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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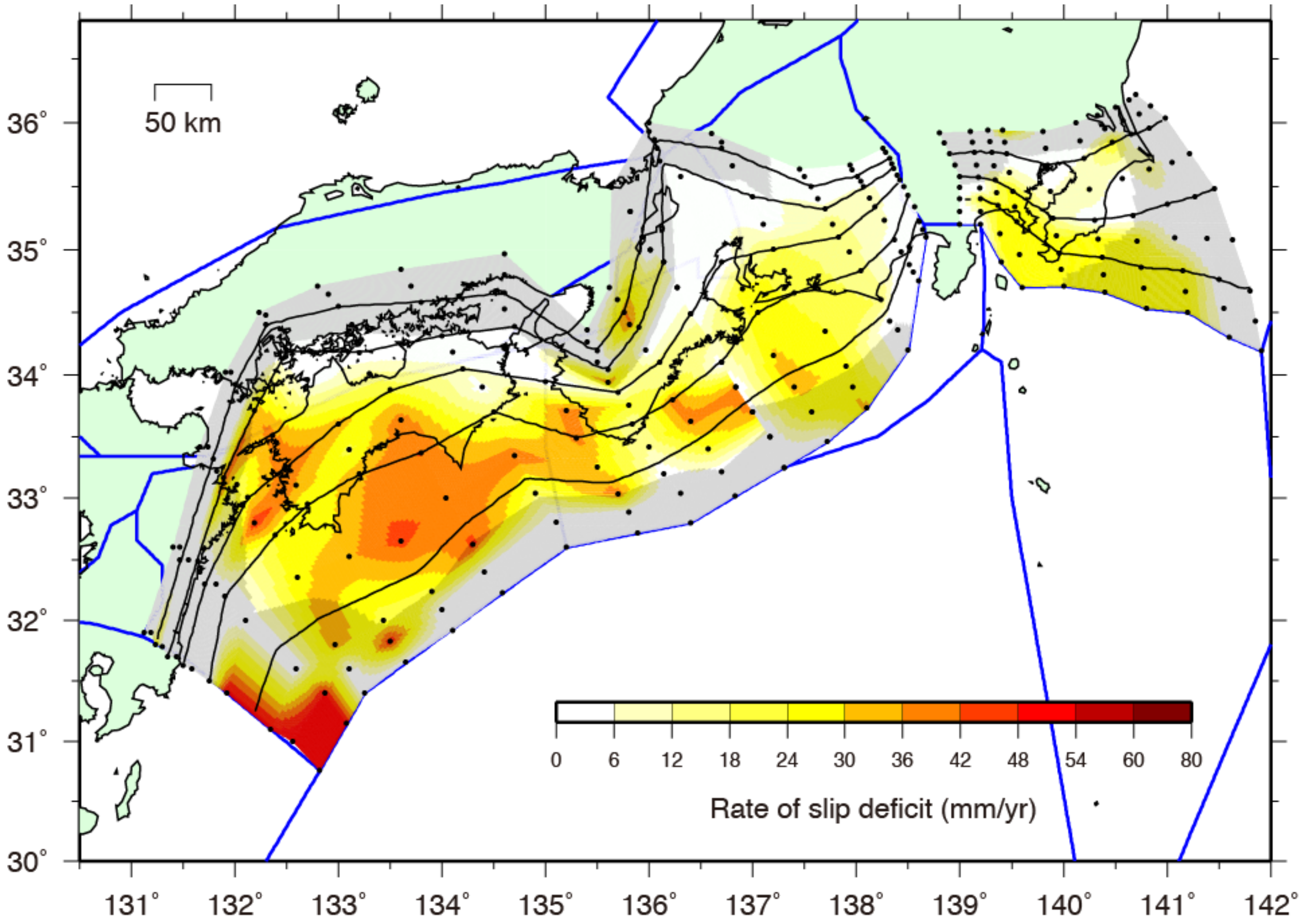
Southwest Japan is situated along the northern margin of the Philippine Sea plate. In the subduction zone along the Nankai trough, megathrust earthquakes historically hit southwest Japan with an interval of 100-200 years. Various slow earthquakes including slow slip events (SSEs) and low-frequency tremors 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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24
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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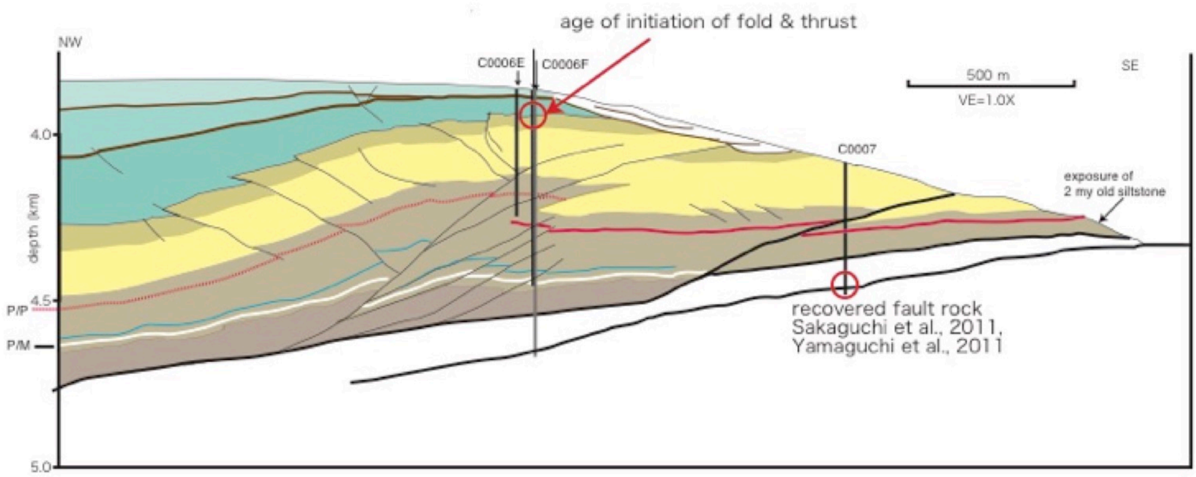
The Nankai accretionary prism was developed since ~6Ma and the growth has been accelerated after ~2Ma. Seismic reflection profiles at the toe of the prism clearly present frontal thrust ramping up and making an axial thrust of the anticline (Figure). The fault analyses recovered from the basal decollement 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
C0007
500 m
VE=1.0X
4.0
4.5
5.0
depth (km)
P/P
P/M
exposure of
2 my old siltstone
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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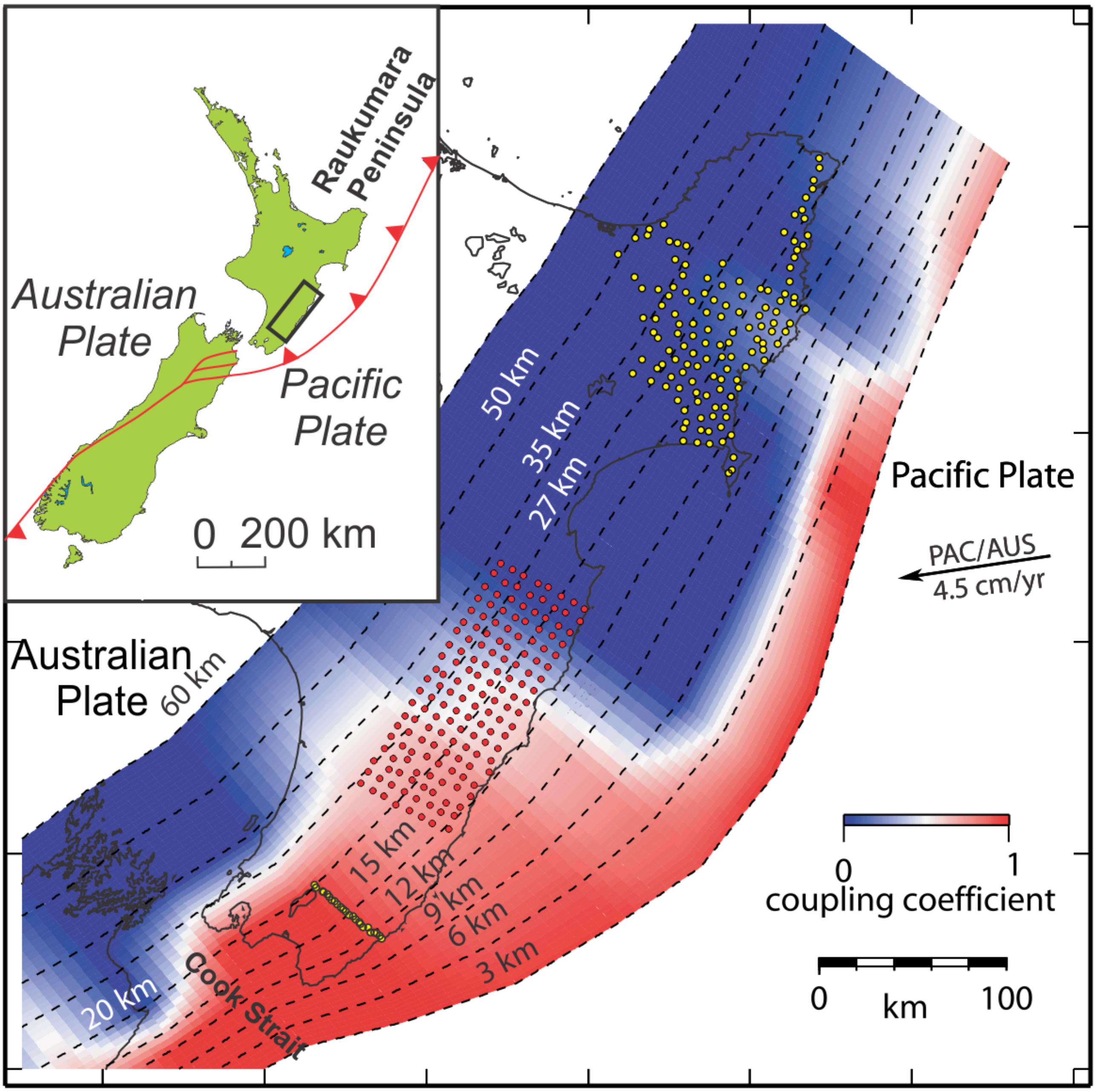
Along the Hikurangi margin on New Zealand’s east coast (Figure 1), plate-coupling changes from weakly coupled in the north to locked in the south. Slow slip events occur at shallow depth where the margin is weakly coupled. The conditions needed for slow slip are poorly understood but the presence of 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
Pacific Plate
PAC/AUS 4.5 cm/yr
Australian Plate
60 km
50 km
35 km
27 km
20 km
15 km
12 km
9 km
6 km
3 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