abundant bending fault enables hydration of the crust and upper mantle based on a reduction in P-wave velocity from seismic refraction data. The thickness of sediment on the incoming plate also changes along strike. Up to 1.5 km of sediment are observed on the incoming oceanic plate in the Semidi segment. In the Shumagin Gap, the incoming sediment section is >0.5 km thick and more pervasively faulted at the outer rise.

These changes in bending faulting, hydration and sediment thickness on the incoming plate correlate with variations in changes in plate boundary properties and interplate and intermediate depth intraslab seismicity. In the Semidi segment, we observe a continuous 600- to 900-m-thick low velocity zone along the plate boundary to distances >30 km from the trench that we interpret as a subducted sediment layer. The subducted sediment layer in the neighboring Shumagin Gap is thinner and irregular and can only be traced to <10 km from the trench. We estimate that differences in velocity of subducted sediments relate to differences in pore fluid pressure. Although the Semidi segment is locked and capable of producing great earthquakes, very little interplate seismicity occurs here compared with the adjacent Shumagin Gap, which appears to be creeping and exhibits abundant seismicity. We suggest that the faulted oceanic crust with limited sediment entering the Shumagin Gap contributes to a more heterogeneous plate boundary at depth, which may partially account for the relative abundance of small earthquakes here compared with the Semidi segment. The Shumagin Gap is also characterized by more intermediate depth earthquakes than the Semidi segment. We suggest that more water enters the subduction zone at the Shumagin Gap

than the Semidi segment largely due to favorably oriented remnant structures, and thus more water is available to drive dehydration embrittlement and possibly intermediate-depth seismicity here.

Keywords: subduction zone, Alaska, earthquakes

Imaging the Plate Interface at the Hikurangi Subduction Margin, New Zealand

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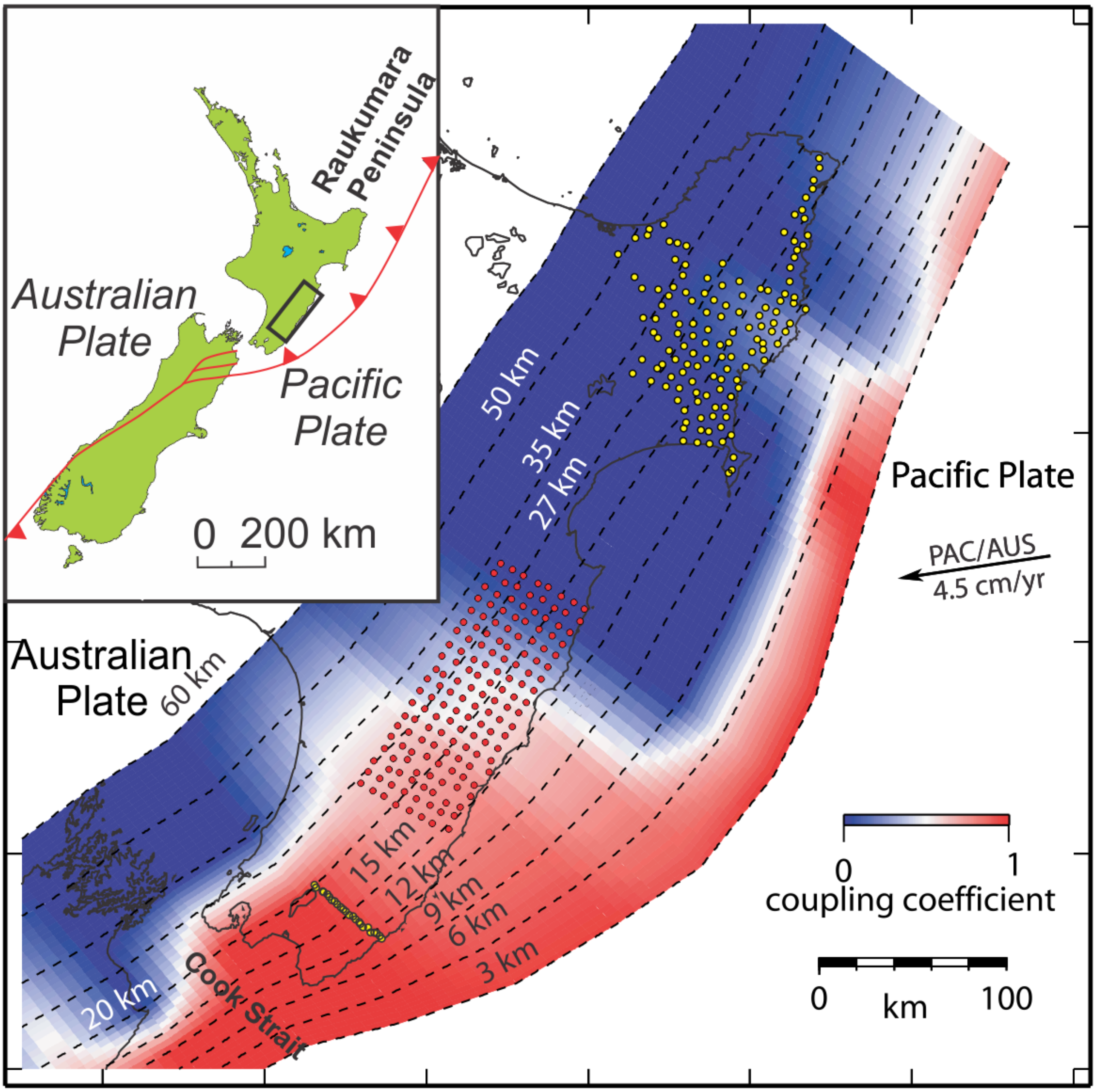
Along the Hikurangi margin on New Zealand’s east coast (Figure 1), plate-coupling changes from weakly coupled in the north to locked in the south. Slow slip events occur at shallow depth where the margin is weakly coupled. The conditions needed for slow slip are poorly understood but the presence of fluid and/or clay rich sediments may play an important role in controlling the frictional strength of the interface and thus inter-seismic plate coupling.
Magnetotelluric (MT) measurements from the northern part of the Hikurangi margin have shown that a dipping electrically conductive zone is present above the subduction interface and it is interpreted to mark fluid and/or clay rich sediments within the subduction-interface-shear-zone. A more detailed 3-D follow-up study showed that the plate is heterogeneous and higher resistivity areas of the conductive interface correlate with similar areas of seismicity within a few km of the interface. This correlation suggests that more resistive regions correspond to regions with greater frictional-strength.
A joint project between the Royal Society of New Zealand and the Japan Society for the Promotion of Science in currently underway to test this correlation. 160 MT site have been collected across the transition from weakly to strongly coupled plate interface (Figure 1) in Hawke’s Bay. Here we present the results of the data analysis and preliminary 3-D inverse modelling.

Figure 1: Map of Hikurangi subduction interface plate coupling, with a coupling coefficient of 1 being fully locked. Dashed contours show the depth to the to the subduction interface. The black arrow shows the motion of the Australian Plate relative to the Pacific. Locations of the MT measurements in the northern part of the Hikurangi margin are shown by yellow dots. Green dots show a line of measurements in the southern part of the margin and red dots the new MT sites of the joint RSNZ - JSPS research project. Insert shows the location of the Hawke’s Bay MT survey in relation to Hikurangi subduction zone where the Pacific Plate is being subducted beneath the North Island.

Keywords: plate coupling, subduction, magnetotellurics


Raukumara
Peninsula
Australian
Plate
Pacific
Plate
0 200 km
50 km
35 km
27 km
Pacific Plate
PAC/AUS
4.5 cm/yr
Australian
Plate
60 km
15 km
12 km
9 km
6 km
3 km
20 km
Cook Strait
0
1
coupling coefficient
0
km
100

Structure and physical characteristics of the Hikurangi subduction zone derived from seismic full waveform imaging

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Slip behavior along the megathrust has been shown to be closely related to the evolution of pore fluid pressures at the plate interface. Fluids released due to mineral dehydration and tectonic loading may play an important role in the onset of seismogenesis, and elevated pore fluid pressures appear to be a key environmental factor promoting shallow transient slip phenomena such as very-low-frequency earthquakes, episodic tremor and slow sleep events.

In recent years, seismic attributes and velocity images obtained from active source seismic data have provided a promising opportunity to infer porosity, fluid pressure and effective stress at the plate interface and within the overlying accretionary wedge. However, due to the limitations underpinning traditional velocity analysis and ray-based tomography approaches, the resolution and accuracy of existing velocity models remain limited. Full waveform inversion (FWI) is a powerful alternative to those traditional approaches. It uses the phase and amplitude information contained in seismic data to produce structurally accurate high-resolution physical models of the Earth.

Here, we applied elastic FWI along a 90-km-long 2D multichannel seismic profile crossing the southern Hikurangi convergent margin, New Zealand. Our processing sequence included: (1) a downward continuation of the seismic data to the seafloor, (2) 2D traveltime tomography, and (3) full waveform inversion of both refracted and reflected energy. Our final model provides exceptional constraints concerning the structure and physical properties of this convergent margin. We will describe the implications of our results for the first-order structure of the overthrusting plate, the distribution of high pore-fluid pressures and the distribution of slow-slip events along the southern Hikurangi margin.

Keywords: convergent margin, subduction zone, Hikurangi margin, full waveform inversion, pore fluid pressure, slow slip events

Continuous shear wave signals following 2014 Mw 6.8 SSE in the Hikurangi subduction margin offshore New Zealand

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The Hikurangi Plateau having anomalously thick oceanic crust subducts under the Australian plate along the Hikurangi subduction zone offshore the North Island of New Zealand. The plate interface is shallow and some characteristics on the plate interface such as seamounts and seismic high reflectivity zones were identified by seismic surveys (Bell et al., 2010). At the Hikurangi subduction margin, slow slip events (SSEs) occur at intervals of 18 to 24 months with durations of 1 to 2 weeks. From May, 2014, to June, 2016, the Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip (HOBITSS) observation was conducted in the northern Hikurangi margin. During this observation, Mw 6.8 SSE occurred in September through October, 2014, directly beneath the ocean bottom seismometer (OBS) network.
In this study, we used continuous waveform data recorded by these OBSs, and applied a shear wave splitting analysis (Ando et al., 1983) and a polarization analysis for monitoring shear wave signals. These methods have been successfully applied to waveform data from onshore seismic networks in Cascadia subduction zone by Bostock and Christensen (2012) and in Shikoku Island, Japan, by Ishise and Nishida (2015).
As a result, we detected continuous arrival of shear wave signals that appeared to have started in the later half of the SSE duration reported by Wallace et al. (2016). Parts of the continuous signals were identified as tremors and their source locations have been determined by the envelope cross-correlation method (Todd et al., 2016). Our result, however, suggests that the transmission of the signals were rather continuous than sporadic as individual events, and they appeared to last for more than two weeks. Polarization direction became stable in synchronous with the continuous signals and its orientation is different from that in the other times. Arrivals of such continuous long-duration signals with a stable polarization direction are only seen during this period through the year-long OBS records. Our analysis requires less OBSs than envelope cross-correlation methods for monitoring such shear wave signals, which may enable us to detect as yet to be unidentified continuous signals in the Hikurangi margin where seismic attenuation has been known to be large.
Distribution of the OBS stations detecting such continuous signals infers that they were generated only around the subducted seamount adjacent to the slow slip area. A previous study on distribution of this SSE obtained by inversion of seafloor vertical displacement data from ocean bottom absolute pressure gauges (Wallace et al., 2016) showed that the fault slip along the plate interface circumvented the subducted seamount. By combining these results about slip distribution and the origin of continuous shear wave signals, we can put more constraints on relationship between frictional properties along the plate interface and its topographic features.

Keywords: Seismicity, Slow Slip, Hikurangi subduction zone, Subducted Seamount

Widespread slow slip events triggered at the Hikurangi subduction zone by the M7.8 Kaikoura earthquake, New Zealand

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Just after midnight on 14 Nov 2016 (NZ Local time), the M7.8 Kaikoura earthquake ruptured a complex sequence of strike-slip and reverse faults over an approximately 150 km length in the northeastern South Island of New Zealand (Hamling et al., in review). Immediately following the earthquake, continuous GPS sites operated by GeoNet (www.geonet.org.nz) along the North Island’s east coast (above the Hikurangi subduction zone) detected several to 30 mm of eastward motion over the two-week period immediately following the M7.8 event. These sites are located 350-650 km from the M7.8 earthquake. Such large eastward motion along the North Island’s east coast following the earthquake is consistent with the initiation of a large slow slip event along the shallow, offshore portion of the Hikurangi subduction zone. The largest SSE slip is observed offshore the southern Hawkes Bay region (~10 cm), and was accompanied by abundant seismicity in the SSE region, with numerous events in the Mw 2.0-5.0 range, and as high as Mw 6.0. In addition to shallow slow slip (<15 km depth) triggered offshore the east coast, we also observe deeper slow slip (>30 km depth) triggered in the Kapiti region at the southern Hikurangi margin, as well as afterslip on the subduction interface beneath the northern South Island beneath the region of large coseismic slip on crustal faults in the M7.8 earthquake. This observation of slip beneath the northern South Island is the first strong evidence that the far southern end of the Hikurangi subduction zone does indeed accommodate plate motion and undergoes slip, in contrast to the widely held assumption that the plate interface there is “permanently locked”.

Given the large distance of the shallow east coast SSE from the M7.8 earthquake, we suggest that the shallow SSE was more likely to be triggered by dynamic stress changes, while the deeper SSEs closer to the Mw 7.8 were more likely triggered by static stress changes. We show that dynamic stresses induced in the shallow (east coast) SSE source were on the order of 200-700 kPa, which is 1000 times higher than static coulomb stress changes (0.2-0.7 kPa) induced in the SSE source region by the earthquake. The large magnitude and immediate onset of the SSE following the earthquake, long distance from the M7.8 earthquake, and the broad regional extent arguably makes this the clearest example ever documented of large-scale dynamic triggering of slow slip. We show that dynamic stress changes will be largest on the shallow portion of the subduction interface (<10 km) where it is overlain by low velocity sediment, demonstrating that large-scale shallow SSEs may be more easily triggered by dynamic stress changes compared to deep SSEs. We also discuss the role that the triggered slip events may play in the future likelihood of megathrust earthquakes at the Hikurangi margin.

Keywords: subduction , slow slip event, earthquake

Near-source detection of near repeating seismicity triggered by shallow slow-slip, Northern Hikurangi, New Zealand

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The northern Hikurangi margin, offshore from Gisborne, New Zealand, exhibits a diverse range of interrelated seismogenic phenomena, including shallow slow-slip events (SSEs), large M>7 tsunamigenic earthquakes, microseismicity and tectonic tremor. SSEs at the northern Hikurangi repeatedly occur every 18-24 months, last for a few weeks, and exhibit large (>10 cm) displacements. In this study, we utilize data from a network of 15 ocean bottom seismometers (OBS) deployed between May 2014 –June 2015 (the Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip, HOBITSS, experiment). This network was centred above the source region for two 1947 slow tsunami earthquakes and a large shallow SSE that occurred in late 2014 producing maximum slip of 20 cm, with ~5 cm of slip propagating to within 2 km of the seafloor.

Here we focus on characterizing spatio-temporal patterns in microseismicity asssociated with this 2014 SSE. Earlier SSEs in the region are known to have produced increased rates of seismicity down-dip of the geodetically modelled slip patch, consistent with regions of increased Coulomb failure stress on the megathrust as a result of interface slip during the SSE. Our study, which includes data from OBS instruments and terrestrial broadband and short-period instruments from the national GeoNet network, offers an improved, near-field insight into microseismic processes occurring during a shallow SSE, allowing for improved location and detection capabilities, and inferences on triggering processes.

To catalog microseismicity we utilize a network-wide matched-filter detection routine, using templates of clearly identifiable earthquakes to detect further microseismic events. This way, many smaller events are detected, particularly those which may be obscured in the coda of preceeding overlapping events, or those occurring below the noise level, leading to a lower catalog completeness than using classical energy-based detection methods. We initially identify local template events with a high signal to noise ratio using amplitude-based triggering and manual inspection of waveforms. P-and S-phases, cut to 2 second windows, from these template events are then used to perform waveform cross-correlation detection in the frequency domain. Following detection, the spatial pattern of microseismicity is examined by computing high precision relative locations through generation of lagged single channel cross-correlation derived phase picks. This method produces automatic phase picks to sub-sample accuracy, and allows for variation of detection location from that of the template event. We also identify repeating earthquakes, those events which exhibit high correlation coefficients and represent repeated failure of the same asperity, to constrain fault slip rates.

Keywords: microseismicity, slow-slip, subduction, matched-filter, New Zealand, Hikurangi

Seismic images from the outer rise to the Japan Trench for site characterization of new IODP subduction zone drilling projects

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Results of IODP 343/344T JFAST, which was done as a rapid response drilling to the seismogenic fault of the 2011 Tohoku-oki earthquake, shows important new findings to understand a cause of a large slip reaching to the trench axis, e.g., a very low dynamic frictional coefficient obtained by temperature monitoring and a laboratory experiment using a core sample. However, continuous core down to the plate boundary fault have not been recovered. Moreover, since JFAST is a single drill hole to the fault zone, the results from JFAST cannot reveal along- and across-trench variation of physical and chemical property of the fault. In order to examine physical and chemical properties to control variation of the fault slip, two across-trench drilling transects are proposed in the large slip zone and a small slip zone. Another IODP project, H-ODIN, is proposed to drill a fault zone of a large normal fault earthquake in the outer rise close to the Japan Trench. JAMSTEC has been conducting marine geological/geophysical projects to cover the axis of Japan Trench and the outer rise as a part of two JSPS projects. The seismic data from those survey are used to make site characterization of the two IODP projects. In order to meet scientific objectives of JTRACK , and also a technical limitation (i.e., a drilling target should be at around ~1000 m below the seafloor in an area where water depth around 7000 m), we selected the two drilling transects at 38 N as a large slip zone and 38.5 as a small slip zone based on differential bathymetry data and high resolution seismic data. H-ODIN needs to drill an outer rise normal fault. However, a clear normal fault in the Japan Trench have not been imaged. In order to identify a potential normal fault extending from the seafloor to the mantle we, therefore, use seismicity data and deep penetration seismic profiles. Because, some of clusters of the aftershocks of the 2011 Tohoku-oki earthquake, predominantly normal fault aftershocks, extend to deeper in the mantle (~40 km deep) in an area where the Moho reflection is obscure, which is interpreted to be formed by a fault reaching the uppermost mantle through the Moho. In our presentation, we show the new seismic data showing seismic characters of the candidate sites of JTRACK an H-ODIN.

Keywords: seismic imaging, Earthquake, Trench

Could decadal variations in the ocean accelerate plate subduction in the Japan Trench before the 2011 M9 Tohoku earthquake?

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Recent seismological observations have revealed that tides within diurnal bands can trigger non-volcanic tremors occurring on the down-dip extension of the megathrust faults in Cascadia and Nankai. Tidal stresses can be related with the Coulomb Failure Stress (dCFS) associated with fault slip on the plate interface. Previous studies indicate that numbers of tremors tend to increase exponentially with dCFS, implying that plate subduction speed in the transition zone fluctuates in accordance with tides. It was also found that tidal responses of tremors change during the occurrence of a slow slip event (SSE).

Compared with short-term tidal responses, relatively few researches have been conducted for periods longer than a day. Ide and Tanaka (2014) explained annual and 18.6-year variations in tremors and seismicity of shallower earthquakes in the Nankai region with tidal responses. Pollitz et al. (2013) applied a hydrological surface loading model to interpret the periodicity of tremors in Cascadia. Tanaka et al. (2015) showed that subduction speed and seismicity in the Tokai area correlated with the Kuroshio Current.

Mavrommatis et al. (2014) found from GNSS data during 1996—2011 that subduction speed gradually accelerated at depths below the coseismic rupture zone of the 2011 M-9 Tohoku earthquake. Nucleation is a possible interpretation of its cause. However, a rapid acceleration just before the earthquake, which has been predicted by ordinary earthquake-cycle simulations, was not observed. Another interpretation is that a long-term SSE occurred. However, no SSE has been reported so far which keeps accelerating as long as 15 years.

In this study, based on Tanaka et al. (2015), we investigate frictional properties required, if a slip response of the transition zone to long-term variations in the ocean could reproduce the above acceleration. We construct a slip model consisting of two elements, representing the acceleration area and a portion below it. The acceleration area is expressed by a spring slider with velocity-weakening friction having a small value of b-a (>0). Rate-and-state law is employed for this area. The lower portion is phenomenologically described and assumed to have an extremely low effective normal stress, by which slip speed fluctuates by tidal and non-tidal stress changes according to a form of V=V_0 exp (dCFS/A) as in the tremor zones. This portion gives traction to the acceleration area.

The result indicates that, in order that the predicted slip agrees with the observed acceleration, the coefficient A is one order of magnitude smaller than that for tidal responses of tremors. When effective normal stress is equal to 1 MPa or lower, the effect of the non-tidal variation in the ocean with a period longer than 10 years becomes dominant in the slip history, which successfully reproduces the observed acceleration. Moreover, the inferred slip history exhibits smaller-magnitude SSEs with reccurence periods of 2-3 years. This feature is consistent with that obtained from an analysis of repeating earthquakes in the Japan Trench (Uchida et al. 2016) When effective normal stress is larger, the effects of the external stresses are almost negligible and SSEs with larger magnitudes and longer intervals occur as in the Bungo Channel.

Meteorological studies indicate that sea level variations in Tohoku have periods of 10-20 years. If plate subduction speed is subject to long-term ocean loads, slip acceleration should occur also in the past. Actually, the predicted slip velocity during 1990-1995 by the model is faster than in 1996-2000, when M-8 class earthquakes occurred in NE Japan. We will investigate if such a correspondence can be seen between past earthquake/crustal deformation data and long-term variations in the ocean.

Keywords: Slow earthquakes, earthquake triggering , slow slip, crustal deformation, tides, ocean bottom pressure

Along-strike segmentation of Japan Trench and its relevance to co- and postseismic slip of the 2011 Tohoku Earthquake

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Remarkable variations along Japan Trench have been identified in seafloor topography, sub-seafloor seismic structure, and spatial distribution of interplate seismicity, and evident segmentation have been pointed out. We revisit the segmentation of the Tohoku forearc to see if the along-arc segmentation is relevant to the co- and postseismic behaviors of the subduction megathrust ruptured during the 2011 Tohoku earthquake. Prior to the occurrence of the 2011 earthquake, evident aseismic zone is recognized along the Japan Trench. The spatial extent the aseismic zone corresponds to that of material of low seismic velocity and low density along the plate boundary. In the southern part with broad aseismic zone, substantial afterslip on the shallow fault is evidenced by the seafloor geodetic data. Spatial extent of the pre-2011 aseismic zone coincides well to that of the afterslip zone. The correspondences between the low-V and low-density material distribution near the trench axis and the behavior of the plate boundary fault indicate that the material makes the fault to have velocity-strengthening character inhibiting interplate earthquake nucleation but allowing aseismic slip. The aseismic zone has the smallest downdip width in the central part of the Japan Trench, where coseismic slip breached to the trench axis, suggesting that along-strike variation of size of the velocity-strengthening zone controlled the rupture propagation during the 2011 mainshock. It seems there are systematic correlation between the along-strike variation of the segmentation pointed out here and regionality in recurrence cycles estimated from the palaeoseismological records recovered from the trench for past ~ 9,000 years. The segmentation might have been persistent and governed the earthquake cycle along the Japan Trench.

Keywords: Japan Trench, Interplate seismicity, 2011 Tohoku-oki Earthquake

Spatio-temporal variation of the postseismic deformation of the 2011 Tohoku Earthquake based on terrestrial and seafloor observations

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Introduction
On March 11, 2011, the 2011 Tohoku Earthquake (M 9.0) occurred on the plate boundary between the subducting Pacific and overriding continental plates. Clear postseismic deformations are still being detected in terrestrial and seafloor geodetic observations on and around the Japanese Islands, although almost six years have passed since the event.

Sun *et al.* [2014] constructed a viscoelastic structure model based on a horizontal displacement time series from terrestrial and seafloor stations from April to December, 2011 (Period A) by means of the Finite Element Method (FEM). Iinuma *et al.* [2016] applied the FEM model to exclude the effect of viscoelastic relaxation from the observed displacement time series in order to estimate the distribution of postseismic slip on the plate interface.

Recently, Tomita *et al.* [2017, in Review] reported displacement rates at seafloor stations that were newly installed in 2012. They concluded that there is a strong trench-parallel variation in the postseismic displacement rates derived from the difference between dominant postseismic deformation factors. For instance, viscoelastic relaxation is primarily around the main rupture area of the Tohoku Earthquake, while the postseismic slip strongly affects areas south of the main rupture. In this study, we investigated the postseismic deformation field using displacement rates at the seafloor and terrestrial geodetic stations.

Data
We estimated displacement rates based on the daily coordinates at the GNSS continuous stations at the Geospatial Information Authority of Japan and Tohoku University during the period from September 2012 to May 2016 (Period B). The same period in which Tomita *et al.* [2017] estimated displacement rates at the seafloor stations. The displacement rates at the terrestrial GNSS stations were estimated by taking differences between the monthly average positions in May 2016 and September 2012.

Results and Discussion
The difference between the horizontal displacement rate fields in Periods A and B are not initially apparent. Taking a trench-normal profile that runs through the main rupture area of the Tohoku Earthquake, in the forearc region, the trench-normal displacement rates during Period B were as large as one fourth of those in Period A. The B:A ratio increases nearly monotonically, to one third, with distance from the Pacific coast. In contrast, the differences between the vertical components in Periods A and B are very clear. The large local subsidence around the Ou Backbone Range observed in Period A had almost vanished in Period B, while the uplift rates in Period B were more than half those in Period A. The low viscosity beneath the Ou Backbone Range hypothesized by Muto *et al.* [2016] to account for the large local subsidence, also accounts for the rapid decay of local deformation.

As described, the inland rheological heterogeneity strongly affects the vertical displacement rate field, while large spatial scale deformations dominate the horizontal displacement rate field. These observations suggest that viscous flow in the mantle wedge and beneath the oceanic lithosphere is the main factor controlling the horizontal displacement field.

Therefore, we estimated the distribution of interplate coupling and postseismic slip based on horizontal displacement rates and applying Sun *et al.* [2014]' s model to exclude the effects of viscoelastic relaxation. Preliminary results indicate that postseismic slip occurred at the shallow plate interface off the Fukushima and Ibaraki Prefectures and at the deep portion beneath the Pacific coast of the Iwate Prefecture during Period B, the same as Period A. Estimated back-slip in the main rupture areas of the 2011 Tohoku Earthquake indicates interplate coupling at the main rupture area has already recovered.

Keywords: The 2011 Tohoku Earthquake, Postseismic deformation, Seafloor geodesy, GNSS, Postseismic Slip, Viscoelastic relaxation

Sequential activation of reverse and normal faulting in the upper plate during the 2011 Tohoku earthquake

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The Japan Trench was generally thought to belong to the erosive margin category, on which various mechanisms have been proposed to explain its fore-arc evolution over geological time scales. On the other hand, the occurrence of the 2011 Tohoku earthquake has challenged many aspects of existing subduction zone models. In particular, recent seismic survey (Boston et al., 2017) reveals that the upper plate above the large slip area of the 2011 Tohoku earthquake contains spatially mixed reverse and normal faults, which cannot be simply explained by a long-term segmentation of basal friction along the dip direction. Various other models, such as the subducting seamount model and the dynamic Coulomb wedge model, may allow alternating faulting regime in the upper plate as a response to fluctuations in basal conditions. However, they also have their own limitations: seafloor topography map does not seem to support recent seamount activity in the main slip region of the 2011 Tohoku earthquake, while the dynamic Coulomb wedge model was primarily constructed for margins hosting non-trench-breaking megathrust earthquakes. Therefore, we need to seek other solutions for understanding the coeval development of reverse and normal faults in the upper plate near the Japan Trench.

Here we propose that some reverse and normal faults in the upper plate were dynamically activated in sequence during two distinct stages of the up-dip rupture evolution of the Tohoku earthquake. The key concept emphasizes the temporal evolution of slip profiles during trench-breaking megathrust earthquakes, augmented with the free surface effects at different stages (Xu et al., 2016). At the earlier stage before a deeply nucleated rupture reaches the trench, its slip profile shows a half-elliptical shape with a negative gradient towards the trench, while the still locked portion of basal fault near the trench is strengthened by free-surface induced clamping (Oglesby et al., 1998). Both effects promote dynamic compression and thus reverse faulting in the upper plate. At the later stage after the rupture reaches the trench, its slip profile dramatically changes to a quarter-elliptical shape with an overall positive gradient towards the trench, while the already slipped portion of basal fault near the trench is weakened by free-surface induced unclamping. Both effects now favor extensional deformation and thus normal faulting in the upper plate. Since the same near-trench portion of the upper plate can sequentially experience dynamic compression followed by dynamic extension, it allows for a final state of mixed faulting structures. Due to the nature of dynamic loadings and a possible compensation between compression and extension, the spatial extent and the total displacement of each activated fault in the upper plate could be limited. From a viewpoint of stress wave evolution, the dynamic process proposed above shares a similar physics with rock failure during an impact and spalling test. In the latter case, mixed crack families dictating different principal stress orientations can emerge, due to an overprinting of incoming compressional stress wave and reflected tensile stress wave from the end free surface. Given the rough validation by the analog rock failure test, our proposed mechanism may provide a clue for understanding the upper plate faulting structure near the Japan Trench, contributed by past megathrust earthquakes of the type similar to the 2011 Tohoku. Since this mechanism is expected to hold for any rupture that energetically reaches the trench, its validity can be further investigated in other regions known to host trench-breaking ruptures.

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Keywords: Subduction zone, Megathrust earthquakes, Upper plate faults

Laboratory insights into the wide range of slip behavior on the Tohoku plate boundary megathrust

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The plate boundary megathrust at the Japan Trench is now well known for the 2011 M_w = 9Tohoku-Oki earthquake, which generated an extraordinarily large amount of coseismic slip (several 10's of meters) at the seafloor and an enormous tsunami. This region has also experienced slow slip events which occurred within the eventual rupture area of the 2011 Tohoku earthquake. This shows that the Japan Trench can exhibit a wide range of fault slip behaviors, and understanding of role of slow earthquakes as they relate to the occurrence of both megathrust earthquakes and tsunami earthquakes is necessary to mitigate these disasters in the near future.
We use laboratory shearing experiments to characterize the frictional behavior of the Japan Trench megathrust. Samples of the plate boundary fault zone in the Tohoku region were recovered during Integrated Ocean Drilling Program Expedition 343, the Japan Trench Fast Drilling Project (JFAST). The JFAST borehole is located ~7 km from the Japan Trench axis, within the region of largest coseismic slip during the 2011 Tohoku earthquake. We use powdered gouge samples of the plate boundary fault zone in experiments conducted in a single-direct shear apparatus. We explore a range of shearing conditions which include effective normal stresses up to 19 MPa, and slip velocities as low as 2.7 nm/s, equal to the plate convergence rate at the Japan Trench (8.5 cm/yr). By employing both constant velocity and velocity-stepping tests, we evaluate both the velocity- and slip-dependence of friction.
Experiments at the plate convergence rate generate discrete strength perturbations which are interpreted to be laboratory-generated slow slip events (SSE). At in-situ stresses (7 MPa) these events have stress drops of ~3-7 % (50-120 kPa) that occur over several hours, and peak slip velocities that reach 10-25 cm/yr. Increasing normal stresses to 19 MPa produces SSE with stress drops of ~12% and peak slip rates of ~50 cm/yr. Velocity-stepping tests reveal frequent instances of velocity-weakening frictional behavior, suggesting that the Tohoku gouge has the ability to nucleate slip instabilities or quasi-instabilities at very shallow depth (~800 mbsf) and very close to the trench, and that the tendency for slip instability should increase downdip.
Because the shallow Tohoku gouge is prone to generating slow slip events, we speculate that how the fault reacts when perturbed may depend on the style of deformation that may be occurring at that particular time. To explore these effects, we analyze the slip dependence of friction induced by changes in slip velocity, using slip velocities relevant to specific slip behaviors in the Tohoku area. We report that for the Tohoku fault zone samples, increasing sliding velocity to above 1 μm/s can induce a change from steady-state friction or slip hardening friction to slip-weakening frictional behavior. In the Japan Trench region, two instances of slow fault slip were observed to be ongoing at the downdip edge of the mainshock coseismic slip zone. One of these is an SSE with a slip velocity of 0.1 μm/s, and one is afterslip of the largest Tohoku earthquake foreshock with a slip velocity of ~2 μm/s. Our measurements show that increasing slip velocity from SSE rates to 140 μm/s (the maximum velocity in our experiments) does not induce slip-weakening friction; however steps from faster rates consistent with afterslip to 140 μm/s do induce slip weakening. This suggests that the portion of the fault undergoing afterslip was likely experiencing active weakening, which may have facilitated the large coseismic slip during the mainshock of the Tohoku-Oki earthquake.

Keywords: Subduction zone, Fault, Friction, Slow Slip, Earthquake

Revealing the cascade of slow transients behind a large slow slip event

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Capable of reaching similar magnitudes to large megathrust earthquakes (Mw > 7), slow slip events play a major role in accommodating tectonic motion. These slip transients are the slow release of built-up tectonic stress along the roots of plate boundaries and are thought to represent a predominantly aseismic rupture along the plate interface that is smooth in both time and space. We demonstrate here that large slow slip events are in fact a complex cascade of short slow transients. Using a dense catalog of low-frequency earthquakes as a guide, we investigate the Mw7.5 slow slip event that happened in 2006 along the subduction interface 40 km beneath Guerrero, Mexico. We show that while the long-period surface displacements as recorded by GPS suggest a six month duration, motion in the direction of tectonic release only sporadically occurs over <60 days and its surface signature is attenuated by rapid relocking of the plate interface. These results demonstrate that our current conceptual model of slow and continuous rupture is outdated and is an artifact of low-resolution geodetic observations of a superposition of small, clustered slip events. Our proposed model of slow slip as a cascade of slow transients has important consequences for the scaling of slow slip events as it implies that we overestimate the duration T and underestimate the moment magnitude M of large slow slip events.

Keywords: slow slip, slow earthquakes, low-frequency earthquakes, subduction

Tremor analysis along the Mexican subduction zone

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In Mexico, slow earthquakes are known to occur in three areas (Guerrero, Oaxaca and Jalisco-Colima-Michoacan) of the subduction. Here we locate tremors with the same process for all parts of the subduction. It allows us to observe the spatio-temporal variations of slow earthquakes along strike. We also detect VLF events as was already done in Guerrero (Maury et al, 2016) for the whole subduction zone. This analysis is carried out for different time periods between 2005 and 2015, depending on the deployment of temporary network along the Mexican coast. In addition, permanent broadband stations of the Servicio Sismológico Nacional (Mexico) are used. The tremors detected in Oaxaca area are located farther west than previously known probably because of the more eastern location of available stations. Our results also show the spatial distribution of moment tensor along the Mexican subduction zone. The VLF sources are located at or close to the plate interface in Oaxaca and Jalisco as is observed in Guerrero. These events have magnitudes of about 3 and very low-angle to low-angle thrust mechanisms in agreement with the varying geometry of the subduction interface. The slip directions of VLF earthquakes are also consistent with the plates convergence vectors. This analysis highlight variations along strike, with tremors distribution going from a wide area with similar energy rate in Oaxaca and Guerrero to thin sparse clusters with high energy rates in the North-West area. Finally, we are comparing these variations in slow earthquakes distribution to structural variations in the Mexican subduction.

Keywords: Variations in tremor distribution along strike, Moment tensor consistent with plate motion for slow earthquakes

Compliant prisms often, but not always, enhance shallow slip and tsunami height

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Subduction zones exhibit great diversity in the size and structure of their frontal prisms, elastically compliant regions of the hanging wall extending a few to more than 30 km inboard from the trench. Many researchers have suggested, based on intuition derived from static elasticity and the assumption of constant stress drop along the plate interface, that compliant prisms would enhance shallow slip, seafloor uplift, and tsunami height during megathrust events. However, the complex rupture dynamics of megathrust events, together with the possibly of different frictional properties, such as rate-strengthening sediments, beneath the prism, motivates more detailed investigation of this problem. We present 2D dynamic rupture simulations of megathrust ruptures that account for compliant prisms, rate-and-state fault friction, and the response of a compressible ocean with gravity. Drawing upon constraints from seismic imaging, ocean drilling projects, and laboratory experiments, we explore a three-dimensional parameter space of prism size, compliance, and sub-prism friction. We find that large, compliant prisms enhance shallow slip and tsunami height when the fault beneath the prism is velocity-weakening. However, when sub-prism friction is velocity-strengthening, large, compliant prisms actually diminish shallow slip and tsunami height. In all cases, the rupture dramatically slows down to a velocity close to the prism shear wave speed as it passes beneath the prism. We also find that small prisms (less than about 10 km width) provide only a local enhancement of shallow slip and relatively little effect on tsunami height. Our study highlights the importance of the detailed prism structure and sub-prism frictional properties on megathrust ruptures and tsunami generation, and motivates subduction-zone-specific models to quantify earthquake and tsunami hazards.

Keywords: subduction zone, earthquake, tsunami, rupture dynamics, frontal prism

Residual topography and gravity anomalies reveal characteristic structure of tsunami earthquake zones

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Tsunami earthquakes are shallow, long-duration events that are depleted in short-period energy and produce larger tsunami than expected given their surface wave magnitudes. Although most explanations for these characteristics invoke weak materials on the shallow megathrust, no unique feature of subduction environments has been linked to their occurrence and tsunami earthquakes have occurred in regions with large sedimentary wedges, no sedimentary wedge, rough and smooth subducting plate bathymetry, and a wide range of convergence rates and plate ages.

We have applied spectral averaging routines to suppress the steep topographic and gravitational gradients across all subduction zones on Earth. This processing shows that tsunami earthquakes tend to occur in regions where the outer-forearc is steep (~5°), narrow (slope break within 60 km of trench) and morphologically rough/faulted. This characteristic structure is observed in nearly all tsunami earthquake zones and along-strike reductions in outer trench-slope gradient in Peru, Nicaragua, Hikurangi and NE Japan all coincide with transitions from tsunami to more typical megathrust earthquakes.

We suggest (1) a stronger basal fault is required to generate these steep wedges, and (2) the slip behavior of this shallow segment is different from its downdip neighbor. It can be strong when it is locked and the downdip region creeps. It can be strong(er) when the downdip region ruptures. For each configuration, compression of the frontal wedge may promote reactivation of out-of-sequence thrust faults, which in some regions may play a key role in tsunamigenesis. We will describe our observations within this framework and consider physical explanations for the along-strike variability implied by tsunami earthquake distributions and residual bathymetry anomalies.

Keywords: Tsunami, Earthquake, Subduction

Locking, creep and the rock record of plate interfaces and fluids

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Locking, creep and the rock record of plate interfaces and fluids

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A number of recent studies have suggested that the interseismic locking degree inverted from geodetic data at convergent plate boundaries may be closely related to slip distribution of subsequent megathrust earthquakes as found for the Maule 2010 and Tohoku 2011 earthquakes. The physical nature of locking, however, remains a matter of debate, just as the associated increasingly observed features such as creep transients and non-volcanic tremor. Linking geophysical and geodetic data collected from recent earthquakes along the Chilean plate boundary and the rock record of the ancient entirely exposed plate interface in the European Alps provides a coherent image of the processes controlling creep, seismogenic rupture and transients along the seismogenic part of a plate interface.
Seismic, seismological and geodetic data collected from the southern part of the Maule 2010 earthquake rupture zone allow identifying the spatial variability of pore fluid pressure and effective stress along the plate interface zone. The reflection seismic and the seismological data exhibit well defined changes of reflectivity and Vp/Vs ratio along the plate interface that can be correlated with different parts of the coupling zone as well as with changes during the seismic cycle. High Vp/Vs domains, identified as zones of elevated pore fluid pressure, spatially correlate with lower locking degree, and exhibit higher background seismicity as expected for partly creeping domains. In turn, unstable slip associated to a higher degree of locking is promoted in lower pore fluid pressure domains. In the gradient zone towards deeper domains locking and the elevated Vp/Vs-ratio gradually decrease to low values and are largely coincident with aftershock clusters and a concentration of geodetically recorded afterslip bursts following the Maule earthquake. We show that variations of pore pressure at the plate interface control locking degree variations and therefore coseismic slip distribution of large earthquakes. Finally, we speculate that pore pressure increase during the terminal stage of a seismic cycle to close to lithostatic pressure with an equivalent reduction of effective strength may be as relevant for earthquake triggering as stress loading from long-term plate convergence.
The rock record of the deeper parts of a former seismogenic subduction thrust corroborates the dominant role of high pore fluid pressures with very low effective stresses also identified with paleopiezometry. In addition, competing fabric styles varying from solution-precipitation creep to brittle fracture, involving also the formation of pseudotachylites, clearly indicate repeated transient changes in shear strain rate in the subduction channel rocks over more than 10 orders of magnitude. Finally, analyzing the scaling properties of the various styles of seismic slip to slow creep and converting theses to properties potentially observable in the rock record, we note that several strain rate regimes are distinguishable separating normal earthquakes from a group of slower features –such as slow slip, afterslip, transient creep etc. –and a final one of creep at convergence rates. At present, it appears not possible to differentiate between the various modes of accelerated slip below seismic speeds to be assigned diagnostic fabric types. Hence, the physical nature of these differences and the factors controlling them continue to be enigmatic.

Metamorphically-induced rheological heterogeneity and the deep tremor source in subduction zones

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We present data from an exhumed subduction interface that closely resembles the geologic environment of modern deep episodic tremor and slow slip (ETS). We focus on Eocene high pressure metamorphic rocks from the Cycladic Blueschist Unit on Syros Island in Greece. Metabasalts on Syros consist of intercalated blueschists and eclogites that record prograde deformation at 12-16 kbar (35-50 km) and 450-550 C-- PT conditions that overlap with the deep ETS source in warm subduction zones such as Cascadia. Textural observations, Si-in-phengite concentrations, and quartz-inclusion-in-garnet barometry indicate that all of the mineral assemblages are in equilibrium, suggesting that variations in metamorphic facies reflect protolith bulk compositions rather than significant differences in PT conditions. Furthermore, field observations reveal that the coexistence of blueschists and eclogites sets up an important rheological contrast between the two metamorphic assemblages. The blueschists exhibit planar ductile deformation fabrics, whereas eclogites distributed within the blueschist matrix exhibit boudinage, brittle shear fracturing, and veins commonly filled with quartz and high pressure minerals. We interpret the high pressure brittle deformation and veining in eclogites to reflect fluid sealing and overpressurization: the high fluid-pressures drive brittle shear and extension in strong eclogitic layers that is dampened viscously into the weaker blueschist matrix. Our observations are inconsistent with models of deep ETS that invoke changes in rate-and-state friction parameters along a narrow planar fault zone, but are consistent with the inferred prominent role of high fluid pressures from geophysical and modeling studies. We suggest a conceptual model in which ETS is controlled by coupled brittle-viscous deformation in partially eclogitized basalts embedded within high-fluid-pressure patches along the plate interface.

Keywords: episodic tremor and slow slip, subduction interface deformation, high pressure metamorphic rocks

Seismic imaging in the trench axis area of Japan and Kuril trenches off Hokkaido

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We conducted a seismic reflection survey off Hokkaido area to obtain detailed seismic reflection profiles around the Japan and Kuril trench axis in December 2016. Seven seismic lines, 4 in the northernmost Japan Trench and 3 in the westernmost Kuril Trench, were acquired during YK16-17 cruise using a 192-channel 1200-m-long streamer cable and 380 inches^3 cluster guns. Seismic images obtained in the northern Japan Trench show the landward dipping reflections in the frontal prism. Thickness of the sediment on the incoming Pacific plate is variable between ~ 200 –500 ms (two-way travel time). The thickness of the incoming sediment is thick as ~ 700 ms (two-way travel time). Stratified trench fill sediments are imaged in the Kuril Trench sections, which were not observed in the Japan Trench profiles. The stratified trench fill sediments might be related to the Kushiro Canyon located at the north of the obtained profiles.

3-D resistivity distribution around an intra-plate slow earthquake area in northern Hokkaido, Japan: relationship between serpentine and slow earthquake

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A slow earthquake of Mw 5.4 is estimated in the Dohoku area, northern Hokkaido Island (Ohzono et al., 2015). Because most of slow earthquakes have been reported in the vicinity of plate boundaries, study of the intra-plate events is important to understand the slow earthquakes. In this study, we estimated a resistivity distribution based on the 3-D inversion of magnetotelluric (MT) data at 45 sites in the Dohoku area. The inverted resistivity model shows the following features. 1) A surface conductive layer is distributed in the most part of the study area. The thickness of the conductor increases toward westward and reaches approximately 5 km at the Japan Sea side. The conductive layer is interpreted as Tertiary-Quaternary sedimentary rocks. 2) An ultra-conductive area (0.1-10 ohm-m, 0-10 km depth) is distributed around the fault of the slow earthquakes. Based on the surface geological distribution and magnetic anomaly (GSJ, 2005), the conductor possibly reflects serpentine-related geological unit associated with the slow slip events. However, a careful interpretation is required because a serpentinite sampled from a few ten meters depth at about 10 km south of the study area is not so conductive (10-100 ohm-m) (Okazaki et al., 2011). This possibly indicates that conductive fluid from deep earth fills pores of serpentine and decreased resistivity.

Stress drops of earthquakes on the Pacific plate off south-east of Hokkaido, Japan: Implications for the spatial heterogeneity of frictional properties

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We analyzed stress drops of 721 earthquakes with the magnitude of 4.0 to 5.0 off south-east of Hokkaido, Japan and investigated the spatial heterogeneity of the difference of shear strength and dynamic stress level on the Pacific plate. We deconvolved observed P and S waves with those of collocated small earthquakes and derived the source effect of the earthquakes. We then estimated corner frequencies of the earthquakes and calculated stress drops by using a circular fault model. The values of stress drop showed a spatial pattern consistent with slip distributions of historical large earthquakes. This suggests that frictional properties on the plate interface show little temporal change and their spatial pattern can be monitored by stress drops of moderate-sized earthquakes. The spatial heterogeneity would give clues for estimating the slip pattern of a future large earthquake and discussing a policy for the disaster mitigation, especially for regions where slip patterns of historical large earthquakes are unclear.

Keywords: Stress drop, Frictional properties on the Pacific plate, Spatial heterogeneity

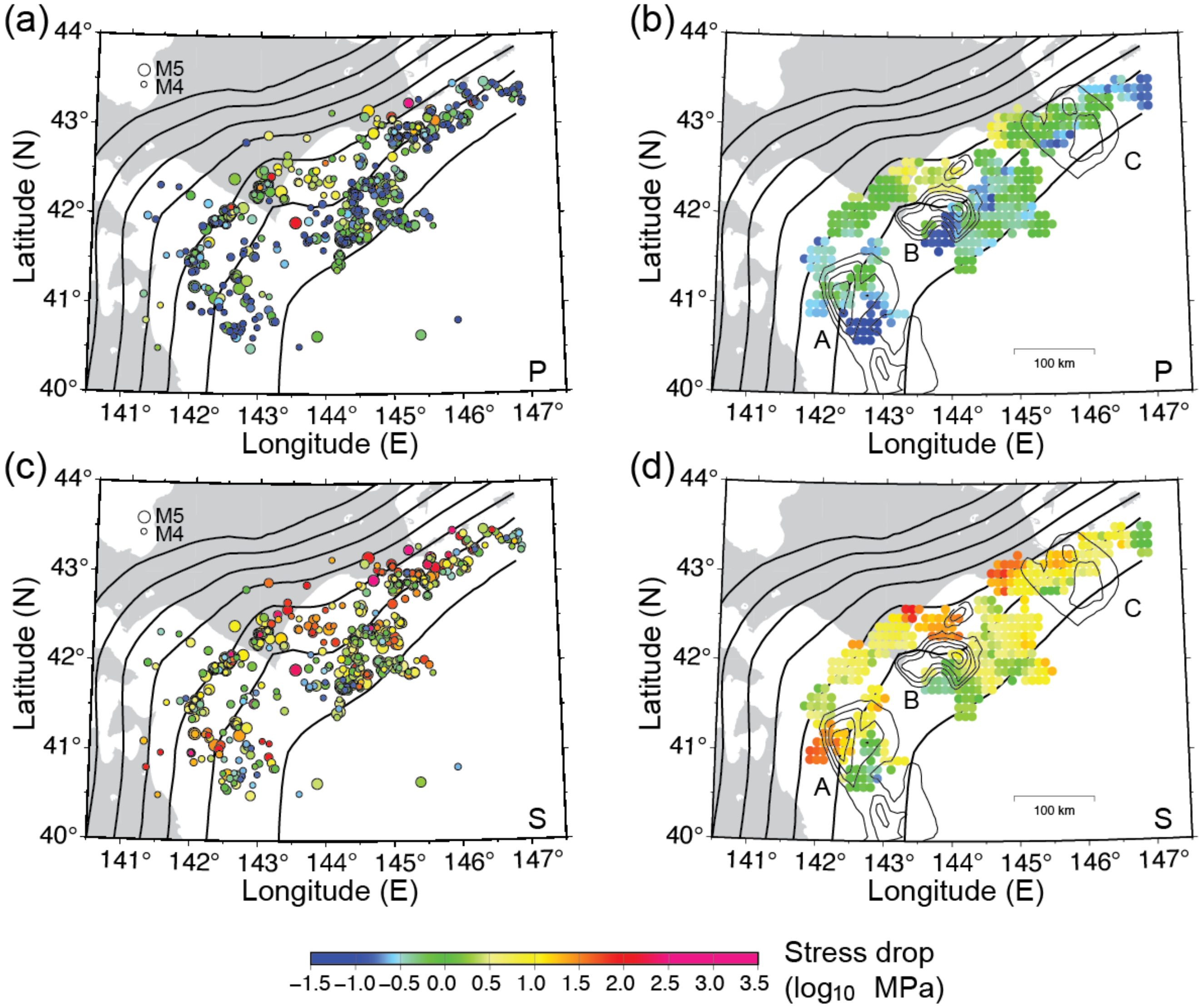

Figure 1. (a) Stress drops for individual earthquakes estimated from P waves. Scale and colour of circles indicate earthquake magnitude and value of stress drop, respectively. Thick lines show the surface depth of subducting Pacific plate (Kita et al. 2010). (b) Spatially smoothed stress drop derived from (a) at grid points with an interval of 0.1 degree in latitude and longitude. A value at each grid point was calculated as an average of stress drops of earthquakes within 15 km of the epicentral distance from the grid point. We did not put any values at grid points with less than four earthquakes within 15 km of the epicentral distance. Thin contours A through C show coseismic displacements for the 1968 Tokachi-oki (Nagai et al. 2001), the 2003 Tokachi-oki (Yamanaka and Kikuchi 2003), and the 1973 Nemuro-oki earthquakes (Yamanaka 2006), respectively with an interval of 1 m. (c) Stress drops estimated from S waves. (d) Map view of spatially smoothed stress drop derived from (c).

Source process of moderate size repeating earthquakes in eastern Japan

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In the Tohoku-Hokkaido subduction zone, several small to moderate earthquakes have occurred repeatedly at almost the same location, radiating almost identical waveforms every time. This phenomenon has been understood as repeated rupture of a patchy structure surrounded by aseismic slip area on the plate boundary (e.g., Matsuzawa et al., 2002, Igarashi et al., 2003). A typical example is the Kamaishi-Oki repeating earthquake sequence of about M4.9 recurring at almost 5.6-year interval. Many smaller earthquakes occurred in clusters in and around the slip area of the main events, suggesting some hierarchical structure in the source region. Such hierarchical structure is considered as a source of diversity in earthquake process, and may control foreshock activities. The lack of aftershocks (Uchida et al., 2012) also suggests that the rupture of main events releases almost all accumulated strain energy around this structure.

Despite a seemingly reasonable interpretation for the Kamaishi sequence, the universality of this interpretation has not been proved. It is not obvious whether similar characteristics are observed for other repeating earthquake sequences. Therefore, this study investigates several repeating sequences of moderate (M4~5) earthquakes, to discuss the applicability of the above interpretation in the Tohoku-Hokkaido subduction zone. We focus on sequences occurred almost beneath the coastline, where seismic activity looks isolated near the bottom of the seismogenic layer. Relatively good station coverage gives high resolution for source imaging. The study regions are Katori in Chiba prefecture, Mito-Oki, Naka-Oki in Ibaraki prefecture, Futabagun-Oki and Iwaki-Oki in Fukushima prefecture, and Kushiro-Oki, Urakawa and Hidaka-Oki in Hokkadio.

In each study region, we selected M > 1 earthquakes from the JMA catalog since 2002, and relocate them using the Network Cross Correlation Method (Ohta & Ide, 2008). Data are velocity records of 1 Hz short-period seismometers in vertical component at stations operated by the National Research Institute for Earth Science and Disaster Resilience (NIED), the Japan Meteorological Agency (JMA), Earthquake Research Institute (ERI), University of Tokyo, Hokkaido University, and Tohoku University. The original sampling frequency is 100 Hz, and we used 2-8 Hz bandpass filter.

In the Kushiro-Oki region, earthquakes of M~4.9 occurred fairly regularly at ~6.6 year recurrence interval. Figure 1(b) shows the relocated hypocenters by circles of approximate source size calculated using the formula of Eshelby (1957), assuming the stress drops of the earthquakes are 3 MPa. The cluster of small earthquakes are located inside the source are of the main event, suggesting some hierarchical structure. Magnitude of these small earthquakes increased before the main events, and seismic activity is relatively low after main events. Similar behavior is observed in the other seven regions.

We also estimate the slip distribution of the main events in repeating earthquake sequences using an empirical Green's function (EGF) method. Data is the same as the relocation analysis, except that 1-8 Hz bandpass filter is used. Figure 1(e) shows an example of tentative results for the Kushiro-Oki region. EGF event is a small earthquake occurred inside the slip area of the main event. The snapshots indicate that the location of the initial rupture of the main event is a little shallower than that of the EGF event (cross).

References: Igarashi, T., T. Matsuzawa, and A. Hasegawa, JGR, 2003; Matsuzawa, T., T. Igarashi, and A. Hasegawa, GRL, 2002; Ohta, K., and S. Ide, EPS, 2008, Uchida, N., T. Matsuzawa, W. L. Ellsworth, K. Imanishi, K. Shimamura, and A. Hasegawa, GJI, 2012.

Keywords: Repeating earthquake, Hierarchical structure

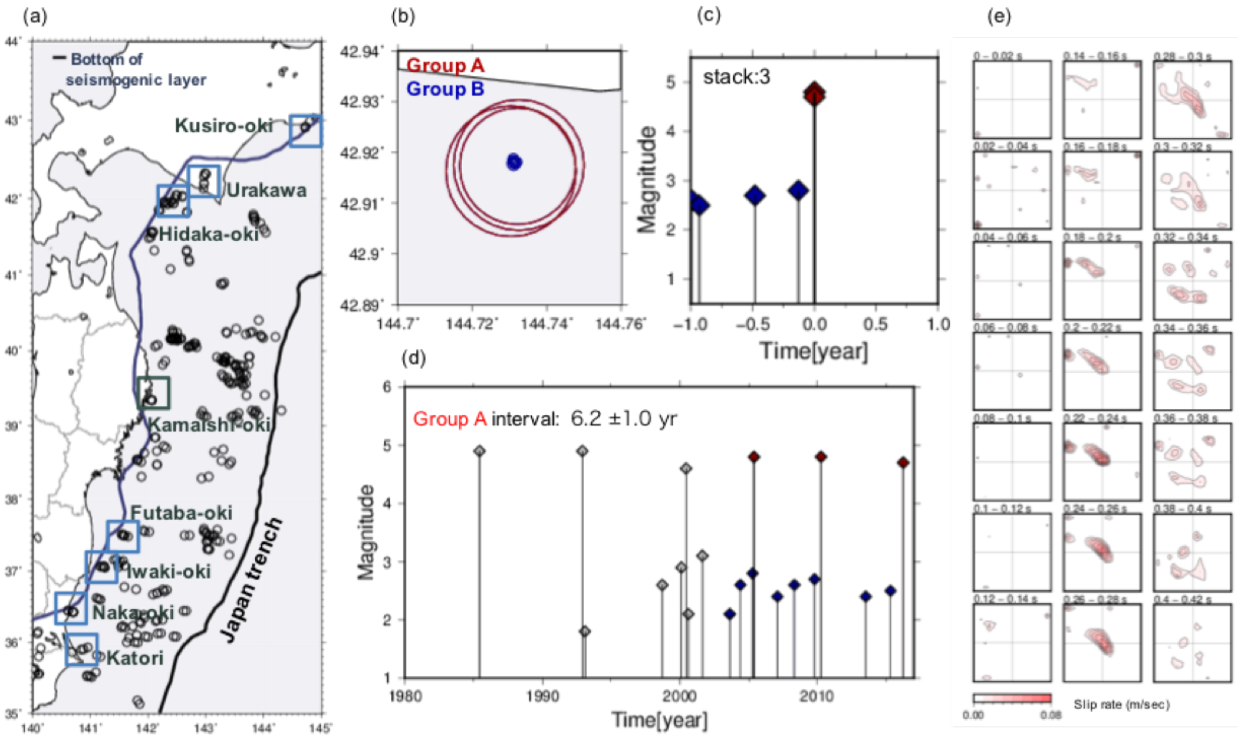

Figure 1. Source process analysis of Kushiro-oki repeating earthquake.
(a) Study region. (b) the location of hypocenter and the size of circle shows the approximate source size calculated using the formula of Eshelby (1957), assuming the stress drops of the earthquakes are 3 MPa. (c) MT diagram for one year before and after the M ~ 4.9 sequence. The data for 2005, 2010 and 2015 earthquakes are collapsed based on the occurrence time of the each earthquake. (d) MT diagram for Kushiro-Oki region. (e) Slip evolution of the 2010 earthquake.

Finite fault model of the 2012 intraslab earthquake doublet and its implication for coseismic stress change in the Pacific plate associated with the 2011 Tohoku-Oki earthquake

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On December 7, 2012, an intraslab earthquake doublet, composed of a thrust deep earthquake (subevent 1, 57.8 km, Mw 7.2, Global CMT) and a normal shallow earthquake (subevent 2, 19.5 km, Mw 7.2) with time interval of 12 s, occurred near the Japan Trench, where the extremely large coseismic slip happened during the 2011 Tohoku-Oki earthquake (Mw 9.0). In the subducting Pacific slab in the area, the horizontal tensional and compressional stress fields associated with the slab bending had been developed in the shallow part and the deep part, respectively, prior to the 2011 earthquake (e.g., Gamage et al., 2009, JGR). Obana et al. (2012, GRL) found that the depth of the lower limit of the shallow normal faulting earthquake activity was deepened after the 2011 Tohoku-Oki earthquake, and suggested the stress state in the subducting slab changed.
Since it is expected that the vertical extents of the faults of the two subevents correspond to those of the tensional and compressional stress field in the subducting slab after the Tohoku-Oki earthquake, the vertical stress variation can be discussed by estimating fault models of the subevents in detail. But it is not easy to separate the source processes of the two subevents because two subevents occurred almost simultaneously. However, since the shallow subevent 2 is expected to excite tsunami much more efficiently than the deep subevent 1, it is expected that tsunami data will put strong constraint on the fault model of the subevent 2, which is especially difficult to constrain the source process from the seismic data. In this study, we analyzed the tsunami data associated with the 2012 doublet observed by the ocean bottom pressure gauges deployed around the focal area. Based on the results of tsunami data analyses, we discussed the depth variation of the stress field in the subducting slab after the Tohoku-Oki earthquake.
We first inverted the tsunami waveforms for the spatial distribution of seafloor vertical deformation (the tsunami source model). The obtained distribution has a zone of large subsidence and another with smaller uplift. The location and spatial extent of the subsided area are consistent with those of the seafloor displacement field expected from the Global CMT solution of the subevent 2. We estimated the fault model of the subevent 2 based on the spatial pattern of the seafloor subsidence and the aftershock distribution (Obana et al., 2014, EPS; 2015, AGU FM). The seafloor displacement field due to the subevent 1 was obtained by subtracting the seafloor deformation field, which is calculated from the fault model of the subevent 2, from the tsunami source model and we sought the optimum fault model of subevent 1 explaining the vertical displacement field. We reanalyzed teleseismic data to obtain CMT solution of the subevent giving additional constraint on the fault model. Based on the estimated fault model, the bottom of the shallow normal-faulting subevent 2 and the top of the deep thrust-faulting subevent 1 were located at 35 –40 km and 45 –50 km, respectively. These depths are obviously deeper than the lower limit of the normal-faulting earthquakes (~25 km) and the upper limit of the thrust-faulting earthquakes (40 –45 km) before the Tohoku-Oki earthquake by ~ 5 –10 km. The depth changes are probably caused by the static stress change associated with the Tohoku-Oki earthquake. However, considering the vertical stress gradient of the bending stress (~15 MPa/km) expected from the geometry and elastic property the Pacific plate, the static stress change associated with the Tohoku-Oki earthquake (~10 MPa) cannot change the depth profile of the intraslab field as large as seen in the change in

seismogenic depth we observed. This suggests that the depth change is caused not only by the static stress change of the Tohoku-Oki earthquake but also the increase of the normal-faulting seismicity at ~35–40 km depth associated with the decrease of the fault strength after the Tohoku-Oki earthquake.

Keywords: tsunami, The 2011 Tohoku-Oki earthquake, intraslab earthquake

Seafloor displacement in the northern Japan Trench examined by bathymetric surveys after the 2011 Tohoku-oki earthquake

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Maximum tsunami height caused by the 11 March 2011 Tohoku-oki earthquake (M_W 9.0) was observed at the coast of Sanriku, the northern Tohoku at ~39.5N [The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011]. Therefore, in order to explain the tsunami source, some papers have introduced additional large fault slip of the megathrust up to ~40 m near the Japan Trench [e.g. Satake et al., BSSA 2013]. Alternatively, others preferred to put a large change in seafloor elevation, ~100 m uplift and down-drop, associated with a submarine landslide along the lower trench slope [e.g. Tappin et al., Marine Geology 2014].

After the earthquake, we have carried out multibeam bathymetric surveys in the rupture zone. Survey tracks were aligned along the tracks obtained before the earthquake across the Japan Trench, and we analyzed the difference in bathymetry before and after the earthquake in the area near the trench. For the analysis, apparent offsets of the absolute values of depth soundings and the uncertainty of ship position were examined on the seaward side because the seaward was thought to have suffered little change from the earthquake.

The extraordinary coseismic seafloor displacement caused by the 2011 earthquake was indeed detected by the bathymetric surveys. For the survey track crossing the trench axis at 38.1N, off the coast of Miyagi Tohoku, near the epicenter, there were large relative differences landward extended up to the trench axis, suggesting the earthquake fault rupture reached the trench axis [Fujiwara et al., Science 2011; JpGU 2015; Kodaira et al., Nature Geosci. 2012].

Eventually, we had an opportunity to survey the bathymetry near the Japan Trench off Sanriku between 39.2 and 39.5N by the German research vessel Sonne in 2012 and the last year 2016 (SO219A, SO251A cruises). We acquired two survey tracks. One survey track was on the track of the JAMSTEC R/V Kairei in 2010 (KR10-12 cruise) crossing the trench axis at 39.2N and extending to the landward trench middle slope (~143.5E, 39.3N), ~50 km from the trench axis (SO219A-KR10-12). And the other was on the track of the R/V Kairei KR07-08 cruise in 2007 crossing the trench axis at 39.5N and extending to the landward trench middle slope (~143.5E, 39.4N) (SO251A-KR07-08).

As the result of comparison of the bathymetry before and after the earthquake, horizontal and vertical seafloor displacements were within the error of the analysis because the results may incorporate errors of several meters in vertical displacement and about 20 m in horizontal displacement. Very large fault slip or very large submarine landslide is unlikely at least on the two survey tracks.

Keywords: 2011 Tohoku-oki earthquake, tsunami, Japan Trench, Sanriku, multibeam bathymetry, seafloor displacement

Direct and precise geodetic measurement across the Japan Trench after the 2011 Tohoku-oki earthquake

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The 2011 Tohoku-oki earthquake (Tohoku Earthquake: M_w 9.0) caused over 50 m coseismic slip. After then many geodetic observations such as on-shore GNSS, GPS/Acoustic (GPS/A), and others, have been carried out. Especially, GPS/A played important roll to reveal large off-shore coseismic displacement and subsequent postseismic deformation, which can be interpreted by viscoelastic relaxation (Sun et al., 2014, Nature; Watanabe et al., 2014, GRL; Tomita et al., 2015, GRL) and/or afterslip. Because GPS/A observation alone cannot reveal the afterslip of megathrust in the shallow dip of the trench, "direct-path acoustic ranging", which can measure precise relative distance (e.g., ~ mm/yr precision for 1 km baseline) between two stations, was used across the trench. It periodically measures two-way travel-time and is corrected the calculated sound velocity after the recovery. Prior to this study, the same observations were conducted twice; they were 2013 (~150-days) (Osada et al., 2014, JpGU) and 2014-2015 (~250-days) (Yamamoto et al., 2016, JpGU), respectively. These observations proved the capability to measure as long as ~10 km baseline and found no significant relative motion across the trench.
In September 2015, we installed five instruments at the same, the region of large coseismic slip (e.g., Iinuma et al., 2012, JGR) and recovered in September 2016 (~360-days observation). The result shows no significant movement across the trench axis like as in the previous surveys. This result shows fully locked state and may clarify the absence of postseismic slip in the shallower part in this area and at least 2013-2016.
In March 2017, we plan to install five instruments across the Japan Trench off-Fukushima, where instead large postseismic slip (e.g., Sun and Wang, 2015, JGR; Iinuma et al., 2016, Nature Comm.). This auxiliary observation may reveal spatial variation of convergence rate along the trench axis.
Acknowledgement: This observation is supported by JSPS KAKENHI (26000002). The installation and recovery of the instruments were carried out during the KAIREI (KR15-15) and SHINSEIMARU (KS-16-14) cruises.

Keywords: 2011 Tohoku-oki earthquake, Tohoku Earthquake, seafloor geodesy, acoustic ranging

Seismic structure around the SSE event source in northeastern Japan forearc deduced by an airgun-ocean bottom survey

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Various kinds of slips have been observed along the plate boundary (PB) in the Japan Trench subduction zone. The 2011 Tohoku-oki earthquake ruptured the large area of PB fault along the Japan Trench, and a huge slip (> 40 m) happened at 37.5–38.5N in the Miyagi-oki region. Prior to the Tohoku-oki earthquake, slow slip events (SSE) also happened in 2008 and 2011 at 37.7–38.7N (Ito et al., 2012). Faults hosting slow slip events are often characterized by low seismic velocity anomalies (e.g., Obara and Kodaira, 2009). Although it is expected that the distribution of the interplate low velocity material can be identified by strong seismic reflectivity of the interface, a detail structure in the Miyagi-oki SSE source area remains unknown. To clarify a structural characteristic near the PB, which would provide useful information to understand the occurrence mechanism of SSE, we made an airgun-OBS (Ocean Bottom Seismometer) survey in the SSE source area.

The survey was carried out in 2014. Survey lines with 180 km length were slightly oblique to the Japan Trench axis and overwrapped the SSE source area at the southern section. We deployed 17 and 20 OBSs along each line with 10 and 8 km intervals. An airgun array with a total volume of 100 liter was shot with 50 m intervals along those lines.

To obtain a seismic velocity structure beneath each line, we performed a tomographic inversion using first arrival traveltimes (Fujie et al., 2013). Results of checkerboard resolution test indicated that velocity anomalies with > ˜ 15 km and ˜ 4 km in horizontal and vertical sizes can be resolved down to ˜ 25 km in depth. To investigate spatial distribution of reflectors with their intensities, we applied a traveltime mapping method (Fujie et al., 2006) to observed reflected arrivals. This method directly projects picked arrival times of observed reflection signals onto corresponding reflection points in a depth-distance domain.

The P-wave velocity (Vp) model estimated by the tomographic inversion showed distinct variation of Vp in the overriding plate; high Vp of > ˜ 4 km equivalent to the island arc crust material was estimated to the south of 39 N, whereas low Vp of < ˜ 3 km/s corresponding to unconsolidated sedimentary layer distributed in the northern part of the survey line. On the reflection mapping images, the PB was imaged as a continuous reflector at depths from 8 km to 14 km, where Vp is ˜ 5 km/s. This reflector is more distinctive beneath the island arc crust than that beneath the sedimentary layer. Since the Vps of the island arc upper crust and the oceanic layer 2 may not be different significantly, the distinctive reflections from the PB suggest the existence of a low Vp channel layer along the PB. The spatial extent of high-Vp overriding crust and the highly reflective PB, identified to the south of 39N, almost coincides with the SSE source location estimated by Ito et al. (2012). Therefore, our survey results suggest that the Miyagi-oki SSE source area is characterized by the presence of low-Vp channel layer along the PB beneath the high Vp overriding crust.

Keywords: Crustal structure, interplate reflectivity, Slow slip event

A coupled model of stress-driven frictional afterslip and viscoelastic relaxation following the 2011 Tohoku-oki earthquake

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Postseismic deformation following the 2011 Mw9.0 Tohoku-oki earthquake has been captured by both on-land GNSS and seafloor GPS/Acoustic networks. Previous studies have shown that the observed postseismic displacements can be reproduced as a sum of contributions from viscoelastic relaxation of coseismic stress changes in the upper mantle and afterslip on the plate interface surrounding the coseismic rupture. In most previous studies, viscoelastic relaxation and afterslip were modeled separately and afterslip was estimated kinematically. In this study, we develop a three-dimensional coupled model of stress-driven frictional afterslip and viscoelastic stress relaxation in order to investigate the frictional properties on the plate interface, upper mantle rheology, and the relative contributions of the viscoelastic relaxation and afterslip to the overall postseismic deformation following the 2011 Tohoku-oki earthquake.

We assume that afterslip is governed by a rate-strengthening friction law that is characterized with a friction parameter (a-b) σ. Viscoelastic relaxation of the upper mantle is modeled with a biviscous Burgers rheology that is characterized with the steady-state and transient viscosities. We calculate the evolution of afterslip and viscoelastic relaxation using an assumed coseismic slip model as the initial condition.

We examine the effects of the friction parameters, mantle viscosities, elastic thickness of the slab and upper plate, and coseismic slip distribution on the model prediction and explore the range of the parameters that can fit the observed postseismic displacements. We also examine if afterslip overlaps regions that ruptured seismically during M6.3-7.2 earthquakes from 2003 to 2010. We find that significant overlap between afterslip and the historical M6.3-7.2 coseismic rupture areas are required to fit the horizontal displacements.

Keywords: postseismic deformation, afterslip, friction, viscoelastic relaxation, 2011 Tohoku-oki earthquake

Distribution of earthquakes around the subducted seamount off Ibaraki in response to the largest Mw7.8 aftershock of the 2011 Tohoku-oki earhtquake

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M7 class earthquakes have repeatedly occurred ~100 km offshore of the Ibaraki prefecture at fairly constant time interval of 20 years. It has been revealed that there exists a subducted seamount up-dip of the source region of such repeating M7 earthquakes (Mochizuki et al., 2008). Therefore, the seamount itself does not appear to be an asperity of the large earthquakes.

The region coincides with the southern limit of the fault region of the 2011 Tohoku-oki earthquake, where its largest aftershock with Mw7.8 occurred 30 minutes after the main shock. Spatio-temporal distribution of seismicity following such large earthquakes provides important information for understanding changes of the state of the stress caused by such a large fault slip and mechanisms of earthquake generation in relation to the topographic features of the plate interface.

We collected one-year long seismic data using ocean bottom seismometers equipped with 3-component 1 Hz velocity sensors. Data were recorded at a 200 Hz sampling frequency. We installed a dense OBS array using 35 instruments around the subduction front of the subducted seamount at a spatial interval of ~6 km for about a year from October, 2010, through September, 2011. In the middle of the observation period, the 2011 Tohoku-oki earthquake and its largest aftershock occurred. The epicenter of the largest after shock is located only ~30 km to the west (donw-dip) of the array, and its rupture propagated up-dip toward the seamount. Recent studies on its rupture propagation (Honda et al., 2013; Kubo et al., 2013) revealed that the rupture stopped before it reached the subducted seamount so that its rupture area occupies the area in subduction front of the seamount. In spite of such severe situation for seismic observation, we successfully recovered data from 31 stations.

More than 20000 earthquakes around the OBS array were recorded. Visual identification and manual picking of P and S arrivals through the records of ~30 stations are unrealistic. Therefore, we applied an automatic picking method that we developed by referring to Grigoli et al. (2014). The observed waveforms were converted to characteristic functions that have high sensitivity to arrivals of seismic phases. Having 3-D seismic velocity structure around the region that has been compiled by referring to the existing seismic profiles, the characteristic functions were migrated according to the travel times from the stations to the grid points in the structure volume, and then they were stacked. We determined the hypocenter of each event by finding the maximum stacked value among the grid points.

The resulted distribution of the earthquakes shows two primary layers of seismicity. The upper layer may represent distribution of small scale faults above the seamount. We found seismically quiet region in front of the subducted seamount that appears consistent with the rupture area of the largest aftershock.

Keywords: 2011 Tohoku-oki earthquake, largest aftershock, aftershock distribution, subducted seamount

Three dimensional attenuation structure beneath the eastern part of Kii Peninsula, southwest Japan, derived from small earthquake spectra

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Low Frequency earthquakes (LFEs), one of slow earthquakes that occur in subduction zones, have been observed in the southwest Japan, especially in the Kii Peninsula. Clusters of LFEs are distributed along the isodepth contour of 30 to 40 km of the subducting Philippine Sea plate’s surface and more concentration is seen in the eastern part. Previous studies for seismic velocity and conductivity structures suggested that occurrence of such LFEs is closely related to the existence of fluid.
Q value, the parameter of seismic attenuation, has been used to study LFE because its values vary sensitively to the presence of fluid. For instance, Tsumura et al.(2016) estimated a three-dimensional attenuation structure in the Kii Peninsula, and revealed that a high Qp zone exists near LFE cluster in the western part of the study area. In the eastern part of the Kii Peninsula where LFE's activity is high, however, a detailed attenuation structure has not been estimated. Therefore in this study, we applied the inversion method (Tsumura et al., 2000) to estimate P wave attenuation structure there.
Adding to the data recorded in routine seismic stations, we used the data of the three dense seismic arrays which were settled in perpendicular or parallel direction in the east, the west and the south part of Kii Peninsula. The array length were about 90km (or 60km) with 1km station interval. Observation period were from December 2009 to May 2010 (for the E-W line in the south), from December 2010 to June 2011 (for the N-S line in the west), and from May 2015 to December 2015 (for the E-W line in the east).
We selected 302 earthquakes which were recorded at 172 seismic stations and calculated 11133 spectra for P arrivals of time window ls for taking into account ray distribution. The sampling frequency is 100 or 200 Hz for the permanent stations and 200 Hz for the temporary stations. Furthermore, in order to express a three-dimensional Q structure, we divided the study region into 9, 11, and 6 portions in latitude, longitude, depth- direction respectively.
Derived Qp images show that a low Qp zone is seen at the depths of 30 to 40km in which high activity of the DLFEs in the eastern part of the Kii Peninsula. On the contrary, we can find patch-like high Qp zones were distributed in the same depth range at the western part of the Kii Peninsula. These high Qp zones coincide with the regions where the DLFE clusters exist. Both of these high and low Qp zones corresponds to the lower Vp and high Vp/Vs regions derived from travel time tomography. Although seismic velocities derived from travel time tomography and conductivity structures indicate that the existence of fluid in the source regions of LFEs, we can see the difference between attenuation parameters estimated for the eastern and western parts of the Kii Peninsula. These results may reflect the different physical properties of the eastern and the western parts and it affects the difference of LFEs’ activity in each side of the Kii Peninsula.

Keywords: seismic attenuation, low frequency earthquake, Kii Peninsula

Heterogeneous structure in and around the slow-earthquake source region beneath the eastern Kii Peninsula, SW Japan

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The Nankai trough region, where the Philippine Sea Plate (PHS) subducts beneath the SW Japan arc, is a well-known seismogenic zone of interplate earthquakes. Recently, various slip types, including episodic tremors and very low-frequency earthquakes, have been recognized at or near the up-dip and down-dip limits of seismogenic zone (e.g., Obara, 2002; Ito and Obara, 2006). Obara(2002) suggested fluids as a source for tremor. Previous studies indicate the fluid pressure on a plate interface is one of the key factors to understand the fault slip process (e.g., Saffer and Tobin, 2011). Seismic reflection characteristics and seismic velocity variations can provide important information on the fluid-related heterogeneity of structure around plate interface. In 2006, active-source seismic experiment was conducted to obtain the subduction structure beneath the eastern part of the Kii Peninsula (Iwasaki et al., 2008). Iwasaki et al. (2008) revealed the geometry of the subducting PHS. However, little is known about the deeper part of the plate boundary, especially Vp/Vs structure in and around the source region of the slow-earthquake. Passive seismic data is useful to obtain a deep image including the S-wave velocity. Therefore, we conducted passive seismic experiment in the eastern part of the Kii Peninsula. Ninety portable seismographs were installed on a 90-km-long line nearly parallel to the direction of the subduction of the PHS with approximately 1 km spacing. Each seismograph consisted of a 1.0-Hz 3-component seismometer and an offline recorder. Waveforms were continuously recorded during the period from May 26, 2015 to December 8, 2015. The continuously recorded data obtained by the offline recorders were processed in the laboratory subsequent to the observations. First, they were divided into event files, each of which had waveform data that started from an origin time determined by the Japan Meteorological Agency. In order to obtain a high-resolution velocity model, a well-controlled hypocenter is essential. Due to this, we combined the seismic array data recorded by the offline recorders with the telemetered seismic data. We used 116 telemetered seismic stations in the present study. P- and S-wave arrivals for the 275 local earthquakes were picked, yielding 17,957 P-wave and 15,442 S-wave arrival times that were used in our analysis. To investigate the earthquake locations and three dimensional Vp and Vp/Vs structures, the double-difference tomography method (Zhang and Thurber, 2003) was applied to the P- and S-wave arrival time data obtained from 275 local earthquakes. The initial 1-D velocity model used in the present study was obtained by resampling the 1-D velocity model calculated by the joint hypocenter determination technique (Kissling et al., 1994). The final 3-D velocity structures are resolved down to 50 km depth. Hypocenter distribution associated with the underthrusting of the PHS is located beneath the subducting oceanic Moho. Most low-frequency earthquakes (LFEs) are located within subducting oceanic crust. Reported strong reflector interpreted to be the top of the PHS (Iwasaki et al., 2008) well corresponds to the top of the LFE zone. LFEs are also located in and around the low Vp and high Vp/Vs zone. The low Vp and high Vp/Vs zone generally suggests the existence of fluid (e.g., Zhao et al., 1996). The obtained fluid-related heterogeneous structure is clearly correlated with the source region of the LFE. These results indicate the occurrence of the LFEs may be associated with fluids. Previous research has indicated that zones of high pore-fluid pressure are marked by high reflectivity and/or high Vp/Vs (e.g., Kodaira et al., 2004). These studies suggest that fluids dehydrated from the PHS may control the degree of plate coupling.

Keywords: Philippine Sea plate, Seismic tomography, Velocity structure, Low-frequency earthquake

Lateral variation of low S-wave velocity zone in the Nankai accretionary prism derived from Rayleigh admittance

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A cabled seafloor network (DONET: Dense Oceanfloor Network System for Earthquake and Tsunamis) has been constructed on the accretionary prism at the Nankai subduction zone of Japan since March 2010. DONET contains 22 stations in DONET1 (eastern network) and 29 stations in DONET2 (western network), and the their observation periods exceed more than 5 years and 10 months, respectively. In this study, using Rayleigh waves of microseisms and earthquakes, we calculate the Rayleigh admittance (Ruan et al., 2014, JGR) at the seafloor for each station, i.e., an amplitude transfer function from pressure to displacement, particularly for the frequencies of 0.1–0.2 Hz (ambient noise) and 0.04–0.1 Hz (earthquake signal), and estimate one-dimensional S-wave velocity (Vs) structure beneath stations in DONET.
Each station contains broadband seismometers and absolute and differential pressure gauges. We calculated the displacement seismogram by removing the instrument response from the velocity seismogram for each station. The pressure record observed at the differential pressure gauge was used in this study because of a high resolution of the pressure observation. In addition to Rayleigh waves of microseisms in ambient noise, we collected waveforms of Rayleigh waves for earthquakes with an epicentral distance of 15–90º, M>5.0, and focal depth shallower than 50 km. In the frequency domain, we smoothed the transfer function of displacement/pressure with the Parzen window of ±0.01 Hz. In order to determine one-dimensional Vs profiles, we performed a nonlinear inversion technique, i.e., simulated annealing.
As a result, Vs profiles obtained at stations near the land show simple Vs structure, i.e., Vs increases with increasing depth. However, some profiles at the toe of the acceretionary prism in southwest and southeast of the Kii Peninsula have a low-velocity zone (LVZ) at a depth of 5–7 km within the sediment. The Vs reduction is approximately at most 30 %. On the other hand, such Vs reductions cannot be seen south of the Kii Peninsula. Park et al. (2010) reported a large reduction in P-wave velocity within the region of DONET1 (eastern network and southeast of the Kii Peninsula), but our result shows the LVZ in the regions of both DONET1 and 2 (2: western network and south-southwest of the Kii Peninsula). This indicates lateral variation of low Vs zone at the toe of the Nankai accretionary prism. We will discuss the spatial relationship between the LVZ distribution and the active regions of very low frequency earthquakes.

Keywords: Low velocity zone, Accretionary prism, Lateral variation

Low velocity zones along subducting plates: comparative study between southwest Japan and Cascadia subduction zones

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Low velocity zones (LVZs) along subducting oceanic plates are a ubiquitous feature of subduction zones worldwide. The LVZ has been interpreted as a hydrated oceanic crust from its high Vp/Vs ratio and is thought to affect generation of episodic tremor and slip (ETS) events. Southwest (SW) Japan and Cascadia subduction zones are well-investigated in terms of the LVZ properties. However, a direct comparison of LVZ properties between these subduction zones is difficult due to the difference in analysis methods: tomographic methods are often used in SW Japan, versus receiver function methods in Cascadia. In this study, we solve for LVZ properties beneath SW Japan through receiver function inversion analysis. This analysis optimizes model parameters (thickness, Vp/Vs ratio, dip angle and strike of layered structure) such that synthetic waveforms reproduce observed waveforms recorded by a linear array of seismographs installed in the Tokai region in 2008 (Kato et al., 2010, GRL). The results show that the LVZ is characterized higher Vp/Vs ratios (> 2.0) than previous estimates from tomographic analyses. In addition, the Vp/Vs ratio shows along-dip variation, culminating where ETS and long-term slow-slip events occur. This suggests that high pore fluid pressure plays an important role in generating ETS and long-term slow-slip events. A detailed look at high-frequency receiver function waveforms suggests that the LVZ is likely to be composed of two layers. Such high Vp/Vs ratios (> 2.0) and two-layer structure of the LVZ are also reported for Cascadia. However, whether along-dip variation of Vp/Vs ratio exists or not is still open question for Cascadia. Further efforts to reveal such variations at Cascadia is left for future study. Detailed comparison of LVZ properties may lead to improved understanding of ETS mechanisms.

Keywords: Subduction zone, Low velocity zone, Receiver function analysis

Improved 3D seismic image in Nankai Trough off Kumano

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In Nankai Trough off Kumano, a 3D seismic survey was conducted in 2006 as a preliminary site survey of IODP NanTroSEIZE project. It has revealed three-dimensional structures of the magasplay fault system, details of deformation in frontal thrust zone, and development of forearc basin system in this area. However, it is still unclear about details in older accretionary sediments beneath Kumano forearc basin due to low signal-to-noise ratio and low resolution image in the complex structures after the initial data processing and depth imaging in 2006. In order to improve the seismic reflection image of dynamic deformation, we reprocessed the 3D seismic dataset from the original field records by applying new technologies advanced in a decade after the data acquisition and initial processing.

Big matters of the seismic data are effects of multiple reflections smearing the deep target signals in the deep-water and of the cable feathering due to high-speed Kuroshio current. The multiple reflections and the strong noise were better attenuated by applying advanced processing techniques in combination. Non-uniform fold distribution due to the cable feathering could be regularized by means of the optimized 4D trace interpolation, which is important to improve the data quality, too. The recent broadband processing with full deghosting and optimized zero phasing could enhance low frequency energy and improve the image quality with enhanced broadband signals. Then, velocity model building (VMB) and pre-stack depth migration (PSDM) considering tilted transversely isotropic (TTI) anisotropy media were carried out with a data-driven algorithm updating the velocity model based on a reflection tomography with Beam PSDM.

The final improved reflection images show new geological aspects, such as clear steep dip faults around the notch, and fine scale faults related to main thrusts in frontal thrust zone. It is expected that the anisotropic PSDM can image the complex structures at true locations with the steep dip or deformation. In the deeper part after multiple reflections were well attenuated, some dipping reflectors can be clearly observed above the megasplay faults. The mega-splay fault has curved surface with downward convex, and the new velocity model indicates the existence of high velocity zone above the mega splay fault with 1.5 - 2.0 km thickness and the maximum value more than 5,000 m/s. In further studies, we should investigate relationship of the reflection structures and the velocity profile using other seismic data in this area, because the depth is larger than the length of the streamer cables. In addition, the detail structure interpretation of the three-dimensional dynamic deformation and analysis of physical properties derived from the improved seismic data with velocity information will contribute to understanding the plate subduction system and success of the deep drilling towards seismogenic zone in the Nankai Trough.

Keywords: Nankai Trough seismogenic zone , 3D seismic survey

Connecting faults and fractures with clay formation and fluid movement in the accretionary prism of the Nankai Trough: NanTroSEIZE IODP Expeditions 338/348, Site C0002

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During the International Ocean Discovery Program (IODP) Expeditions 338 and 348, which is part of the NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) project, three deep riser holes were drilled south of the Kii Peninsula at Site C0002. The site is located in the Kumano forearc basin above the seismogenic portion of the plate boundary thrust. Hole C0002F (Expedition 338) was drilled down to 2004.5 mbsf. Hole C0002N/C0002P (Expedition 348) was drilled down to 3058.8 mbsf. Hemipelagic mudstone and sand/silt sediments are the predominant lithologies (Moore et al., 2014; Tobin et al., 2015). A complete set of logging while drilling (LWD) data, including borehole images, was collected during IODP Expeditions 338/348. Also rock-cuttings and spot cores. Distinct sections of intense fracturing and faulting within the very clay-dominated lithology were characterized on LWD borehole oriented images and other geophysical logs (Boston et al.,2016). The intense deformation of the generally homogenous lithology is characterized by bedding that dips steeply (60-90°). Smectite and illite are the most common clay minerals. Underwood and Song (2016) documented the abundance of smectite expandability of clay minerals in both holes. However, the properties and the role these minerals play in influencing fluid flow specifically in fractures, faults and folds within the accretionary prism is still not well understood.

The main focus of this contribution is on the analysis and potential link between structure development and the associated formation of clay minerals in the accretionary prism. We analyzed the relationship between the fractures, faults and the changes in clay mineralogy as derived from post-cruise cutting sample analyses. The comparative analysis of clay mineralogy reveals an increase of intensity observable in smectite and illite at specific depth intervals that are related to fault and fracture zones at 2350-2400 mbsf, at 2600-2800 mbfs, and also at 2150 mbsf. This increased intensity reflects an increase in the amount of smectite and illite in those areas, that could be related to due to abundant fluid-rock interaction processes. The connection between structures characterized on borehole images and the changes in clay mineralogy for Hole C0002P suggests that mineralogical changes are associated to structures of the Nankai accretionary prism. This is critical for a better understanding of clay-fluid interaction and mechanical properties during fault displacements and seismogenesis. We interpret a defined connection between the occurrence of fracture and/or faults in the accretionary prism and the abundance of illite and smectite clay minerals. Ongoing postcruise research on hole C0002 N and C0002P (Expedition 348) should confirm these results.

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Keywords: Nankai Trough Seismogenic Zone, Clay-fluid interaction, Accretionary prism, Borehole imaging, Logging while drilling

Active shallow structures of Muroto-off Ashizuri uplifted ridges, SW Japan

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Several topographic highs such as the Muroto, the Nishi-Muroto and the Ashizuri Knolls are intermittently developed from Cape Muroto to off Cape Ashizuri exhibiting a reverse L-shaped. A seismic reflection survey revealed an asymmetric anticlinal structure cut by a reverse fault at the eastern wing and consisted of a gentle slope at the western wing, and suggested beginning of uplift around late Pliocene to early Quaternary (Okamura and Joshima, 1986, GSJ Marine Geology Map). This reverse L-shaped uplifted zone is thought to be caused by oblique subduction of the Philippine Sea Plate to the Nankai Trough (Sugiyama, 1989, Bull. Geol. Surv. Japan).

We carried out deep-towed subbottom profiler (SBP) survey during R/V Hakuho-maru KH-15-2 and KH-16-5 cruises to detect sedimentation and deformation structures associated with uplift movements. A high resolution profile was successfully obtained by deep-towing operation of a chirp system (EdgeTech DW-106) at approximately 15 m above the seafloor using
ROV NSS (Navigable Sampling System).

The survey areas are the Nishi-Muroto Knoll 45 km south of Cape Muroto and an unnamed knoll (called Minami-Ashizuri Knoll tentatively) 70 km south of Cape Ashizuri. The Nishi-Muroto Knoll consists of NE-SW trending highs and the survey was conducted across the two major summits from SE to NW. The sedimentary basin southeast of the south summit shows northwestward dipping and the dip angle increases with burial depth. The sedimentary sequence northwest of the south summit steeply dips northwestward and about 100 meters' displacement is estimated at the southeast scarp of the south summit. The slope northwest of the south summit is also characterized by a NE-SW trending deep valley. In contrast, few reflectors are recognized at the north summit suggesting exposure of older sequence than the south summit. The small basin between the north and south summits indicates relative uplift movement of the north summit to the south summit. A NE-SW trending lineament is developed in the southern slope of the Minami-Ashizuri Knoll. The survey was conducted across this structure from SE to NW and showed the horst structure bounded by a high angle fault and a flexure. Our high resolution SBP survey successfully revealed characteristic sedimentation and deformation associated with recent tectonics along the uplifted zone from Cape Muroto to off Cape Ashizuri.

Keywords: active fault, active fold, outer ridge, subbottom profiler, Navigable Sampling System

Unsolving the formation of a massive bivalve colony grave at the eastern Nankai subduction zone from a geological and geochemical view

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Cold seep activity in the Nankai and Tokai regions are common, supporting wide varieties of chemosynthetic communities. This study focuses on an extinct *Calyptogena* spp. bivalve colony covering an area over 47,000 m^2 discovered on the south slope of the Daini Tenryu Knoll off Tokai. The unusual size and the condition of these shells raises questions on the process involved in forming a chemosynthetic community this size. Methane seeps are known to be ephemeral allowing for possibilities that the colony was gradually formed over time. Yet the sheer volume of dead shells may suggest that past major geological events may have disrupted the underlying methane hydrate layer that is known to be found in this region. ^{14}C radiocarbon dating was adopted on shells found at the colony (600 m) off Tokai using a Single-Stage Accelerated Mass Spectrometer (AMS) at AORI, UTokyo (Yokoyama et al., 2007, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms), revealing three ^{14}C age groups (ca. 1400, 1912 and 6000 cal BP). Suitable calibration model was created for this environment using δ13C DIC measurements of the shell (3‰) and the gill (-39‰) suggesting that the bivalve incorporates carbon from different sources for growth. The δ13C DIC value of porewater collected from the sediments below the bivalve colony also matches the gill measurements collected in this study (Tomonaga et al., 2016, Blue Earth Symposium). Seawater ^{14}C DIC depth profile of the region were also measured at 50-100m intervals to observe for any abrupt changes near the colony. Geological analyses of sub-bottom profile (SBP) data below and around the colony region using ROV Navigable Sampling System (NSS) highlights multiple areas with steep and shallow faults facing in a NE-SW direction which matches the major Kodaiba thrust that exists in the region. Majority of these faults feature further south of the colony. The region directly below the colony revealed a depression which may have been a result from a past tectonic activity possibly disrupting the underlying structure which could have provided the necessary passage for hydrocarbon rich fluids to pass through to support such a large colony.

Keywords: Cold seeps, Active fault, Radiocarbon dating, Bivalve shells

Thermal fluid migration in the Kumano forearc basin, Nankai Trough, estimated through vitrinite reflectance measurement

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Sediment analysis and the thermal history of the Kumano forearc basin and slope basin sediments in the Nankai Trough were studied through chemical and mineral composition analyses and the vitrinite reflectance measurement of sediments from Integrated Ocean Drilling Program Sites C0004, C0007, and C0009. The immobile component ratio (TiO_2/P_2O_5) suggests that the depositional source of sedimentary rock underlying the Kumano forearc basin (Unit IV of Site C0009) is different from those in the Kumano forearc basin (Unit III of Site C0009). The results support that Unit IV is not a basin sediment but a part of an old accretionary prism. The source of Unit IV is similar to that of the Shikoku basin sediment currently situated in the accretionary toe and subduction input, based on mineral composition analysis. The similarity is well explained by sediment transport from the East China Sea. In the Kumano forearc basin, a paleothermal anomaly was detected at Site C0009 using vitrinite reflectance measurement. The anomaly peak is 200 m wide with a maximum temperature of 79 ºC. Estimation of reflectance increase through vitrinite reaction promotion suggests that 80–100 ºC thermal fluid had passed with at least 100 ky, thus causing the anomaly. The thermal fluid upwelling might relate to ancient splay fault activity near Site C0009. The thermal anomaly zone in the Kumano forearc basin at Site C0009 coincides with the currently fluid conduit zone. These results indicate that massive fluid circulation occurs spatially and temporally through a large thrust in the subduction zone.

Keywords: Nankai Trough, Vitrinite reflectance, Kumano forarc basin, Thermal fluid

Activity of deep low frequancy tremor triggered by teleseismic earthquakes.

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Deep low frequency tremor in subduction zone is sometimes triggered by surface waves from teleseismic earthquakes. This type of tremor is called as triggered tremor. Amplitude of triggered tremor seems to be modulated by each phase of surface wave trace of teleseismic earthquake. Such triggered tremor has been observed in the ambient tremor zone where short-term slow slip events episodically occur. However, triggered tremor is not distributed in the entire source area of ambient tremor, but is rather concentrated in several spots. In this study, we investigated finer spatiotemporal characteristics of triggered tremor in order to reveal its activity.
We applied matched filter technique (Shelly et al., 2007) to detection of triggered tremor episodes in northern Kii and western Shikoku area, where triggered tremor episodes were observed at many times. The data obtained at NIED Hi-net stations were used in this analysis. We used waveforms of low frequency earthquake based on the JMA hypocenter catalog as templates of tremor. We analyzed continuous waveform data for one hour from the origin times of 67 teleseismic events with magnitude larger than 7.5 which occurred after Dec. 26, 2004.
Triggered tremor episodes were detected at 9 teleseismic events in northern Kii and at 15 teleseismic events in western Shikoku. Triggered tremor episodes were detected in one spot at northern Kii, and in two spots at western Shikoku. The areas where triggered tremor episodes occurred are not same at some teleseismic events. Along-dip migrations of triggered tremor were observed in both areas. Migration speed of triggered tremor is 5–20 km/h in northern Kii and about 40—100 km/h in western Shikoku. In northern Kii, the directions of migrations are same in all cases. In western Shikoku, both up-dip and down-dip migrations were observed.
Although migration speed of our result is much faster than that of episodic tremor and slip, about 10 km/day, tremor episodes having migration speed similar to our result has been reported during non-triggered tremor in previous studies. In northern Kii, migration of triggered tremor is similar to rapid tremor reversal (RTR) and rapid tremor forward (RTF) (Houston et al., 2011). Then, migration of triggered tremor may correspond to RTR and RTF. In western Shikoku, migration of triggered tremor is similar to rapid streak (Ghosh et al., 2010).
Ghosh et al. (2010) proposed two models about rapid streak. The first one is the apparent velocity model. The second model is effect of fluid. If we try to explain the observed migration in western Shikoku by the apparent velocity model with an assumption of actual migration velocity of 20 km/h obtained on northern Kii, the initiation of the background slip must be located at longer than 20 km away from the streak because apparent velocity at tremor streak would be about 60 km/h. However, the triggered tremor is excited at the same time as the arrival of the surface wave. Therefore, the apparent velocity model is not suitable for migration of triggered tremor and the fluid model might remain as one of reasonable models. However, another model may be reasonable for migration of triggered tremor. This is tremor asperity model, which predicts occurrence of real high-speed rupture due to existence of strong tremor asperities.

Keywords: Deep low frequency tremor, triggered tremor

Development and evaluation of modified envelope correlation method for deep tectonic tremor

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We develop a new location method for deep tectonic tremors, as an improvement of widely used envelope correlation method, and applied it to construct an updated tremor catalog in western Japan. Using the cross-correlation functions as objective functions and weighting components of data by the inverse of variances, the envelope cross-correlation method is redefined as a maximum likelihood method. This method is also capable of multiple source detection, because when several events occur almost simultaneously, they appear as local maxima of likelihood.

The average of weighted cross-correlation functions, defined as ACC, is a nonlinear function whose variable is a position of deep tectonic tremor. The optimization method has two steps. First, we fix the source depth to 30 km and use a grid search with 0.2 degree intervals to find the maxima of ACC, which are candidate event locations. Then, using each of the candidate locations as initial values, we apply a gradient method to determine horizontal and vertical components of a hypocenter. Sometimes, several source locations are determined in a time window of 5 minutes. We estimate the resolution, which is defined as a distance of sources to be detected separately by the location method, is about 100 km. The validity of this estimation is confirmed by a numerical test using synthetic waveforms. Applying to continuous seismograms in western Japan for 4 years, the new method detected 27% more tremors than a previous method, owing to the multiple detection and improvement of accuracy by appropriate weighting scheme.

The distribution of ACC tends to be anisotropic, even after removing the anisotropy due to the inhomogeneous distribution of stations. When we fit the ACC as a quadratic function of travel time difference, the insensitivity direction is consistent with the dip direction. It suggests the tremor source extends along the dip direction. The sensitivity of ACC is decreased with the duration, and the slope can be fitted as the inverse of the square root of duration. This suggests tremor migrates diffusively in duration. These features of tremor source should reflect the heterogeneity on the plate surface. From tremor activity, the source has been considered as brittle patches aligned along the dip direction in a ductile background. The result of this thesis is consistent the concept and suggests the tremor source has the anisotropy in the smaller scale.

Keywords: Deep tectonic tremor, Location method

Estimated seismic tremor energy for small amplitude tremors

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Various types of slow earthquakes, such as tectonic tremor [Obara, 2002] and slow slip events [e.g. Rogers and Dragert, 2003] have been recently observed at both the updip and downdip edges of the coseismic slip areas [Obara, 2002; Yamashita et al., 2015]. The frequent occurrence of slow earthquakes may help us to reveal the physics underlying megathrust events as useful analogs [Kato and Obara, 2016]. Maeda and Obara. [2009] estimated spatiotemporal distribution of seismic energy radiation from low-frequency tremors. They applied their method to only the tremors, whose hypocenters had been decided with multiple station method. However, a lot of tremors with small amplitude could be prone to underestimate on their detection. The events with small amplitude should not ignored to reveal slow earthquake activity and to understand strain condition around a plate boundary in subduction zones.
Here, we apply the modified frequency scanning method (mFSM) at a single station to NIED Hi-net data in the southwestern Japan. The original frequency scanning method [Sit et al., 2012] proposed a tremor detection method of calculating envelope waveform ratios through different bandpass filters of broadband data in the Cascadia margin. We modified this analysis for short period seismic Hi-net data recorded in the Southwest Japan. Three bandpass filters of 2–8 Hz, 10–40 Hz, and 0.25–1.0 Hz, corresponding to the dominant frequency band of tremors, local earthquakes, and seasonal noise, respectively. In addition, we removed the regular earthquake events by considering these envelope waveform shapes are similar to exponential curve in 2–8Hz band. We do not use three minutes continuous seismic data when correlation coefficient value is greater than 0.8 between envelope waveform and given simple exponential function.
Our results with mFSM is corresponded to those with multiple method in Southwest Japan. On the other hand, our results include small amplitude tremors which can not be detected with multiple methods. We also estimated their seismic tremor energy including small amplitude tremors which were detected by mFSM at each sites. Amplitudes observed at each site was corrected using the site amplification factors estimated with the coda normalization method and the Euclidean distance between the tremor source and the station, The estimated energy in this analysis may indicates more realistic strain release rate around the plate boundary.

Keywords: slow earthquake, seismic energy

Locating triggered tremors using envelope back projection

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Surface waves radiated from large teleseismic earthquakes sometimes trigger a series of deep non-volcanic tremors with intervals of 20-30 seconds, which are dominant periods of surface waves [e.g. Miyazawa & Brodsky 2008]. Dynamic stress perturbation due to surface waves in the tremor source region is as low as a few kPa, indicating the tremor source fault is quite sensitive to the stress change. Not all the large surface waves, however, induce triggered tremors. Necessary conditions for triggered tremor are still unknown.

Most of previous studies used the envelope correlation method (ECM) [e.g. Obara 2002] or a method derived from ECM [Wech & Creager 2008] to locate triggered tremors. Time resolution in tremor location is therefore limited by data length used in ECM in those studies. The method with higher time resolution is required because tremor is phenomenon whose time scale is approximately one second. The back-projection method is possible to give higher time resolution because it uses only amplitude information. The source-scanning algorithm [Kao & Shan 2004] is a kind of back-projection method, but not fully applied to triggered tremors. In this study, we applied the envelope back-projection method to records of triggered tremors to determine high-resolution space-time transition of tremor sources.

We focused on triggered tremors in the western Shikoku region of the Nankai subduction zone. We set 2629 source grids with the horizontal interval of 2 km on the model plate boundary [Baba et al. 2002; Nakajima & Hasegawa 2007; Hirose et al. 2008]. Theoretical traveltimes were computed using the 1-D seismic velocity model JMA2001 [Ueno et al. 2002]. We used records from 60 seismic stations of Hi-net, F-net, JMA, GSJ, ERI, Kochi and Kyushu Universities. Records of ground velocity were bandpass-filtered between 2 and 10 Hz and then envelopes were computed using three-component records. We obtained site amplification factors for 2-10 Hz using the coda normalization method [Takemoto et al. 2012] and used them in the analysis. We back-projected squared envelope amplitudes averaged in 0.5 second to the source grids to create back-projection maps with a time interval of 0.5 second. We used only the data from the stations whose epicentral distances are less than 60 km. Tremor epicenter was determined as a weighted average of source locations whose back-projection value is greater than or equal to 90 % of the maximum value.

We searched for clearly triggered tremors in the western Shikoku region between 2004 and 2016 and found them for 9 large earthquakes. Most of envelope peaks were able to be identified as space and time peaks in back-projection maps, and epicenters were determined. The results show that the triggered tremors in the western Shikoku region form two clusters, which correspond to the well-known clusters of tectonic tremor in this region. The western cluster is known as the tremor sweet spot in which tectonic tremors occur most frequently. It has an elongated shape along the NW-SE direction: NW and SE parts correspond to deep and shallow source regions, respectively. Most of the tremors belong to this cluster are located in the shallower part, though some were located in the deeper part. The triggering by the 2004 Sumatra earthquake is particular because triggered tremors occurred widely along the western cluster. Other detailed source characteristics and results for other regions will be shown in the presentation.

Keywords: non-volcanic tremor, triggering, back-projection, Nankai subduction zone

Detection of tectonic tremor using a monitoring method of seismic anisotropy

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We have been investigating temporal variations in seismic anisotropy around the source region of low-frequency tremor, one of the families of slow earthquakes associated with the Nankai trough mega-thrust earthquake [e.g., Ishise and Nishida, 2015 JpGU, 2015 SSJ, 2015 AGU]. Seismic anisotropy has close relationships with stress state and physical properties of the medium such as water content. Therefore, a temporal change in seismic anisotropy is a good proxy for the temporal and spatial evolution of tremor activity, which is related to temporal changes in the stress state and various physical properties.

In this study, we investigated tremor episodes in the eastern part of Shikoku by applying the monitoring method of seismic anisotropy. As a result, we detected that temporal variations in anisotropy and polarization directions of incoming waves occasionally indicate an event with a characteristic temporal pattern. Further, we found that the spatio-temporal distribution of the detected events includes all located spatio-temporal distribution of tremor activities in the study area [e.g., world tremor database, Idehara et al., 2014]. Therefore, we interpreted that the events with characteristic temporal patterns are manifestations of tremor activity and assumed that the monitoring method can be used to detect tremor activity.

As briefly mentioned above, we estimate back azimuth and incident angle of incoming wave from the polarization direction through this monitoring. Therefore, given the depth of tremor source regions from other studies, we could determine the source location of tremor with the aid of known back azimuth and incident angle of the incoming wave. Under an ideal situation, even source locations of the tremor may be possible using only a single-station data. This method is complementary to conventional source location determination methods that require observation of coherent seismic signals at several stations [e.g., Obara, 2002]. Then, it is expected that the tremor detection method with the seismic anisotropy monitoring provides a detailed spatio-temporal distribution of tremor activities. In addition, this tremor detection method is feasible for a study of offshore tremor activity, because the quality and quantity of marine observation data is limited in various aspects compared with those of land-based observation data. This will eventually discover some unknown phenomena.

Then, we started to study on offshore tremor activity by applying the seismic anisotropy monitoring method to ocean bottom seismometer data. As a first step, we applied the monitoring method to seismograms of an offshore seismic network, DONET, off southwest Japan along the Nankai trough, and examined the efficiency and validity of the offshore tremor study. In this presentation, we show a preliminary result of the investigation of tremor activity associated with the Mw 6.0 earthquake offshore the Kii Peninsula of southwest Honshu, Japan on 1 April 2016.

Keywords: low frequency tremor, seismic anisotropy monitoring, tectonic tremor detection method

Improvement of a system for monitoring very-low-frequency earthquakes

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We have improved a system for detecting and locating regular and very-low-frequency earthquakes (VLFEs) based on array-signal-processing technique. Using this system, we have analyzed filtered seismograms (pass band: 0.02-0.05 Hz) observed by high-sensitivity accelerometers (tiltmeters) in the approximately 700 NIED Hi-net and have revealed spatiotemporal distribution of VLFEs in and around Japan [Asano et al, 2008]; however, critical error of event location have been found in the surrounding areas of the tiltmeter network due to ill-conditioned station coverage. Therefore we have tried to analyze not only tiltmeter data but also additional data observed at seven F-net and three temporary stations in the surroundings such as southern Kyushu and Ryukyu areas. We separated these ten stations into three arrays and applied semblance technique to the continuous seismograms observed during the periods of May. 26-27, 2015 and Feb. 12-14, 2017, when VLFEs were located in Hyuga-nada, southeast off Kyushu, by the routine system only analyzing tiltmeter data. Estimated directions of coherent seismic waves at northern two arrays suggest that these VLFEs were widely distributed from off Amami to Hyuga-nada. On the other hand, incident wave directions at southwestern array far from these VLFEs were east for most of all VLFEs probably due to guided wave along the Ryukyu trench. These present results show that data observed at the neighbor arrays not so far from the VLFEs are useful to reject ill-conditioned VLFE epicenters and can constrain them in the future.

Acknowledgment
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Keywords: very-low-frequency earthquake, array

Precise hypocenter determination of deep low-frequency earthquakes in the Tokai area of the Nankai subduction zone using a 3D array and Hi-net

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We have developed a novel method that uses a 3D array to detect the P and S waves of deep low-frequency earthquakes (LFEs) that occur along the Nankai subduction zone of the Philippine Sea plate in southwest Japan. Obtaining accurate hypocenters of LFEs is very difficult because their seismic waves are characterized by low amplitude and the absence of sharp pulses. In particular, identifying P phase arrivals is not readily possible using only conventional seismic networks. To determine their hypocenters accurately not only their epicenters but also their depths we tried to find their P and S wave pairs and obtain S-P times by using a 3D array (6 km x 4 km area) with 14 seismic stations in the Tokai area including ones with deep (600 m at the deepest) borehole seismographs. We observed remarkable LFE activity occurring in the Tokai area over November 10-30, 2010. We calculated the semblance distributions for their seismic waves of 75 LFEs to identify P and S phases and obtained their propagation parameters (back azimuths and incident angles) . Using the back azimuths and incident angles of S waves, and S-P times with high quality result, we calculated the preliminary hypocenters of 15 LFEs by using a shooting method. Referring to those identified P and S phases we manually picked the arrival times of not only both P and S waves of the 3D array stations but also S waves and rarely P waves of Hi-net stations. Using the arrival times we relocated precise hypocenters of the 15 LFEs. Those hypocenters distribute in the depth range from 26 km to 34 km (red stars in Fig.1) approximately along the plate interface (Hirose et al., 2008) inclining in depth from 30 km to 32 km. The errors of those hypocenters estimated from residuals of the arrival times are 0.2-0.9 km in horizontal and 0.4-0.8 km in depth, respectively. By using the same procedure as we explained for LFEs, we also relocated precise hypocenters of 13 regular earthquakes occurring in the subducting Philippine Sea plate. Those regular earthquakes belong to the intra-slab events which are normal-fault or strike-slip type earthquakes, with the T–axis oriented in an E-W direction (e.g. Miyoshi and Obara, 2010). Those hypocenters distribute in the depth range from 35 km to 45 km (light blue squares in Fig.1). We found that the hypocenters of LFEs did not overlap with the regular earthquakes in depth. In Fig. 2 we compared the depth distributions of LFEs and the regular earthquakes with a simple model of inter-plate structure under Tokai area. From Fig.2 we may conclude that LFEs occur not only along a thin subduction interface (less than about 1(?) km in width) but also in the nearly whole layer of oceanic crust and several km width in wedge mantle. And the total depth range of the LFEs obtained from the standard deviation is about 5 km. This distribution of LFEs may support the undrained condition model (Nakajima and Hasegawa, 2016) of enhanced pore-fluid pressure for LFE activity.

(Acknowledgment) National Research Institute for Earth Science and Disaster Prevention (NIED) , Japan Meteorological Agency (JMA)

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Keywords: deep low-frequency earthquake, precise hypocenter determination, 3D array, plate boundary, P and S waves, Hi-net

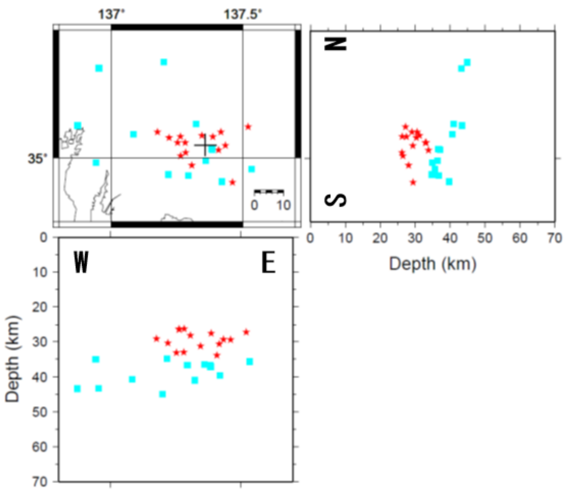

Fig.1. Hypocenter distribution of LFEs (red stars) and regular earthquakes (light blue squares) determined by using the data of a 3D array and Hi-net.

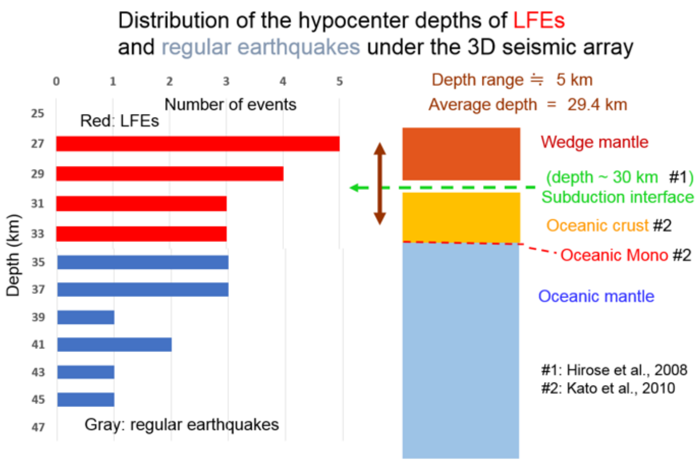

Fig.2. Comparison of hypocenter-depth distributions (left) with schematic inter-plate structure (right).

Quality control of tilt and strain data for automated detection of slow slip events within the Nankai subduction zone, Japa

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In the Nankai subduction zone, a large amount of high-quality geodetic and seismic data enables us to study the slow earthquakes such as the slow slip events (SSEs) and the nonvolcanic deep low-frequency tremors in detail. In order to reveal the source physics of various interplate slip phenomena, it is important to understand the relationship among members of slow earthquakes. Source models of short-term SSEs estimated from geodetic data objectively and independently of seismic slow earthquake catalog (e.g., Kimura et al., 2011) are essential to clarify the relationship. We have developed an automated method to detect SSEs from tilt and strain data, and in order to apply the method to data with the length of one year or longer, it is necessary to treat temporal changes of background noise levels appropriately. To assume incorrect noise parameters is possible to cause a miss detection or an excessive detection.

In this study, we evaluate temporal changes in noise levels of geodetic data. We assumed that continuous geodetic data contains background linear trend, random-walk noise and white noise, and estimated the noise strengths for a 30-day moving time-window using maximum likelihood method. Typical strengths of the random-walk and white noises are approximately 1.0-5.0 nrad/hr$^{0.5}$ and 1.0-5.0 nrad, respectively, for tilt data, and 0.5-1.0 nstrain/hr$^{0.5}$ and 0.5-1.0 nstrain, respectively, for strain data. The random-walk noise strengths of tilt data at MASH station in Kii Peninsula had been 1.0-2.0 nrad/hr$^{0.5}$ and almost constant from 2001 to 2012. They were increasing in 2013 and reached 10-20 nrad/hr$^{0.5}$. This increase in noise levels lowered the detection capability for SSEs in Kii Peninsula.

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A stress-constrained geodetic inversion method for spatiotemporal slip of a slow slip event with earthquake swarm

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Geodetic inversions have been performed by using GNSS data and/or tiltmeter data in order to estimate spatio-temporal fault slip distributions. They have been applied for slow slip events (SSEs), which are episodic fault slip lasting for days to years (e.g., Ozawa et al., 2001; Hirose et al., 2014). Although their slip distributions are important information in terms of inferring strain budget and frictional characteristics on a subduction plate interface, inhomogeneous station coverage generally yields spatially non-uniform slip resolution, and in a worse case, a slip distribution can not be recovered.
It is known that an SSE which accompanies an earthquake swarm around the SSE slip area, such as the Boso Peninsula SSEs (e.g., Hirose et al., 2014). Some researchers hypothesize that these earthquakes are triggered by a stress change caused by the accompanying SSE (e.g., Segall et al., 2006). Based on this assumption, it is possible that a conventional geodetic inversion which impose a constraint on the stress change that promotes earthquake activities may improve the resolution of the slip distribution.
Here we develop an inversion method based on the Network Inversion Filter technique (Segall and Matthews, 1997), incorporating a constraint on a positive change in Coulomb failure stress (Delta-CFS) at the accompanied earthquakes. In addition, we apply this new method to synthetic data in order to check the effectiveness of the method and the characteristics of the inverted slip distributions.
We model a horizontal square fault with its area of 80 x 80 km^2 at 15 km depth in a half-space. This fault is divided into 64 square subfaults with each dimension of 10 x 10 km^2. We define the four subfaults at the center of the modeled fault as "slip patch" where slip lasts for five days and evolves to 50 cm. 49 GNSS stations are located on grid points on the surface with 20 km spacing. Theoretical surface displacement time-series at each GNSS station are calculated based on Okada's (1992) formulation. Pseudo observation data are generated by adding Gaussian noise with its standard deviation of 1 mm in horizontal components and 3 mm in vertical components, respectively, to the calculated displacements. These data are inverted with or without the Delta-CFS constraint, and both of the estimated slip distributions are compared. We test two GNSS station distributions: (a) all of the 49 stations are included; (b) reduced 28 stations which cover only a half area of the fault. The triggered earthquake hypocenters are located at the center of each subfault around the assumed slip patch where Delta-CFS is calculated. The same focal mechanism of these earthquakes is assumed as that of the SSE for the stress calculation.
In case (a), because the station coverage is sufficient to reproduce the given slip distribution, the difference between the inversion results with and without the Delta-CFS constraint is small. In case (b), where the observation condition is worse than (a), the inversion result with the Delta-CFS constraint has larger slip (closer to the assumed slip amount) on the slip patch and smaller smearing on the surrounding subfaults than that without the Delta-CFS constraint.
These show that there is a case in which the reproduction of a slip distribution is better with earthquake information than without it. That is, it is possible to improve the reproducibility of a slip distribution of an SSE with this new inversion method if an earthquake catalog for the accompanying earthquake activity can be used when insufficient geodetic data are available.

Keywords: Delta-CFS, crustal deformation, GNSS, earthquake swarm, plate interface

Estimation of the spatiotemporal evolution of the slow slip events in the Tokai region, central Japan, since 2013 using GNSS data

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In the Tokai region, central Japan, the previous long-term slow slip event (L-SSE) was very slow and long-term aseismic slip, observed on the subducting Philippine Sea Plate (PSP) from 2000 to 2005. In addition, many short-term slow slip events (S-SSEs) accompanied by low frequency tremors (LFTs), have been detected using not only tiltmeter and high sensitivity seismograph from the NIED Hi-net but also GNSS from the GEONET recently. Although several previous studies have reported the spatiotemporal evolution of L-SSEs, there are few previous studies that estimated the spatiotemporal evolution of S-SSEs. In this study, we applied a time-dependent inversion method to GNSS data to obtain the spatiotemporal evolution of an L-SSE and S-SSEs on the PSP beneath the Tokai region, since 2013.
GNSS data from January 1, 2008 to December 31, 2015 were used in this study. The GIPSY-OASIS II software was used to estimate daily coordinates of 222 GNSS stations from the GEONET in the Tokai region. It is well known that GNSS time series have many systematic signals that do not result from SSEs. These systematic signals include, for example, seasonal variations and post-seismic deformation of the 2011 Tohoku-oki earthquake (Mw9.0). After removing these systematic signals, we applied a modified Network Inversion Filter (NIF) [Fukuda et al., 2008]. The original NIF [Segall & Matthews, 1997] assumes a constant hyperparameter for the temporal smoothing of slip rates and thus often results in oversmoothing of slip rates. The modified NIF assumes a time-variable hyperparameter, so that changes in slip rates are effectively extracted from GNSS time series.
The results indicate that the moment magnitude and maximum cumulative slip of the L-SSE were estimated to be Mw˜6.5 and ˜6.5 cm from January 1, 2013 to December 31, 2015, respectively. In addition to the L-SSE, we found several periods of slip acceleration that can be regarded as S-SSEs, but we discuss only S-SSEs which are larger than the estimation error. The biggest S-SSE in analysis period occurred at the end of January, 2014 around the Ise Bay. Maximum cumulative slip of this S-SSE was estimated to be˜1.1 cm from January 17, 2014 to February 1, 2014, respectively. We also found several other S-SSEs that occurred around the Ise Bay in the down-dip area of the L-SSE. These S-SSEs are correlated with LFTs, suggesting that LFTs were triggered by the S-SSEs.
Our results suggest that the slip peaks of the L-SSE and S-SSEs do not overlap and that the temporal variation of moment in the central area of the L-SSE is smooth and is not affected by the S-SSEs. In addition, LFTs [Obara et al., 2010] do not occur near the center of the L-SSE. In order to further investigate the relationship among the L-SSE, S-SSEs, and LFTs, we additionally processed data from GNSS stations constructed by the Japanese University Consortium for GPS Research and operated by Earthquake Research Institute at the University of Tokyo and allied universities. We will present results of joint analyses of these additional data and the GEONET data in the presentation.

Keywords: SSE, GNSS, Tokai region

Episodic shallow tremor off southeast Mie prefecture and its monitoring

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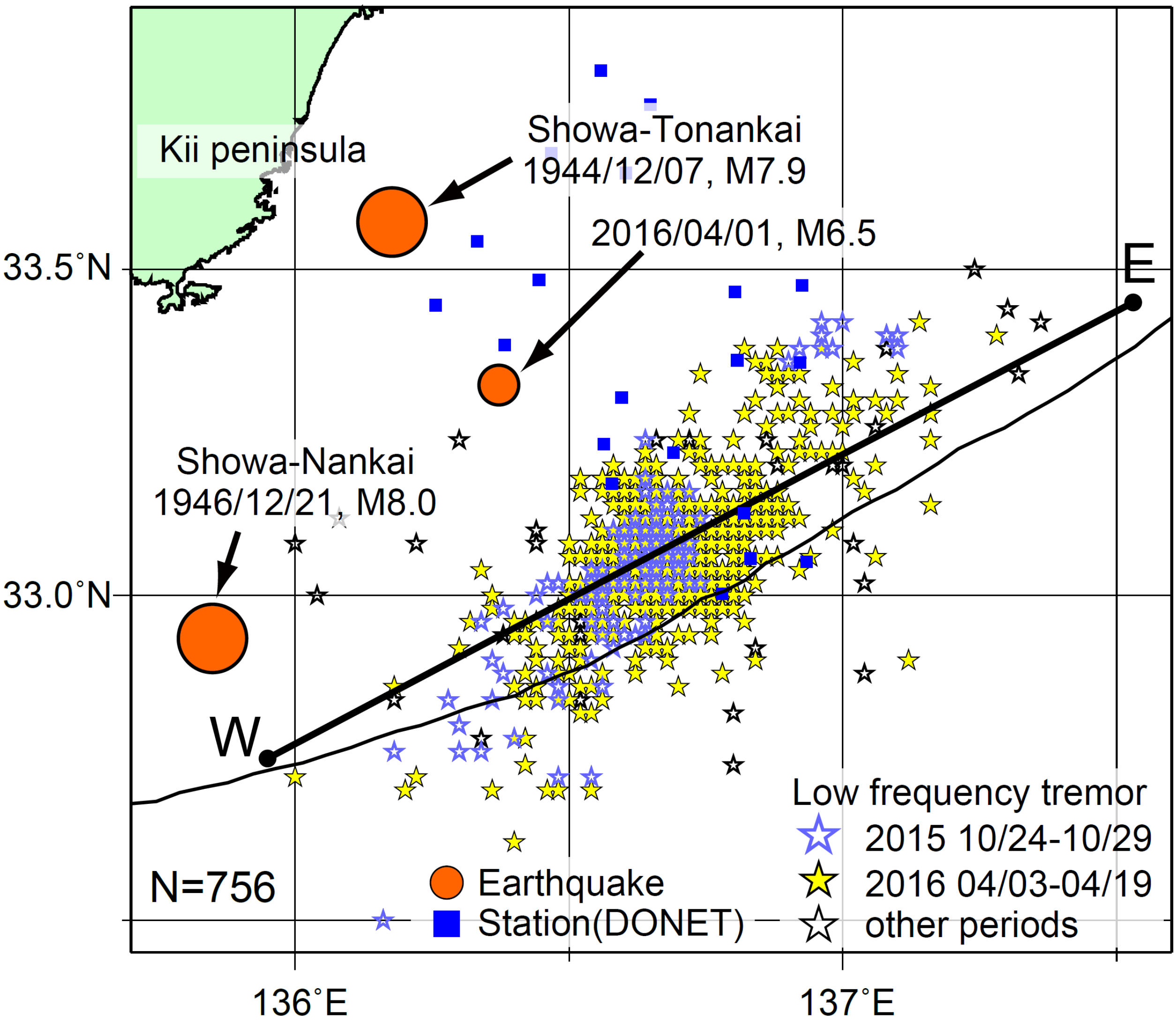
We analyzed long-term continuous seismic records (from September 2015 to April 2016) of DONET deployed off southeast Mie prefecture and we investigated activity of shallow tremor near the trough axis with the envelope correlation method. We found that shallow tremor was active only in two periods of October 2015 and April 2016 and their durations were about 6 days and 2 weeks respectively.
In the episode of April 2016, migration property was observed. Because of the migration properties, it is inferred that slow slip events were related to activities of shallow tremor similar to the case of deep tremor. We observed three migrations with different speed (from several km per day to 20 km per hour). Triggering property was also observed after M7.3 Kumamoto Earthquake on 16 April. This is also the same with well-known triggering property of deep tremor by teleseismic wave.
This shallow tremor is sensitive to stress perturbation because it was triggered by teleseismic wave as is the case with deep tremor. Furthermore, shallow tremor in this research was located in the vicinity of the initiation points of past megathrust earthquakes in Nankai (M7.9 Showa-Tonankai earthquake in 1944 and M8.0 Showa-Nankai earthquake in 1946). Therefore, monitoring this tremor activity will be very important to reveal stress accumulation process of megathrust earthquakes.
We are now developing automatic monitoring system to detect shallow tremor in JMA. The system first determines candidate hypocenters of tremor using envelope correlation method and then excludes false detection such as regular earthquakes or artificial explosions by detecting spike-shaped waveform. We will introduce this method in the system as well.

Acknowledgement: We used continuous seismogram data of DONET operated by National Research Institute for Earth Science and Disaster Prevention (NIED) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Keywords: episodic shallow tremor, Nankai Trough, subduction


Kii peninsula
Showa-Tonankai
1944/12/07, M7.9
2016/04/01, M6.5
Showa-Nankai
1946/12/21, M8.0
33.5˚N
33.0˚N
136˚E
137˚E
W
E
N=756
Earthquake
Station(DONET)
Low frequency tremor
2015 10/24-10/29
2016 04/03-04/19
other periods

Shallow Slow Slip Event Off the Kii Peninsula in April 2016, Japan

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On 1 April 2016, an earthquake (Mw=5.9, hereafter mainshock, USGS) occurred off the Kii Peninsula, Japan. The mainshock occurred around the expected focal region of the so-called Tonankai earthquake. After the mainshock, strain and pore-pressure changes caused by the slow slip event (SSE) were observed by the three borehole strainmeters of AIST. The source region of this SSE is located on the plate interface at southeast side of the mainshock. An equivalent magnitude of this SSE is Mw 6.0, and duration is about 7 days. From after just a few days from the mainshock, in and around this SSE source region, intensive activity of shallow low frequency tremor has been observed for about two weeks, it is assumed that these shallow tremor events were induced by this SSE.
In off the Kii Peninsula, VLF and Low Frequency Earthquake has been often observed, but SSE had not been observed by geodetic method. The slip deficit rate of this SSE source region is about 3 cm / year (Yokota *et al.*, 2016), and the plate convergence rate is 5.0 to 6.5 cm / year (Heki and Miyazaki, 2001). Therefore, in addition to this case, there is a possibility that SSE frequently occurred in this region.

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Keywords: SSE, Slow earthquake, Low frequency earthquake

Shallow tremor activity around the source areas of the Nankai and Tonankai earthquakes by using LTBMS and DONET

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Several studies reported the activities of the non-volcanic tremors, Slow Slip Events (SSE) and the Very Low Frequency earthquakes (VLF) had occurred along the Nankai trough, southwest Japan (e.g., Obara, 2002; Obara and Hirose, 2006; Sugioka et al., 2012). SSEs were accompanied by tremors and VLFs, and those migrated with various pattern in response to SSEs (e.g., Obara 2011; Yamashita et al., 2015). Although tremors were well detected at the plate interface deeper than the source areas of mega-thrust and large earthquakes along the Nankai trough, tremors were little detected at the shallower part except for off southern Kyushu at where Yamashita et al. (2015) reported by the means of ocean bottom observation. It is considered as a reason why the shallow tremors along the Nankai trough were rare to be detected that S/N ratios of those signals are low because of the long distance between those sources and the onshore seismic network.
Japan Agency for Marine-Earth Science and Technology (JAMSTEC) installed the cabled observation system called Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) in the source areas of the Nankai and Tonankai earthquakes, southwest Japan, to monitor earthquakes and tsunamis (Kaneda et al, 2015; Kawaguchi et al., 2015). In addition, JAMSTEC installed the borehole observation system called Long-Term Borehole Monitoring System (LTBMS) for seismic, geodetic, and hydrological observation in the seafloor targeting on the seismogenic faults along the Nankai trough as a part of the NanTroSEIZE by IODP program (e.g., Kopf et al., 2011), which is connected to DONET system. LTBMS and DONET stations can cover from coast to trough axis and are connected to land stations with fiber optic cables. The digitized data of them are continuously transferred in real-time to our laboratory at JAMSTEC. Therefore, we can continuously monitor the tremor activity occurred at shallow part of the source areas of the Nankai and Tonankai earthquakes. In this study we purpose to investigate the characteristics of the shallow non-volcanic tremor activity around the source areas of the mega-thrust earthquakes.
We detected non-volcanic tremors that occurred between Jan. 2011 and Dec. 2016, around the source areas of the mega-thrust earthquakes by applying the envelope correlation method (Ide, 2010, 2012) to the records of the broadband seismometers deployed to LTBMS and DONET stations. Shallow tremors have stably occurred around the aftershock area of the 2004 off Kii peninsula earthquake that occurred near the trough axis. Episodic shallow tremors were activated after the large earthquakes such as the off Mie earthquake (Mw = 6.0) on 1 April 2016. In addition, some episodic shallow tremor activities were observed without the large earthquakes. Several tremor activities were synchronized with deviations of the pore pressure deployed to LTBMS.

Keywords: tremor, Nankai trough, DONET, LTBMS, borehole, SSE

Investigation of tidal-induced poroelastic responses at IODP Sites C0010 and C0002 along the Kumano Transect - SE Japan

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The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a multi-expedition Integrated Ocean Drilling Program (IODP) project along the Nankai Trough subduction zone with the purpose of better understanding subduction-zone earthquakes and seismogenic processes. Long-term pressure and temperature monitoring along the Kumano transect produced valuable data records, which constrain potential fluid flow paths and help to identify regions of strain accumulation/release. Simultaneous pressure and temperature records are available for IODP Site C0002 and IODP Site C0010.

The recent IODP Exp. 365 in April 2016 recovered an autonomous borehole observatory named “GeniusPlug”. The GeniusPlug was recovered from Site C0010, were it was installed within the megasplay fault zone at 407 mbsf. The GeniusPlug observatory was equipped with temperature loggers and two pressure sensors. One pressure sensor is used as hydrostatic reference, while the other measures formation pressure. The GeniusPlug recording has a sampling period of 30 sec from November 2010 –April 2016. Complementary formation pressure data at various depths (PPI 940 mbsf, PPII 920 mbsf, PPIII 770 mbsf) and a hydrostatic reference are available via the C0002 long-term borehole monitoring system (LTBMS) installed in November 2010. Hence, formation pressures can be compared via monitoring at the megasplay fault zone and the inner accretionary prism/deep Kumano Basin.

Amplitude and phase of formation pressure variation have been determined relative to tidal pressure variations at the hydrostatic reference. Mean formation pressure amplitudes are reduced to 62 - 74 % and not shifted in phase. Theory of porous media response to periodic loading allows the calculation of frame bulk modulus, specific storage, hydraulic diffusivity and strain sensitivity. This approach allows investigation of formation-scale hydraulic and mechanical properties for the fractured mega splay fault sediments in C0010, and the inner accreted sediments of Unit IV at C0002 and the Kumano Basin sediments of Unit II at C0002.

Keywords: Poroelastic properties, Borehole observatory, Fluid pressure, NanTroSEIZE

Tidal modulation of slow slip detected using tiltmeters in Nankai subduction zone

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Episodic tremor and slip events have now been observed at many subduction zones worldwide. It has been shown that tectonic tremors are controlled by tides and passing surface waves, suggesting high sensitivity to small stress disturbances. Hawthorne and Rubin (2010) has detected that the slow slip events are also controlled by tides by using borehole strainmeters in Cascadia subduction zone. We address whether tidal modulation of slow slip is a general phenomenon by using tiltmeters in Nankai subduction zone, following the procedures proposed by Hawthorne and Rubin (2010).

We use tiltmeters at two stations of Hi-net operated by National Research Institute for Earth Science and Disaster Resilience. A set of analysis windows are selected to include slow slip events occurred from January 2001 to January 2013. Tilt record includes large undesired signals due to local deformation caused by the ocean loading and body tides. Therefore, we estimated local deformation empirically using tilt data without slow slip signals, and subtracted it from the original data to obtain signals caused by slow slip. The processed signals are modeled as a summation of sinusoids at four tidal periods and a linear trend, and simultaneously fit for all analysis windows.

The tidal modulation of the tilt rate is significant at 12.4 h (M2) period, at the 99% confidence level, which is consistent with the result of Hawthorne and Rubin (2010). The phase of maximum tilt rate at the M2 period appears to correspond to the maximum shear stress in the direction of plate motion on the plate interface right beneath each station.

Reference: Hawthorne, J. C., and A. M. Rubin (2010), J. Geophys. Res., 115, B09406.
Yabe, S., Y. Tanaka, H. Houston, S. Ide (2015), J. Geophys. Res. Solid Earth, 120, 7587-7605.

Tidal modulation of slow slip events in the Nankai subduction zone detected by borehole strainmeter

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Slow slip events (SSEs) often occur in the Nankai subduction zone, Japan. SSEs are believed as shear slip on the plate interface, where the frictional property changes from velocity weakening to strengthening in the dip direction. SSEs are also suggested that they alter the stress condition of the adjacent area, where megathrust earthquakes occur. Therefore, the dynamics of SSEs may give some hints to understand the depth dependent friction and plate subduction process. The tidal modulation of SSEs has been identified by statistical analysis using strain data of Plate Boundary Observatory, in the Cascadia subduction zone. We perform similar statistical analyses in western Japan using strain data recorded at borehole stations maintained by National Institute of Advanced Industrial Science and Technology. Target SSEs are detected using tremor catalog. The correlation between the oscillation in SSEs and tidal stress is confirmed statistically. However, the tidal components which modulate SSEs are diurnal tides, and different from a semidiurnal tide in the previous study in the Cascadia subduction zone. This result shows that the responsiveness of SSEs is not so simple that SSEs depend on any of tidal components and suggest that total tidal stress should be considered. Hence, we try to directly compare the slip rate and total tidal stress on the plate interface. Simulated strain from tremor activity is qualitatively similar to observed strain from SSEs. Thus we assume that tremor hypocenters represent the slipping region of SSEs, and calculate the temporal change of slipping region of SSEs. Quantitatively estimating the effect of the relative location between the station and the slipping region, we compare the slip rate on the plate interface inferred from strain data with total tidal stress. The slip rate and tidal shear stress are positively correlated. This result suggests that the frictional law acting on SSEs occurring region is of velocity strengthening type. This is the first evidence of the velocity strengthening friction law in the transition zone derived using geodetic data. If this method is applied to the other SSEs occurring region, we may comprehensively understand the frictional property of the plate subduction zone.

Keywords: Slow Slip Event (SSE), strainmeter, tidal stress, slip rate, velocity strengthening friction law

Tidal response in shallow micro low-frequency tremors

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Various types of slow earthquakes, such as tectonic tremor [Obara, 2002], low-frequency earthquake [Katsumata and Kamaya, 2003] and slow slip events [e.g. Rogers and Dragert, 2003] have been recently observed at both the updip and downdip edges of the coseismic slip areas [Obara, 2002; Yamashita et al., 2015]. Here, we show micro low-frequency activity with very weak amplitudes detected using the modified frequency scanning method (mFSM) at a single station [Sit et al., 2012], and successfully detected micro low-frequency tremors (mLFTs) that have not been previously reported. These mLFTs are the almost same as ordinary tectonic tremors, but we define them here in this matter in order to discuss the differences and distinguish the tremor amplitudes, which have amplitudes that are one tenth of the amplitude of tremor detected by the envelope correlation method [Yamashita et al., 2015].
We also evaluated tidal response of the tremor activity at each site. The clear response to tides of slow earthquake activity at depth is well known [Ide, 2010], but the relationship between shallow slow earthquakes and tides is still debatable. We calculated the sea surface change due to the Earth using a computational model, and evaluated the relationship between shallower tremor activity and tidal stress changes ocean loading tides from the model NAO.99b [e.g. Matsumoto et al., 2010]. We used perturbation of the tides at each OBS site and statistically evaluated the relationship based on the Schuster *p* test. We consequently found high tidal responses of shallow tremors especially latter part of tremor migration which reported Yamashita et al., (2015). Specifically, mLFTs have clear response to tides.
We suggest two different occurrence mechanisms for slow earthquake activity off south-eastern Kyushu. The start of the tremors is mainly modulated by larger stress changes, such as from nearby, slow slip events, and later controlled by ambient shear stress perturbations such as tides. In other words, tremor, especially mLFTs could have been induced under the neutral stress regime by tidal stress perturbation.

Keywords: slow earthquake, shallower part of the subduction zone , tidal responses

Fortnightly tidal modulation of shallow very low frequency earthquakes in Hyuga-nada and off Cape Ashizuri

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We investigated correlations between fortnightly tides and shallow very low frequency (VLF) earthquakes in Hyuga-nada and off Cape Ashizuri. We focused on three active swarms in 2003, 2010, and 2015, for which strong correlations with semidiurnal tides have been observed (Tanaka et al., 2011, 2015). We detected and located VLF earthquakes by applying a cross correlation technique (Asano et al., 2015) to the seismograms recorded by the F-net broadband seismograph network. For each event, we calculated tidal Coulomb stresses with a friction coefficient of 0.2 (Tanaka et al., 2002), and assigned a fortnightly tidal phase at the time of occurrence from the smoothed stress amplitude envelope (Curchin and Pennington, 1987). For the fault plane, we assumed a landward-dipping reverse fault from a well-determined focal mechanism solution by using the centroid moment method (Ito and Obara, 2006). Based on the distribution of tidal phases, we tested whether they concentrate near some particular angle or not by using the Schuster's test. In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the VLF earthquakes occur randomly irrespective of tidal phase angle. As a result of analysis, we observed significantly small p-values for all the three swarms; the p-values for 2003 (N = 423), 2010 (N = 1506), and 2015 (N = 739) swarms are 4E-16, 7E-52, and 7E-15, respectively. The frequency distributions of tidal phases exhibit a peak where the tidal stress amplitude is at its maximum. 65%, 68%, and 69% of the events occurred during the half (50%) of tidal phase range with large stress amplitudes. These results indicate that the occurrence of VLF earthquakes is strongly modulated by fortnightly tidal stress variations and is well correlated with large tidal stresses.

Acknowledgment: This work was supported by JSPS KAKENHI Grant Number JP16H06473.

Keywords: shallow very low frequency earthquakes, Earth tides, triggering

Small-scale along-dip variations of deep low frequency tremor activity detected in western Shikoku, southwest Japan

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It is reported that deep low frequency tremor occurs more episodically at the updip part of the tremor region compared to the downdip part in Shikoku in southwest Japan (Obara et al., 2010, 2011) and Cascadia (Wech and Creager, 2011). In this study, we focused on the updip cluster in western Shikoku analyzed in Obara et al. (2010) in order to investigate tremor activity in a finer scale along the dip direction.

We detected tremor activity by using the matched filter technique (Shelly et al., 2007) in western Shikoku. The continuous waveform data from 2013 to 2015 at 12 Hi-net stations operated by National Research Institute for Earth Science and Disaster Resilience are used after applying band-pass filter of 2 to 8 Hz. As template events, we selected several low frequency earthquakes located within a streak-like tremor cluster along the dip direction of the subducting plate from the catalog of Japan Meteorological Agency (JMA). We used the time window of four seconds from one second before the arrival time of S-wave detected by JMA at each station. We applied two thresholds for detection: 8 and 8.5 times of median absolute deviation for the distribution of correlation sums.

We found stepwise tremor activities at all spots corresponding to episodic tremor and slip (ETS), which recurs at intervals of about half a year in western Shikoku. At the northern (deeper) part, the number of detected events during ETS was smaller, and small tremor bursts were more frequently detected during inter-ETS compared to the southern (shallower) part. This result is consistent with the general trend of tremor activity in wider scale in southwest Japan and Cascadia. For both thresholds, the characteristics of the results are almost the same.

Some tremor episodes were detected only at the up-dip part of the tremor cluster, although individual ETSs are mainly initiated at the deeper part and migrate upwards in western Shikoku (Obara et al., 2011) and Cascadia (Wech and Creager, 2011). This may suggest that some ETSs initiate at the updip part.

Keywords: deep low frequency tremor, slow earthquake, ETS

The 1st report of the Network-MT survey in the Western part of Shikoku Island, SW Japan

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In the Bungo channel region at the western margin of the Nankai megathrust rupture zones, the long-term slow slip events (SSE) repeatedly occurred about every 6 or 7 years. They activated deeper episodic tremors and slips (ETS) in the transition zone between locked and steady state slip zones along the sliding zones on the plate interface. The SSE also activated shallow very low frequency earthquakes (VLFE) off the Cape Ashizuri. All of these activities are releasing accumulated stress between the subducting Philippine Sea Plate and the SW Japan without generating a megathrust rapid rupture. Since the last major SSE occurred in 2010, we have not observed the major SSE yet and we will soon have the next one (in 2017 or 2018).

In order to examine mechanism of the SSE and/or concurrent ETS activities, especially to clarify influence of interstitial fluids on occurrence of the events, or to detect movement of the fluids associating with the events, we have started the Network-MT survey in the western part of the Shikoku Island facing the Bungo channel since April, 2016. In the Network-MT method, we use metallic telephone line network of the Nippon Telegraph and Telephone Corp. to measure temporal variation of the electrical potential difference with long baselines of from several kilometers to 10 and several kilometers. We selected 17 areas in the western part of Ehime and Kochi prefectures and installed 3 or 4 electrodes in the respective areas. By using those electrodes and metallic telephone lines, we measure the potential differences in 3 or 4 directions in the respective areas. The electrical potential differences measured in this way are known to be less affected by small scale near-surface lateral resistivity heterogeneities (e.g. Uyeshima, 2007). We also measure geomagnetic field at two stations in the target region. With the aid of the BIRRP code (Chave and Thomson, 2004), we estimated the frequency-domain response functions between each voltage difference and two component horizontal magnetic fields. From these response functions, we can estimate the regional deep resistivity structure. As the first report of this survey, in this presentation, we will show stability of the long-term electric field time series and discuss on the spatial distribution of the Network-MT response functions.

This study is supported by JSPS KAKENHI Grand Number JP16H06475 in Scientific Research on Innovative Areas “Science of Slow Earthquakes. It is also partly supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program. We acknowledge staffs of the Nippon Telegraph and Telephone WEST Corporation for their cordial support in the survey. We also thank Drs. H. Abe, A. Takeuchi and Y. Suwa in ERI for their help in preparing and installing instruments.

Keywords: Nankai Subduction Zone, Nework-MT survey, slow slip event, episodic tremor and slip, resistivity structure prospecting

Large-scale electrical resistivity structure around the long-term Slow Slip Events beneath the Bungo Channel region, southwest Japan

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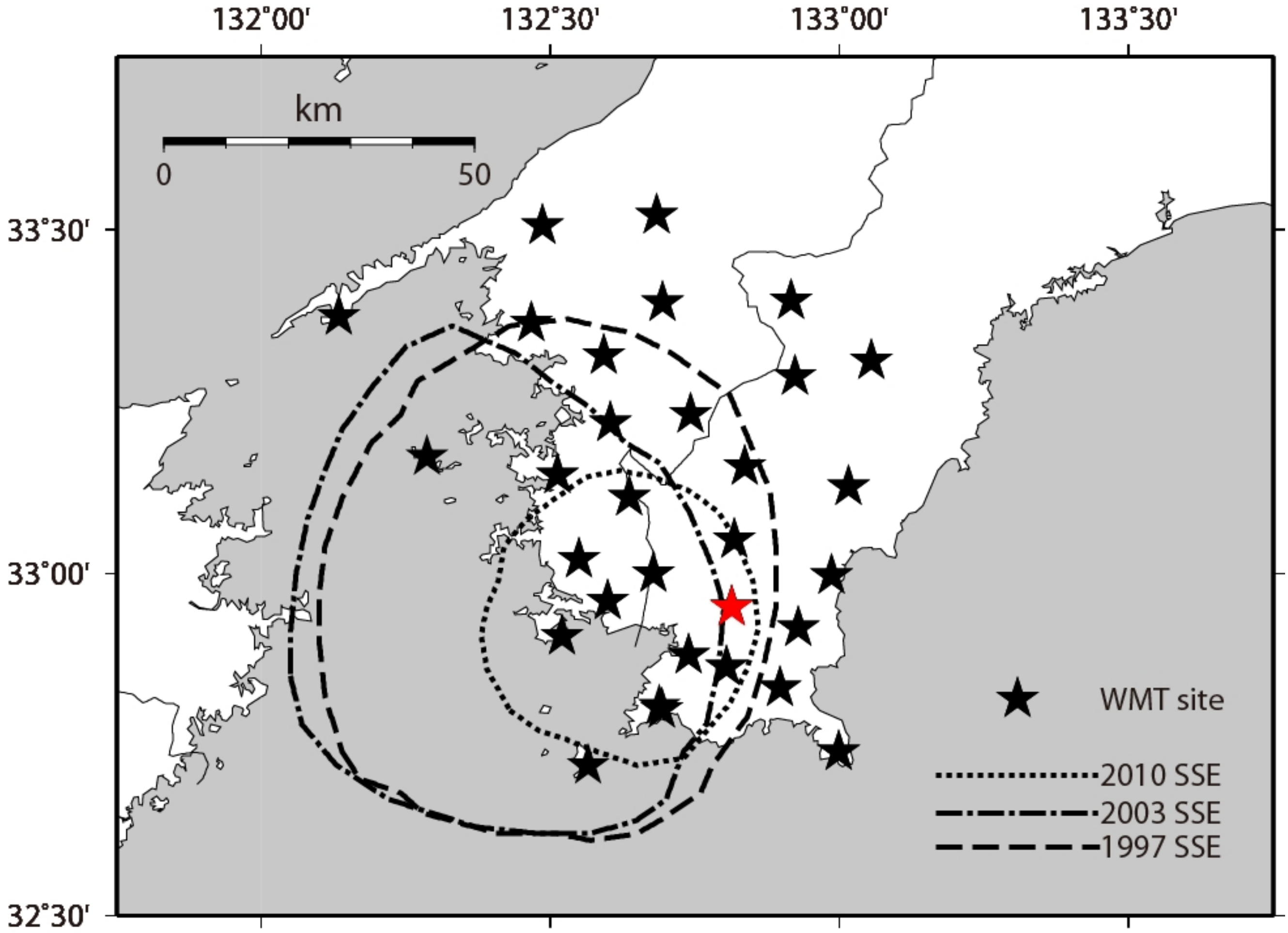
Recent geodetic observations detect recurrent slow slip events (SSEs), which occurred beneath the Bungo Channel and southwest Shikoku Island, with interval of approximately 6 years (e.g. GSI, 2010). In order to reveal a large-scale three-dimensional resistivity structure around SSEs region, we carried out wideband magnetotelluric (MT) surveys around the western part of Shikoku Island. We also plan to establish a permanent long-term MT monitoring network that aims to detect temporal changes of resistivity structure during SSE cycle. As of June, 2016, MT surveys were performed at 31 sites by using Phoenix wideband MT instruments. In the most of sites, high quality MT responses were obtained using the BIRRP code (Chave and Thomson, 2004) for the period range 300 Hz to 10,000 sec. The spatial distributions of the phase tensor ellipses and the induction vectors suggest that resistivity contrasts are located surrounding SSEs. In this presentation, we show the results of the data analysis and preliminary inverted three-dimensional model around the transition zone between SSEs and stick-slip regions.

Keywords: slow slip events, Bungo Channel, resistivity structure


132°00'
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WMT site
2010 SSE
2003 SSE
1997 SSE

Simultaneous estimation of a long-term and short-term slow slip events in the Bungo Channel region with MCMKF-based inversion

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We estimated space-time evolution of slow slip events (SSE) in the Bungo Channel region with the Monte Carlo Mixture Kalman Filter (MCMKF) based Network Inversion Filter [Fukuda et al.,2014]. The Bungo Channel region is well known site where long-term SSEs (duration is about one year) repeatedly occur with the recurrence interval of about 6-7 years. In addition, short-term SSEs (duration is several to ten days) have been reported by analyzing tiltmeter data. In this study, we use GNSS time series of GEONET stations proceeded by GIPSY [Takuya Nishimura, pers. comm.] between Jan. 1, 2009 and Dec. 31,2012 to estimate both long-term SSE and short-term SSEs simultaneously. MCMKF-based inversion has an advantage that the temporal smoothing parameter is temporally variable and chosen to follow the temporal variation of fault slips. In the light of this advantage, we estimated both long-term SSE and short-term SSEs simultaneously.

First we pre-processed GNSS time series; we estimate secular velocities, annual and semi-annual variations, coseismic steps and post-seismic deformation based on the least-square method, and subtract them from the original time series.

We employ the plate configuration by Hirose et al. [2008], and select the area of about 200km long to the east and 280km long to the north as the model region. We subdivide it to 719 subfaults, and represent the slip by a series of 24 depleted basis functions. Finally we performed the MCMKF-based inversion to infer cumulative slips and slip velocities. The estimated cumulative slip distribution is consistent with previous studies [e.g. Yoshioka et al., 2015 for the long-term SSE and Nishimura, 2014 for short-term SSEs].

This study may be the first case where both a long-term SSE and short-term SSEs have been estimated simultaneously from GNSS time series.

Keywords: Slow slip, Bungo Channel, GNSS

Spatial distribution of long-term slow slip events beneath the Bungo Channel under sparsity constraints

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It is possible that generation mechanisms of slow earthquakes are affected by certain physical and/or chemical thresholds. However, up-dip and down-dip limits of long-term slow slip events have previously been assumed to be smoothly distributed because of prior constraints to inversion analyses. We have applied an inversion method called generalized fused lasso, a type of sparsity constraint, for evaluation function. We analyzed realistic displacement data for long-term slow slip events (L-SSEs) observed at GEONET stations around the Bungo Channel, southwest Japan. Using fused regularization, we estimated the slip distribution of three L-SSEs that occurred on 1997, 2003, and 2010. As a result, we identified three discontinuous boundaries on the subducting plate interface. These findings will help to reveal the transition mechanism from megathrust earthquakes to slow earthquakes on the subducting plate interface.

Radiation Efficiency of Earthquakes in the Philippine Sea slab

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Although the Philippine Sea (PHS) slab beneath Kyushu is subducting to a depth of >400 km, earthquakes in Kyushu are limited to a depth of ~200 km. The termination of intraslab earthquakes may be related to a change in physical or material properties of the PHS slab at a depth of 200 km. This study estimates radiated energy and radiation efficiency of earthquakes occurring in the depth of 60 ~ 200 km beneath Kyushu, and discusses the depth variation in radiation efficiency.
Precise estimates of the static stress drop and radiated energy are essential to calculate the radiation efficiency. Although the static stress drop depends on the corner frequency and the radiated energy depends on the quality factor, there is a strong trade-off between the corner frequency and quality factor and so it is not easy to determine the two parameters simultaneously. Therefore, in this study, the corner frequency is first estimated by the coda wave spectral ratio method, and the quality factor is then obtained from the shape of amplitude spectra for S waves using the pre-estimated corner frequency.
The obtained results show that the radiation efficiency changes little with depth. The average value of the radiation efficiency in the PHS slab beneath Kyushu is ~0.1, which is relatively small compared to that observed at the same depth range in the Pacific slab beneath Tohoku and Hokkaido. We infer that the small radiation efficiency in the PHS slab is due to high temperatures of the slab compared to those in the Pacific slab beneath northern Japan.

Keywords: Radiation Efficiency

Induced Low Frequency Earthquakes Contributed to Teleseismic Events Along the Ryukyu Islands, Okinawa

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Recently, triggered low frequency earthquakes (LFEs) have been observed during the passage of surface waves from teleseismic earthquakes. The occurrence of the triggered LFE depends on the maximum amplitude of surface wave and its propagation direction (Chao et al., 2011). The triggered LFEs are observed around various places in Japan (Chao et al., 2016), but it has not observed in Ryukyu Trench yet. We investigated the LFEs in the Ryukyu arc by the teleseismic earthquake.
First we picked several teleseismic events witch were Mw>7.5 and >1000km away from Naha. By using F-net data from NIED and short-period seismometers by JMA, we bandpass filtered them at the frequency range 2-8 Hz for horizontal components and 0.02-0.05 Hz for horizontal and vertical components, for the waveforms produced of teleseismic earthquake. Then, we detected the triggered LFEs manually comparing low frequency waveforms (for surface waves) with high frequency ones. Then we compared relation between triggered LFEs and surface wave amplitudes, durations, and wave intrusion directions of teleseismic earthquake. Among 56 teleseismic events, we could observe 18-37 LFEs. Also, LFEs were induced when least 0.1 cm/s of maximum amplitudes intruded. The wave propagation direction might not affect on the occurrence of LFEs; however, the durations of surface waves possibly conditioned to induce LFEs.
We determined the triggered LFEs of three teleseismic earthquakes (Sumatra 2004, Nias 2005, and Sumatra 2012) by using the time differences of S-waves arrival times at each station. The time differences were computed using the Envelope Correlation Method (Obara, 2002), and hypocenter locations were determined by grid-search method (Chao et al., 2013). Thus, some clusters of the LFE hypocenters are distributed at the Trench side and Okinawa Trough side. This suggests that the LFEs were triggered in the subducted plate and backarc area including volcanic zone.

Keywords: Low Frequency Earthquake, Ryukyu Trench, Triggered Earthquake, Earthquake Interaction

An evidence of existence of transition region from slow-slip area to general earthquake area

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Yaeyama Region, Western Ryukyu Islands, is one of tectonically unique regions which have slow-slip, tsunami earthquake and general earthquakes within one are associating with Philippine Sea plate subduction. Repeating slow slips are detected beneath west off Ishigaki island (Heki and Kataoka, 2008) and Nishimura(2014) analyzes detail of slip distribution of each slow slip carefully. Arai et. al.(2016) reported low frequency seismic signals in shallower area by ocean bottom seismic network. By considering with broadband seismic data, these are one of shallow very low frequency earthquakes. Yamamoto et.al.(2016) identified inter-plate general earthquakes using by ocean bottom seismic and islands' telemetered data and located their hypocenters. They suggested that each event of source type locate in different area. It implies that mechanical property around interface of two plates varies in space. Nishimura(2014) and Yamomoto et.al.(2016) shows that Ishigaki island locates just above boundary between slow slip and general earthquake occurrence area. We try to monitor and review broadband seismic data recorded STS-1 sensor (station: ISG) in Ishigaki island. We identified one very low frequency event signal. In short period network in Yaeyama region, short-term tremor-like signals also observed. The feature is same with deep very low frequency earthquake.
By location using envelopes of seismograms, epicenter is determined just below Ishigaki island. Assuming plate shape model proposed by Yamamoto et.al.(2016), constraint analysis shows also that this event just boundary region below Ishigaki island. It supports results of Yamamoto et. al.(2016) and implies existence of transition region of two areas.

Keywords: low frequency earthquake, slow slip

Seasonal variation of tidal response of very low frequency earthquakes in the Ryukyu Trench

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Very low frequency earthquakes (VLFEs) occur along the Ryukyu Trench resulting in tidal changes (Nakamura & Kakazu, 2017) with a response magnitude of several years. Temporal changes in the tidal response are caused by two main factors, changes in the hypocenter locations of the VLFE and in the state of the slip at the fault, in addition to atmospheric pressure (AP) and ocean bottom pressure (OBP) changes. This weak but seasonal pressure change can influence VLFE activity. This study investigated whether the tidal response of the VLFEs changes seasonally and estimated the atmospheric and oceanic effects by calculating the stress for their loadings.
VLFEs that occurred in 2002–2015 were analyzed in this study. Data were selected in two-month intervals, and Fourier transform was applied. The results show that the amplitude of the M2 tide in Okinawa was smallest in summer, at 0.3, and largest in winter, at 0.5. Similar results were obtained in Amami.
The stress change was then computed for OBP and AP. The *Circulation* and *Climate* of the Ocean (ECCO) OBP model was used, as was the monthly averaged AP. Then, the loading was computed for the AP in the land area. Some Programs for Ocean Tide Loading (SPOTL) software (Agnew, 2012) was modified and used to enable computation of stresses at depths according to the point loading. The subducting Philippine Sea plate at a depth of 15 km was employed as the fault parameter.
The computed annual amplitude change of the shear stress was 20 Pa and 15 Pa in Amami and Okinawa, respectively. The shear stress reached its peak and trough in the winter and summer, respectively. However, the shears stress change by atmospheric and oceanic loading corresponded to 3% of the tidal stress. Although the stress change for these loadings was approximately one-third of that which can reproduce seasonal change in the tidal response, the trend was able to be reproduced.

Keywords: very low frequency earthquake, tidal response, Ryukyu Trench

Spatio-temporal evolution of recurrent slow slip events from 2010 to 2013 along the Ryukyu Trench, southwestern Japan

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Various types of slow earthquakes, including slow slip events (SSEs, Heki and Kataoka, 2008, Nishimura, 2014), very low frequency earthquakes (VLFEs, Ando et al. 2012, Nakamura and Sunagawa, 2015), and low frequency earthquakes (LFEs, Nakamura, submitted), are detected along the southern part of the Ryukyu Trench, Japan. In this area, Global Navigation Satellite System (GNSS) stations have been newly installed since 2010 by Kyoto University in addition to the stations operated by Geospatial Information Authority of Japan. This study applies a modified Network Inversion Filter to these GNSS time series from March 2010 to February 2013, to estimate the spatio-temporal evolution of slow slip on the plate interface in detail. Five SSEs with Mw 6.6–6.8 and durations of 30–100 days are found during this period. The main slip region of the five SSEs are similar, located beneath the northwestern side of the Iriomote island. In contrast to the similarity in the spatial location, our detailed analysis newly clarifies the difference in the temporal evolution among the events; three SSEs suddenly accelerated to the maximum slip rate, and the other two SSEs showed a slow acceleration for 20–50 days. The spatial relationship among the SSEs, LFEs, VLFEs, and tsunamigenic earthquake, is complementary along the trench, depending on the depth; tsunamigenic region in the shallowest part, weakly coupled region of VLFEs and LFEs with depths shallower than 30 km, and SSEs deeper than 30 km, reflecting the depth variation of physical properties. VLFEs are sometimes activated 10–20 days after the onset of SSEs that initiate with slow acceleration phase, although the number of SSEs is too small to assert this correlation. Since new GNSS stations are planning to be established, additional data and further analyses will possibly make the correlation clear in the future.

Keywords: slow slip events, Ryukyu Trench, geodetic time-dependent inversion

Finite element eigenvalue analysis of seiche in Nagura dam reservoir: physics-based signal identification for slow seismic event detection

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The oscillations with 11 mHz peak frequency were quite often recorded at Ishigaki (IGK) station of the F-net broadband seismograph network. Since the free oscillation characterized by mHz-level frequency were used to detect slow seismic events and glacial earthquakes (Beroza and Jordan, 1990; Ekström et al., 2003), such oscillations recorded at IGK station obviously interfere in the signal processing for slow seismic event detection.
We first start with signal source identification of the recorded oscillations and assume that the oscillations are produced by seiche because IGK station locates close to Nagura dam reservoir. As the behavior of seiche is governed by linear shallow water equation, its eigenfrequency is easily obtained from an appropriate numerical method such as the finite element method. We implemented the computer program for eigenfrequency on a commercial finite element software (COMSOL Multiphysics) and then a series of eigenvalue analysis were conducted to investigate whether the seiche possesses the eigenfrequency of 11 mHz or not.
As a result, we found five eigenmodes of seiche with 11 mHz eigenfrequency. By taking the fact that the water depth of the dam reservoir is approximately 10 m, those five candidates are narrowed down to the following two candidates: (1) the third eigenmode with the water depth of 9.5 m; (2) the second eigenmode with the water depth of 12.2 m. Given the predominant direction of recorded oscillations (north-south), the eigenmode shape for candidate (2) is more preferable. In any case, these results support our assumption that the seiche in the dam reservoir is the source of the recorded oscillations with 11 mHz peak frequency.

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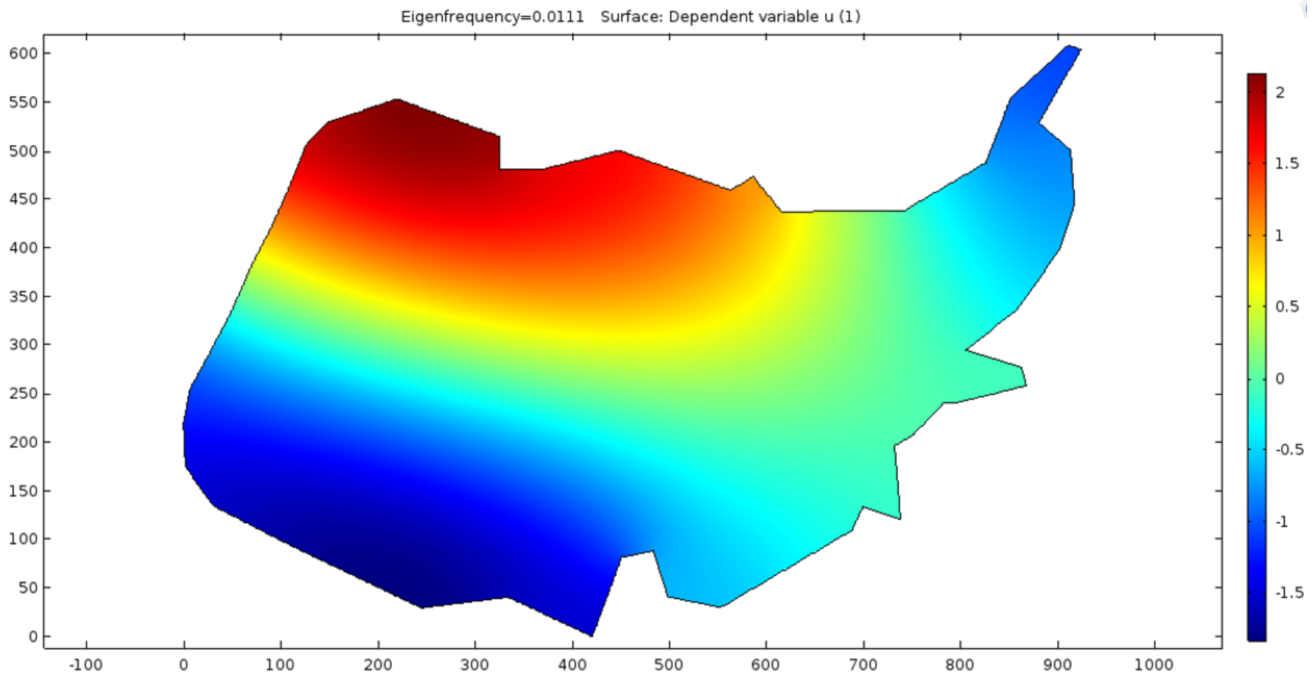
Keywords: oscillation, seiche, eigenfrequency, finite element method


Eigenfrequency=0.0111 Surface: Dependent variable u (1)
600
550
500
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400
350
300
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200
150
100
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0
-100
0
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200
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400
500
600
700
800
900
1000
2
1.5
1
0.5
0
-0.5
-1
-1.5

Sub-slab anisotropy in the western Pacific : The Izu-Bonin and Mariana regions

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Understanding the mechanism of plate subduction helps us put together a whole picture of how the mantle works under plate tectonics. The sub-slab seismic anisotropy serves as a direct tool for illuminating subduction dynamics, implying the flow direction and deformation patterns of subducting slabs.
We measured source-side shear wave splitting with receiver-side correction for the Izu-Bonin and Mariana subduction zones. The initial results show that the deeper slab is associated with larger delay times (dt) in Izu-Bonin region, while delay times of deeper slab in the Mariana are smaller. The fast directions (f) of the two regions seem to be random with respect to the slab contour. However, anisotropy for shallow events in the Izu-Bonin slab is consistent with the relative plate motion. The next step is to consider the radial anisotropy in the receiver-side correction.

The fluid flux and fault rock development along the subduction seismogenic Okitsu Fault, Shimanto accretionary complex, SW Japan

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The Okitsu Fault is pseudotachylyte bearing ancient seismogenic fault of the Shimanto accretionary complex, SW Japan. This paper discusses the relationship between fluid flux and fault rock development. The structural analysis revealed that the Okitsu Fault develops at the roof thrust of the duplex structure of the Okitsu Mélange. Among the mélange zone, the rock around the Okitsu Fault has suffered high temperature, and the fault zone is characterized by many vein minerals and altered basalt blocks. Hydrothermal activity along the fault zone likely transfer the heat from the deep. The fault rock seems to be developed with fluid flow. The hydro-fracturing, vein mineral precipitation and pressure solution deformations are occurred at thick fault area. This fault thickness may vary with fluid flux. The CO_2 flux along the fault zone is estimated from the alteration grade of the basalt blocks within the fault zone. More than 118 kmol/m^2 of CO_2 fluid flux was obtained in thick fault zone, and it drops in thinner fault zone. Such partial distribution of fluid flux implies that the fluid pathway may have existed at same location historically along the fault. The fluid pathway possibly concern with fault rock asperity.

Keywords: accretionary complex, seismogenic fault, fluid

Geological observations supporting a slip model that stress drop varies with characteristic rupture length

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There are two slip models for slow earthquakes proposed by Ide et al (2007). One is constant stress drop model in which displacement is proportional to rupture area. This model is common for regular earthquakes. The other is diffusional earthquake model with constant displacement. For slow earthquakes, however, both two models can be adoptable because the average slip amounts of smaller events are unknown.
In this study, two geological observations are introduced to discuss how the observations support the diffusional earthquake model.
One is from a relationship between heat generation rate and slip duration estimated from decreasing pattern of vitrinite reflectance with distance from a micro-fault observed in the Shimanto Belt, an exhumed accretionary complex, SW Japan. The micro-fault has shear zones with thickness of up to 3.7 mm. Magnitude of vitrinite reflectance decays with distance from the fault. The distance which vitrinite reflectance attenuates to background level is about 4-10 cm. On the basis of the decreasing pattern, we estimated 2300-8600 J/m^2/s of heat generation rate and 10000-98000 s of slip duration. The relationship between heat generation rate and slip duration from natural faults follows the scaling relationship for slow earthquakes with -1 of scale exponent.
The other is from roughness analyses on surfaces of natural faults, which shows the Hurst exponent is less than 1 in the relationship between power spectrum density and wave number. An example from the micro-faults in the cores from Taiwan Chelung-pu fault Drilling Project (TCDP). The roughness of surfaces of micro-fault was analyzed by 3D topographic micro-analyzer. The Hurst exponent is about 0.7-0.76. This kind of Hurst exponent has been reported for the natural fault normally ranging on 0.6-0.8. So the result from TCDP case is also consistent with the results from previous studies. Assuming the elastic shear deformation, the Hurst exponent less than 1 indicates that the stress drop is not constant but negatively proportional to fault length.
These two examples support the diffusional earthquake model is suitable for slow earthquakes. The -1 of scale exponent between thermal generation rate and slip duration can be achieved when displacement is constant. The thermal generation rate $Q = \mu' * P_{eff} * D/T$ (μ' : effective friction coefficient, P_{eff}: effective vertical stress, D: displacement and T is slip duration) is proportional to T^1, indicating that the D is constant because μ' and P_{eff} can be constant.
The Hurst exponent less than 1 indicates that stress drop is negatively proportional to fault length as described above when elastic frictional shear was assumed. Because stress drop is expressed as $dS = \mu D/L$ (μ: rigidity, L: dimension of fault plane), when D is constant, stress drop is not constant but negatively proportional to L.
In conclusion, these geological observations support the diffusional earthquake model expected in mechanisms for slow earthquakes, which can not be adopt to the regular earthquake.

Keywords: fault rocks, slow earthquakes, slip model

Comparison between timescales on formation of quartz-filled shear veins and slow earthquake cycle in the Makimine mélange of the Shimanto accretionary complex, SW Japan

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Geophysical observations have suggested that fluid played an important role on the generation of slow earthquakes. However, geological conditions and deformation processes related to slow earthquakes remain unclear. Quartz-filled shear veins are commonly observed in accretionary complexes exhumed from the source depths of shallow slow earthquakes (less than 15 km). Crack sealing associated with quartz precipitation is expected to contribute decreasing of rock permeability and increasing of fluid pressure, which may induce slow earthquakes. However, the timescale between crack sealing and slow earthquake cycle has been unknown. In this study, we examined and calculated kinetics of quartz precipitation and compared the timescales of formation of quartz-filled shear veins and slow earthquake cycle in the Makimine mélange of the Shimanto accretionary complex, southwest Japan.

Keywords: Quartz-filled shear vein, Kinetics, Sealing time of crack, slow earthquake cycle

Fluid flow, fluid-rock interaction and slow earthquakes at the forearc mantle corner

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The forearc mantle corner in subduction zones is a site of deep slow earthquakes such as low-frequency tremors, very low frequency earthquakes and short-term slow slip events. Geophysical observations suggest that these seismic activities are related to updip fluid flow along the slab-mantle interface and quartz deposition in the crust above the mantle corner (*e.g.*, Audet & Bürgmann, 2014, *Nature*, 510, 389–392; Hyndman *et al.*, 2015, *J. Geophys. Res. Solid Earth*, 120, 4344–4358). The geological evidence for the fluid flow has been reported from many subduction-zone mélanges (Bebout & Penniston-Dorland, 2016, *Lithos*, 240–243, 228–258, and references therein).

The question is, how the updip fluid flow is formed and maintained at the slab-mantle interface? Fractures probably play an important role of fluid pathways, but the life span of individual fractures could be short for the rapid sealing by vein minerals. We propose that fluid-rock interaction in subduction-zone mélange would sustain the fluid flow if reaction-enhanced permeability takes place.

We present an example of fluid-rock interaction and reaction-enhanced permeability in subduction-zone mélanges. The Nagasaki metamorphic rocks in Kyushu, Japan, consist mainly of Late Cretaceous schists and contain serpentinite mélanges. The metamorphic pressure and temperature are close to those of the forearc mantle corner (~0.8 GPa and ~440 °C). The serpentinite typically occurs as mélanges, in which metapelitic tectonic blocks have been albitized along the rims and cracks. The albitization is considered to be the result of fluid-rock interaction. The isocon analysis indicates that the albitization involves a loss of rock volume and extraction of silica from the blocks. The volume loss increases along with the reaction progress of the albitization.

Albitization is commonly found in the subduction-zone mélanges of the blueschist to eclogite facies. This suggests that reaction-enhanced permeability widely takes place at the slab-mantle interface. As a result, the subduction-zone mélanges probably become porous media, which act as sustainable channels of the updip flow of fluids (and silica) towards the site of deep slow earthquakes.

Keywords: Albitization, Reaction-enhanced permeability, subduction-zone mélange, Slow earthquakes

Preliminary results of interstitial water geochemistry from IODP Expedition 362: Subduction inputs to the Sumatra subduction zone

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The Mw 9.2 Sumatra earthquake in 2004 resulted in unexpectedly shallow megathrust slip, which amplified the earthquake magnitude and caused a devastating tsunami. At two sites (Sites U1480 and U1481) International Ocean Discovery Program (IODP) Expedition 362 cored the input sediment with R/V JOIDES Resolution ~250 km seaward of the Sumatra subduction zone to groundtruth the material properties that contributed to the unexpectedly shallow seismogenic slip and a distinctive forearc prism structure of the North Sumatra subduction zone. The recovered sediment comprise a Late Cretaceous to Miocene abyssal-plain environment facies consisting of mixed tuffaceous and pelagic sediments and a series of intercalated pelagic and igneous materials, which is overlain by a thick sequence of siliciclastic sediments (mostly siliciclastic mud, siliciclastic sand and calcareous mud) of the Nicobar fan. Here we present preliminary results from shipboard geochemical analyses of interstitial waters.
The sulfate-methane transition zone (SMTZ) exists at 120 mbsf. Concentrations of ammonium and phosphate have positive peaks above the SMTZ, which reflect the remineralization of organic matter. Low alkalinity and calcium concentration below the SMTZ indicate carbonate precipitation. Release of silica and cations (K^+, Ca^{2+}, Na^+, Al^{3+}) to the interstitial water are indicative of volcaniclastic ash alteration in the upper 20 mbsf. A subsequent depletion of potassium below 400 mbsf to values as low as 1 mM suggest zeolite formation, consistent with observations in the recovered sediment. The high sulfate concentration of 15 mM in pelagic sediment at 1403 mbsf may reflect a presence of sulfate-rich fluid in the basement aquifer. Ongoing post-expedition analyses of interstitial water geochemistry will provide additional insights into fluid-rock interactions and fluid flow processes which will shed light on the evolving properties of the sediment incoming to the North Sumatra subduction zone.

Keywords: International Ocean Discovery Program, Seismogenic Zone, Subduction Zone, Sumatra, Inorganic geochemistry, Interstitial water

Temporal Variation of Interplate Coupling in Java Subduction Zone Based on 2008-2012 GPS Observations

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In the southern Java, the Australian plate subducts beneath Sunda Block at almost perpendicular direction on the western part of Java trench and more oblique along the rest of Java trench. There have been several earthquakes, the 2009 West Java (M7.0), the 2010 West Java (M5.9), the 2011 East Java (M5.7) and the 2011 Bali (M6.1) that occurred as a result of interplate coupling along the Java subduction zone. Since they caused coseismic offsets in the coordinate time series at several GPS sites near the epicenter, we divided them into some specific time periods and estimated the temporal variations of the slip deficit rates along Java subduction zone. We carry out the geodetic inversion analyses of the GPS site velocities from 2008 to 2012 located in Java, Bali, Madura, and Lombok (54 national network sites) and 10 IGS stations, together with the azimuth of slip vector from some earthquakes in Java subduction zone using TDEFNODE software (McCaffrey, 2009). We use the Euler pole parameter from previous result (Longitude: 86.876ºW, Latitude: 48.917ºN, and Angular velocity: -0.330º/Myr) in the inversion. We do several checkerboard tests to examine how well the artificial distributions of coupling ratio with 100% and 0% slip deficits can be restored. The results show that TDEFNODE can recover well the most part of fault surfaces in Java subduction zone except for the plate boundary near the trench.

The locking map before and after the 2009 West Java earthquake demonstrates the low coupling rate of ~30 mm/yr and ~10 mm/yr, respectively, near the hypocenter. The inversion result before the 2010 West Java earthquake cannot detect the significant coupling rate near the hypocenter because the lack of the data but after that earthquake the coupling rate became ~10 mm/yr. The locking map before and after the 2011 East Java earthquake and the 2011 Bali earthquake show the unrealistic result since low ability to resolve the coupling rate in the easternmost of Java Subduction zone. Overall the inversion of the GPS data before the 2012 Sumatra earthquake shows the low coupling rate of ~30 mm/yr in the western part, the coupling rate of ~40 mm/yr in the middle part, and the very high rate of ~70 mm/yr in the eastern part.

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Keywords: Temporal variation, Java Subduction, Interplate Coupling

Shear localization related to frictional strengthening of the biogenic sediments entering subduction zone

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In subduction zones, various seismic activities such as large earthquakes, episodic slow slip events, or silent earthquakes are observed. This variation likely reflects spatial variations in frictional properties along the seismogenic portion of plate-boundary megathrusts (e.g., Bilek and Lay, 1998). The frictional properties of materials entering subduction zones are probably different among various materials. Hence, the frictional properties of main oceanic sediments should be revealed.
A number of studies revealed frictional properties of clay sediments collected from the Nankai Trough (e.g., Brown, 2003). However, studies on the frictional properties of biogenic sediments are limited (e.g., Ikari et al., 2013; Namiki et al., 2014). In this study, we investigated the frictional properties of the biogenic sediments, and performed a series of friction experiments on silicic to calcareous ooze. To understand what controls the mechanism, we observed the shear structure in the samples by SEM. The samples tested in this study were collected offshore Costa Rica (Site U1381) during IODP expedition 334 and 344.
Frictional properties of the silicic to calcareous ooze were different from those of the clay sediments (Namiki et al. 2014). The friction coefficient of the ooze at a constant slip velocity of 0.28 mm/s showed an initial peak at 0.4 to 0.6 and subsequent minor decrease, followed by a gradual increase to attain a constant friction value at 0.6 to 0.8.
For friction experiments a rotary-shear friction-testing machine was used with various slip rates according to the radius of the shear area. The slip rate at the center is zero, and the slip rate on the outside is the fastest. In cross-sections near the outside of shear areas, two types of shear structures were observed: (1) shear localized zone (about 50 to 100 μm thick) mainly composed of fine rounded particles which forms parallel to the shear zone and (2) shear distributed zone, in which the silicic and calcareous shells show preferred orientation inclined to the shear zone at an angle within a range of about 30 degrees. Both of the structures were observed in samples, which have slipped until 0.4 rotations or more. A shear distributed zone could only be observed in samples slipped within 0.02 rotations. The particles in the shear localized zone decreased in grain size with larger displacement.
In cross-sections through the center of shear areas, a preferred orientation of particles in the shear distributed could not be observed as the analyzed cross-sections are vertical to the slip direction. The shear localized zone was observed only in the outer region of samples, which have slipped until 0.4 rotations. For samples slipped until 3.3 rotations, the shear localized zone could also be observed in the inner region.
From these results, displacement is a significant factor to develop shear localization. The observation of cross-sections through the center of shear areas suggests that duration of slip and slip rate seldom affect shear localization. The shear localized zone has formed while the friction coefficient attained a steady-state value after strengthening. The shear localized zone and preferred orientation in the shear distributed zone might correspond to Y-shear and P-shear of Riedel shear, respectively. Thus, Y-shear likely develops with frictional strengthening, and continues to develop during a period while the friction coefficient maintains steady-state value.

Keywords: frictional experiment, shear structure, silicic to calcareous ooze, CRISP

Investigation of friction velocity dependence under the change of pore fluid pressure

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Pore fluid pressure plays an important role in controlling the mode of fault slip, and friction parameter and fault stability change with pore fluid pressure (Scuderi and Collettini 2016). But, there have been only a few experimental studies focused on role of pore fluid pressure. Scuderi and Collettini (2016) conducted experiments on marble gouge and limestone gouge under pore fluid pressure condition. These experiments revealed significant effect of pore pressure on critical slip distance Dc and the friction velocity parameter (a-b). In this study, we conducted friction experiment on silicic to calcareous ooze under the change of pore fluid pressure continuously, and investigated rate-dependence of steady-state friction.

We conducted friction experiment using a rotary-shear intermediate- to high-velocity friction-testing machine. Samples were sediment on the Cocos plate offshore Peninsula, at U1381, during IODP Exp.334. The samples were dried at 60 ˚C and disaggregated gently using pestle. Sample was placed between a simple gabbro cylinder and cylindrical sandstone mounted on a gabbro cylinder. Pore pressure was controlled by a syringe pump. At the start of experiment, normal stress was 6 MPa, pore fluid pressure was 1 MPa. We raised pore fluid pressure from 1 MPa to 5 MPa continuously after friction coefficient attained a roughly steady-state. The additional shear stresses from PTFE O-rings in experiments were calibrated. In this experiment, slip rate was 0.003-0.028 mm/s, displacement was 0.6 m.

As a result, the frictional velocity dependence was negative when pore pressure was from 1 MPa to 2 MPa. But when pore pressure was from 4 MPa to 5 MPa, the frictional velocity dependence was positive. Namiki et al 2014 conducted friction experiment under the drain condition using same sample, and show that friction velocity dependence was negative through experiment. Our results may suggest that friction velocity dependence change with pore fluid pressure.

Keywords: Pore fluid pressure, friction, subduction zone

Frictional properties of hydrated clay minerals and its application to tsunami earthquakes

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Tsunami earthquake excites larger tsunami than expected from its seismic motion. It is possibly related to slow fault motion at the shallow part of the subduction boundary where large amount of clay minerals are dominated. Accordingly, the frictional properties of clay minerals are important to understand the mechanism of tsunami earthquake. Seno (2002) suggests that tsunami earthquakes are induced by existence of pore fluid pressure, because high pore fluid pressure reduce effective normal stress and clay minerals exhibit unstable sliding under such low effective stress. Although previous studies were mostly carried out at dry conditions, frictional property of under hydrate state have not been understood. In this study, we conducted velocity step test under water saturated condition and analyzed the frictional property of hydrated clay minerals. Based on these data, we discuss the possible mechanism of tsunami earthquakes at shallow part of subduction zone.

Friction experiment were conducted by using a biaxial testing machine. The clay gouges were composed of smectites (Na-montmorillonite and Ca-bentonite, saponite). Samples were dried by the vacuum furnace for 24 hours at 100°C prior to experiments, and for hydrated experiment, we used the water tank to saturated fluid in the simulated fault zones. We investigated frictional strength and velocity dependence over a range of normal stresses from 10 to 60 MPa and sliding velocities from 0.3 to 33 μm/s. The velocity dependence was determined from the change in steady-state friction after the abrupt change in sliding velocity. Velocity-strengthening behavior shows an increase of friction coefficient with increasing sliding velocity. In contrast, velocity-weakening behavior shows a decrease friction coefficient with increasing velocity.

Fluid saturated samples exhibited markedly lower friction coefficient than dried samples, and velocity dependence was influenced by the presence of water. Under dry condition, Na-montmorillonite and saponite exhibited velocity-strengthening over a range of studied normal stress, whereas Ca-bentonite tends to exhibit velocity-weakening under low normal stress ($<$ 40MPa). Ca-bentonite showed a transition from velocity-weakening to velocity-strengthening with increasing normal stress. Under hydrated condition, velocity dependence on friction has a relatively small, and all samples show the neutral velocity dependence at low normal stresses.

We applied these experimental data to subduction environments where abundant clay minerals exist under fluid-saturated and low effective normal stress. In such situation, velocity dependence of clay mineral could exhibit neutral velocity dependence. Consequently, seismic slip can propagate through at shallow part of subduction zone. This behavior will generate a relatively slow slip motion compared to regular earthquake, which is consistent with the characteristic of tsunami earthquake.

Keywords: tsunami earthquakes, subduction zone, clay minerals

Characteristics of frictional properties' relationship with slow earthquake migration speed

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The propagation speed of postseismic slip seems to vary from place to place. For the 2003 Tokachi-Oki earthquake (M8), there was a time lag of about 80 minutes for the largest aftershock (M7.4) at about 40 km distance off Tokachi [Miyazaki and Larson, 2008 GRL] and of one year for the M7 earthquakes off Kushiro about 160 km away [Murakami et al., 2006 GRL]. If these aftershocks were triggered by ΔCFS increase in the passage of afterslip [Uchida et al., 2009 Gondwana Res], these time lags suggest that the propagation speed of the afterslip from the mainshock to the largest aftershock is significantly higher than to the M7 aftershocks off Kushiro.
On the Sanriku-Haruka-Oki earthquakes, Matsuzawa et al. [2004 EPS] pointed out that propagation speed of the postseismic slip seems to be on the order of 10 km/day for the shallower part of the subduction plate boundary while it appears to be 10 km/month for the deeper part. These results indicate that the propagation speed of postseismic slip depends on frictional properties and effective normal stress in addition to slip velocity.
To better understand the frictional properties controlling the propagation speed of postseismic slip, some numerical simulations of interplate earthquakes based on a rate- and state-dependent friction law (RSF) [Dieterich, 1979 JGR; Ruina, 1983 JGR] have been recently performed. These previous studies suggest the propagation speed of postseismic slip becomes lower in case of higher frictional stability, longer characteristic slip distance [Kato and Hirasawa, 1999 PAGEOPH], and higher effective normal stress [Ariyoshi et al., 2007 EPSL]. Since we do not quantitatively understand why such cases make the postseismic slip propagation slower, it is necessary to find an analytical relation between the frictional properties and the propagation speed of postseismic slip.
In this study, we develop an expression for the propagation speed of postseismic slip as a function of frictional properties including effective normal stress, and discuss its validity quantitatively by comparing the expression with trial numerical simulation results in addition to previous studies. Since our expression is also applicable to various types of slow earthquake phenomena, the observed slow earthquake migrations can help to constrain the frictional condition in subduction zones.

Keywords: afterslip, rate- and state-dependent friction law, stress perturbation

Estimation of frictional properties and slip evolution on the Long-term SSE fault with Ensemble Kalman Filter -numerical experiments-

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Long-term Slow Slip Events (LSSEs) occur on the plate interface beneath the source regions of the interplate large earthquakes. They are stress-release processes on the plate interface. The activity of SSE possibly changes before large interplate earthquakes and SSEs may directly trigger them. Hence, it is important to know the frictional properties and predict slip evolution on SSE faults. Our final goal is to estimate slip evolution and frictional parameters with the Ensemble Kalman Filter (EnKF), one of data assimilation methods, and then to give some insight into the occurrence of large interplate earthquakes. In this paper, we consider the Yaeyama and the Bungo Channel LSSEs and construct simple models which reproduce SSEs. We perform numerical experiments on estimation of frictional parameters on the fault through EnKF with LSSE model.

At first, we describe the numerical experiments for Yaeyama SSEs in the Ryukyu region, southwest Japan, (recurrence interval: 6 months, duration: 1 month). We set a dipping fault embedded in a homogeneous elastic half space. The friction on the fault was assumed to obey a rate-and state-dependent friction law, and the slowness law of state evolution. The constructed simple model has a circular velocity-weakening (A-B <0) patch (radius R=30km) on the fault plane with the frictional parameters so that R / Rc = 0.4 (Rc: critical nucleation radius). Then, we generated synthetic observed data where we added random numbers to the displacement rates at the ground simulated from the model, and performed EnKF estimations of the frictional parameters A and L on the fault plane and B-A on the patch along with the slip velocities and the state variables.

In this method, when the temporal change of observation becomes large, the innovation (residual of observation and forecast) also becomes large and the forecasted values are greatly updated. Hence, the forecasted values approach the true values during SSEs. However, it was found that we need observational data including several SSE cycles for accurate estimation. On the other hand, since the forecasted values are greatly updated during SSEs, numerical calculations frequently stop. This is an entirely different problem from the estimation ability of EnKF, and is troublesome for numerical experiments assuming various distributions of the observation points, for example. This problem is caused by the rapid temporal change of the observation values during the short duration of SSEs, and therefore we thought that it is avoidable in the assimilation for LSSEs with larger duration times. In addition, it was found that the poorer (e.g., the low density, and the heterogeneous distributions, etc.) distributions of observation points are, the slower are the conversion rates of estimated values to the true ones. It is difficult to observe Yaeyama SSEs with the poor distribution of observation points due to the sea area.

Based on the above experiments, to apply EnKF, the regions of SSEs should satisfy the following conditions:
1. SSEs have been observed more than once
2. The duration of SSEs is long
3. The distribution of observation points

Therefore, we target at the Bungo Channel LSSEs and construct a simple model (the patch radius

R=40km, R/Rc=0.9) which reproduces the LSSEs (recurrence interval: 7 years, duration: 1 year). We perform numerical experiments similar to the Yaeyama case. The results show that if the duration of SSEs is sufficiently longer than the assimilation step, updating is moderately performed and calculation does not stop. As long as we use a very simple model, we can estimate the frictional parameters on the Bungo Channel LSSE fault with considerable accuracy for the actual GNSS station distribution (GEONET).
In our current model, frictional parameters are uniform on the SSE patch. We need to perform numerical experiments for verifying the feasibility of this method when setting more complicated models and increasing estimated parameters.

Keywords: Ensemble Kalman Filter, Slow Slip Events

3D fluid migration due to complex slab geometries and its implications for short-term slow slip events

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In Cascadia and Nankai where relatively dense seismic and geodetic networks are available, short-term slow slip events (SSEs) generally occur at ~30-40 km depth along the subducting plate interface near the continental Moho of the overriding plate. This location roughly corresponds to the down-dip limit of large underthrusting earthquakes where the transition from stick-slip to stable sliding is thought to occur. An important characteristic of short-term SSEs is their spatial variation in activity. The average slip rate tends to be large where the slab geometry is convex (i.e., the slab bends toward the mainland) and it tends to be small where the slab geometry is concave (i.e., the slab bends away from the mainland). Considering that fluids play an important role in generating short-term SSEs, it may reflect the along-arc variation in fluid flux due to complex slab geometries. In this presentation we will demonstrate how fluids migrate in subduction zones by taking into account the effects of 3D slab geometries.
We construct 3D finite element models based on a theory of two-phase flow, which allows us to consider the movement of matrix and fluid phases at the same time. The location of fluid source is determined based on the computed slab surface temperature. Fluids are assumed to migrate in a thin serpentinite layer just above the slab in the direction sub-parallel to the slab surface by the effects of permeability anisotropy in the serpentinite.
We find that fluids migrate in the maximum-dip direction of the slab by the combined effects of permeability anisotropy and 3D slab geometry. It leads to the concentration of fluid paths where the slab geometry is convex and porosity increases there. Fluid paths diverge and porosity decreases where the slab geometry is concave. These results suggest that the along-arc variation in short-term SSEs can be explained by 3D fluid focusing possibly through changing pore-fluid pressure and/or formation of wet clay minerals.

Keywords: short-term slow slip events, fluid migration, slab geometry, subduction zones, serpentinite

2-D thermal modeling along a non-volcanic region in southern Kyushu, Japan

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There is a non-volcanic region sandwiched between the Aso and Kirishima volcanic zones in southern Kyushu, Japan. Several characteristic seismic events were identified around there; Postseismic slip was found associated with the two Hyuga-nada earthquakes (M6.6), which were interplate earthquakes that occurred on October 19 and December 3, 1996. Tectonic tremors were observed around the mantle wedge corner beneath the Pacific coast of Miyazaki prefecture. To investigate the cause of these events, we performed 2-D box-type time-dependent thermal modeling in southern Kyushu, and estimated spatial distribution of water content within the oceanic crust, using a phase diagram of MORB. We set a profile to pass through the regions in the plate convergence direction where tectonic tremors and postseismic slips were identified. To constrain calculated temperature structure, we used surface heat flow data. In our model, we considered the subduction history of the Philippine Sea plate, and changed age of an ocean floor and subduction velocity along the profile at each time step. At approximately 4.5 Ma, the profile passed through the Kyushu-Palau ridge where the age of the ocean floor changed discontinuously at the ridge axis. This discontinuity affected calculated thermal structure remarkably. To explain the low observed heat flow above the mantle wedge corner, we introduced a low viscosity layer at the plate boundary. We changed viscosity, thickness, and a down-dip depth of the layer as free parameters, and performed a grid search to fit the calculated heat flows to the observed ones. It became difficult for mantle flow to intrude into the mantle wedge corner, by incorporating the low viscosity layer, and surface heat flow above there became lower than that without it. Among the three parameters, we found that the thickness of the layer affected thermal structure in the mantle wedge most remarkably. On the other hand, viscosity within the layer least affected it. As a result, the temperature range of the upper surface of the subducting PHS plate where postseismic slip associated with the Hyuga-nada earthquake of December 3, 1996 became approximately 300°C. Interplate temperature where tectonic tremors occurred in Miyazaki prefecture ranges from 400 to 500°C. We also estimated the dehydration process along the profile and used the phase diagram of hydrous MORB in the oceanic crust. As a result, blueshist transformed into lawsonite blueshist in the postseismic slip region, and lawsonite blueshist transformed into lawsonite eclogite in the active region of tectonic tremors.

Thermal regime and slab dehydration in the subducted Juan de Fuca plate beneath the Cascadia subduction zone based on 3D numerical simulation

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Giant earthquakes are considered to have occurred historically and may take place in a near future in the Cascadia subduction zone. In contrast to the cold and thick Pacific (PAC) plate subducted beneath the northeast Japan characterized by numerous interplate earthquakes and comparatively fewer slow earthquakes, the warm and hot Juan de Fuca (JF) plate subducted beneath the North American plate witnesses much more episodic occurrences of tectonic tremors and slow slip events, accompanying less regular earthquakes. This has enabled us to compare and understand the different generation mechanisms between regular and slow earthquakes. Possible candidates to interpret such differences may attribute to slab brittle failure largely determined by different slab thermal regime, while pore fluid pressure variation in the fractures greatly affected by slab metamorphism. We constructed a 3D time-dependent thermal convection model with a size of 1150×700×400 km along the Cascadia Trench, initiating subduction in the northeast direction with calculation time up to 15 Myr. The geometry of the JF plate has been prescribed, being based on the extrapolated data of Slab1.0. Results show a distinct 3D slab dehydration belt and temperature transition zone along the clustered hypocenters of episodic tremors immediately beneath Vancouver Island in the northern part and almost 100 km east of coast of Washington and Oregon in the southern part with temperatures of 500-700℃. Water content in MORB decreased from 2 wt% to 0 wt%. Interestingly, megathrust earthquakes occurred mostly near the triple plate junctions, such as the JF-NA-Explorer and PAC-NA-Gorda plate junctions, and beneath Washington where slab convex portion exists. Regular earthquakes are fewer observed beneath Oregon. The interplate temperatures of the JF plate are averagely 200-400℃ higher than those of the PAC plate beneath Japan at the same depth range (<100 km) with less amount of calculated slab dehydration ratio.

Keywords: thermal regime, dehydration, model

Target oriented seismic tomography: Toward higher-resolution images of subduction zones

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From the classic ray-based traveltime tomography to the state-of-the-art full waveform inversion, because of the ill-posedness of the inverse problem, regularization techniques are always used to get stable but approximated solutions. If the data sampling or the starting model is not good enough, regularization schemes can migrate anomalies of our interests partially away from their correct places and also suppress their amplitudes.
In Japan islands, earthquakes mainly occurred in the upper crust and the subduction zone, and seismic stations are all very close to the surface, resulting that the recorded seismic data do not have a full spherical coverage over the interested subsurface structures. Meanwhile, the crust is sampled by much more regional data than the subduction zone is. The regularized algorithm may “ignore” the less sampled subduction zone. Many experiences tell that the expected high-velocity subducting slabs sometimes do not show up if the starting model is not close enough to the “real” model. It is not surprising that subduction zone images are manly obtained by using teleseismic data. However, low frequency teleseismic data have relatively low resolving ability. To get high-resolution images, we still need to rely on regional data. As discussed, the spatial distribution of regional seismic data requires us to carefully design seismic tomography algorithms.
In this study we propose a target oriented seismic tomography algorithm for imaging subduction zones. The new seismic tomography scheme consists of three main steps. We first construct a large-scale average background model of the whole crust and upper mantle structure of the study area. To avoid being trapped by local minimums, a multi-grid model parameterization is used to decompose the scale of the inverse problem. The second step is a localized tomographic inversion. We only use seismic data generated by earthquakes in the subduction zone. Considering that the first step is likely to yield an accurate average velocity model of the crust, we only perturb the upper mantle model at the second step. The third step is to invert the differential traveltime residual of two neighboring subduction zone earthquakes at the same station. This approach can further refine the subduction zone structures.
We will test this target oriented method in the framework of ray-based traveltime inversion using our newly developed eikonal-based traveltime tomography software package tomoQuake. Real application results in the Japan subduction zone will be demonstrated.

Keywords: Seismic tomography, Subduction zone

Point and Line Attractors Emerging in the System Including the Interaction among Heat, Fluid Pressure and Dilatancy

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We show two geometrically different attractors, point and line attractors, emerge within the framework including the interaction among heat, fluid pressure and dilatancy associated with dynamic earthquake source process. To show that, we consider qualitative behavior of the solution orbit in the \phi-v space, where \phi and v describe the inelastic porosity and the slip velocity, respectively. We first consider nullclines, which are obtained by the conditions \dot{v}=0 and \dot{\phi}=0. For \dot{v}=0, the straight line v=0 and the curve v=1-\beta g(\phi) are nullclines, where g(\phi) is the function describing the porosity evolution law and \beta is a positive constant number. The curve v=1-\beta g(\phi)) on the \phi-v space will be referred to as C^{crit} henceforth. For \dot{\phi}=0, the straight line v=0 and the curve \phi=1 are found to be nullclines. Clearly, the line v=0 is the common nullcline for both equations.

We simply assume that C^{crit} crosses the \phi-axis once, and C^{crit} is ascending with increasing \phi. We consider a solution orbit crossing the v-axis in the region $0<v_0<1$, where v_0 is the slip velocity at \phi=0, since v and \phi are normalized and take values between zero and unity. It should be noted that the orbit is not horizontal nor vertical at the point crossing the line v=0, even though the line is a nullcline. This occurs because v=0 is a nullcline for both equations; both the relationships \dot{v}=\dot{\phi}=0 are satisfied on the line v=0, which enables dv/d \phi to be nonzero there. Moreover, we can confirm the orbit connects the points (0, v_0) and (1, 1).

The solution orbits and the moving direction of the solution conclude that we have attractor and repeller on the \phi-axis; {(\phi_a, 0) | 0 \le \phi_a \le \phi_c} is an attractor, while {(\phi_r, 0) | \phi_c \le \phi_r \le 1} is a repeller, where \phi_a and \phi_r are the real numbers satisfying \phi_a < \phi_c and \phi_r > \phi_c, and \phi_c is the \phi value of the point where C^{crit} and \phi-axis cross. In particular, note that \phi_a and \phi_r take continuous values. These non-isolated fixed points appear because the line v=0 is a nullcline for both equations, and this is characteristic behavior of the present system. In addition, the point (1, 1) is also the attractor because C^{crit} and all orbits are absorbed into the point (1, 1). We can therefore summarize that the attractors are categorized into two geometrically different groups: they are given by the line {(\phi_a, 0) | 0 \le \phi_a \le \phi_c} or the point (1,1). The detail of g(\phi) does not affect the emergence of the attractors.

Keywords: heat, fluid pressure, dilatancy, solution orbit, attractor, repeller

