Polarization evidence for the occurrence of shallow tremors in the Japan Trench subduction zone

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In the Japan Trench subduction zone, northeast Japan, the coincidental occurrences of the tremors with the slow slip events (SSEs) have been identified by using the ocean bottom seismometer (OBS) records (Ito et al., 2013; Ito et al., 2015). However, since the previous detection was based on the amplitude changes of ambient noise levels at few stations near the trench axis, the locations and source mechanisms of tremors are still uncertain. Here we investigate the polarization of OBS data to validate and deduce further source information of shallow tremors beneath the Japan Trench subduction zone.

Following the method proposed by Jurkevicks (1988), we calculate the average particle motion polarization for every 10-minute time window on the basis of the three-component covariance matrix of ground motion. Three principal axes of the best-fit ellipsoid to the particle motion correspond to the eigenvectors of the matrix in the least squares sense. The polarization azimuth is given by the direction of first eigenvector and the degree of linearity is given by the ratio among three eigenvalues. We analyze the continuous velocity seismograms for 5 months from November 2010 to March 2011 recorded at 17 short-period OBS network stations deployed in the Japan Trench axis area off Miyagi, northeast Japan.

We obtain several long sequences of high linearity and nearly constant polarization azimuths associated with tremors from the records of at least three stations near the trench. Three major sequences correspond to the tremor sequences reported in Ito et al. (2015). The stable and nearly constant azimuths in these sequences indicate the similarities of focal mechanisms and epicenters of tremors. The dominant polarization azimuth shows the angle of about 130 degrees, which may suggest shear slips in the subduction direction of the Pacific plate. Furthermore, the azimuths slightly change toward the timing of the largest foreshock of the 2011 Tohoku-Oki earthquake, which possibly indicates the migration of tremor sources.

We further apply the method to three different frequency bands (0.5-2 Hz, 2-8 Hz, 10-20 Hz) of OBS data to examine frequency characteristics. While the results from three bands show quite different background polarization azimuths, the specific polarization patterns associated with the SSE are only shown at the frequency of 2-8 Hz, which also supports the occurrences of tremors.

Keywords: Japan Trench, tremor, polarization analysis, OBS

Tremor activities beneath the Hinagu fault zone (2)

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Non-volcanic tremor induced by dynamic stresses has been detected in the Hinagu fault zone (Chao and Obara, 2015). We notice that the tremor occurred at the deep extension of the fault zone (Miyazaki et al., 2015). In addition, from the velocity structure estimated by seismic tomography (Matsubara and Obara, 2011), there are low P-wave velocity zone at the deep part of the source region and high P-wave velocity anomaly in the shallow seismogenic zone. Therefore, the tremor is possibly occured in the transient zone between the seismogenic zone and the ductile lower crust (Miyazaki et al., 2015).

The existence of the “ambient” tremor is a clue to understand the source process. In previous study, we applied the matched filter technique (Gibbons and Ringdal, 2006) to the continuous seismic records and recognized some small tremor activities (Miyazaki et al., 2014, SSJ). In this study, we report the results from other template events that were detected in the previous study and characterized by apparently short duration compared with triggered tremors.

We also tried to estimate magnitude-frequency relation of the detected events. Magnitudes were distributed between -0.4 and -1.0. However, most detected events had low signal-to-noise ratios. The b-values of tremor activities are relatively higher than that of shallow earthquake activities.

In addition, we found several tremor burst episodes. Its typical time constant was several ten minutes. Detected signals during the burst had not large amplitude and sometimes they were comparable with noises. The rise of amplitude with long duration like ambient tremor discovered in the plate boundaries (Obara, 2002) were not seen clearly. That might be from small slip area that was characterized by high Vp/Vs ratio compared with plate boundaries (Shelly et al., 2006; Matsubara and Obara, 2011).

Acknowledgement
We used the data recorded at Kyushu University, Kagoshima University, the Japan Meteorological Agency and the National Research Institute for Earth Science and Disaster Prevention.

Keywords: the Hinagu fault zone, inland active fault, non-volcanic tremor

Develop and evaluate modified envelope correlation method for deep tremor

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Since the discovery of the deep tremor in southwest Japan [Obara, 2002], the tremor has been studied by many researchers. For base of these studies, the hypocenter determination of the deep tremor is necessary and the envelope correlation method [Obara, 2002] have been widely used. As an alternative, Wech and Creager (2008) proposed a method to maximize the sum of cross-correlation functions. The present study develops a new code based on Wech and Creager (2008), to improve the precision of hypocenter location and the detection completeness.

In the conventional envelope correlation method, hypocenter is determined to minimize the difference of relative arrival times. The new code determines the hypocenter to maximize the sum of the cross-correlations similarly to Wech and Creager (2008), except for their weighing scheme. This is equivalent to minimize the sum of the square of the difference of the normalized envelope functions. We optimize the objective function using the gradient method started from a preliminary solution calculated by the grid search.

Here, we apply this code to Hi-Net data in southwest Japan and detected tremors. The error of hypocenter location is estimated to be about 1 km in horizontal and vertical directions by the bootstrap method. This is smaller than the reported precision of the envelope correlation method (e.g.; Ide, 2010). The conventional envelope correlation method is able to detect only one tremor or earthquake for one time window. However, by the proposed technique, it is confirmed that each tremor and earthquake appears as a local maximum when some tremors and earthquakes occurred in one time window.

Keywords: Deep tremor, Hypocenter determination, Envelope correlation method

A detection method for P and S waves of deep low-frequency earthquakes using a 3D array in the Tokai area and its application to hypocenter determination

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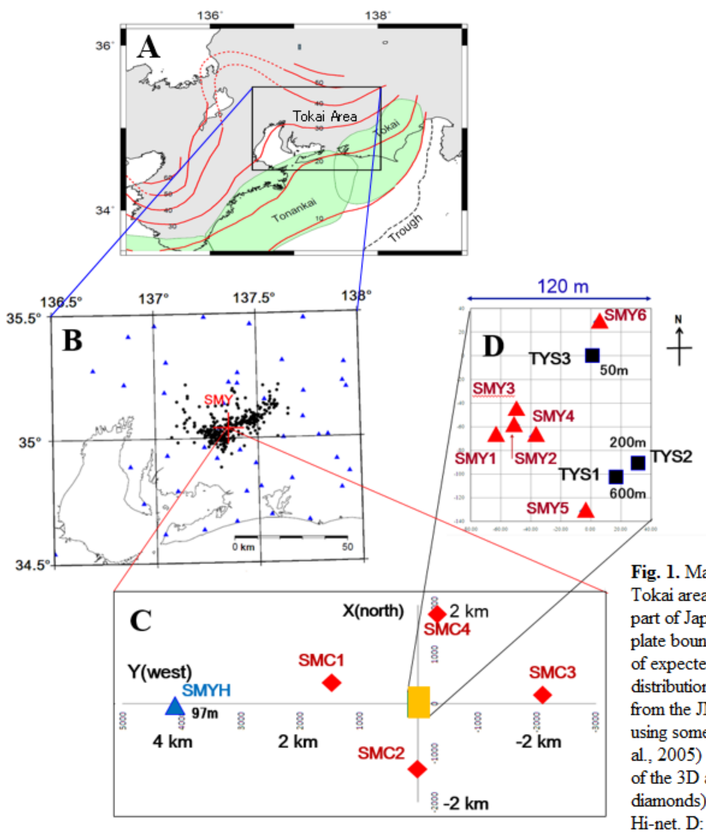
We have developed a novel method that uses a 3D array to detect the P and S waves of deep low-frequency earthquakes (LFEs) that occur along the subduction zone of the Philippine Sea plate in southwest Japan. Obtaining accurate hypocenters of LFEs is very difficult because their seismic waves are characterized by low amplitude and the absence of sharp pulses. In particular, identifying P phase arrivals is not readily possible using conventional methods and seismic networks. To determine their hypocenters accurately-not only their epicenters but also their depths-we tried to find their P and S wave pairs and obtain S-P times. We constructed a 3D array (6 km x 4 km area, see Fig.1) using 14 seismic stations in the Tokai area with three component seismographs, including ones with deep (600 m at the deepest) borehole seismographs. We observed remarkable LFE activity occurring in the Tokai area over November 10-30, 2010. We successfully detected not only S waves but also very weak P waves of LFEs using the 3D array data and the semblance method. Assuming a homogeneous half-space model with P wave velocity=4.5 km/s and S wave velocity=2.2 km/s in the 3D array, we calculated the semblance distributions for more than 20 LFEs to obtain their propagation parameters (back azimuth and the incident angle of seismic waves) and to identify P and S-waves. Using the time of the maximum value of the semblance in each component, we detected the direct P wave in the vertical component and the S wave in the horizontal component, providing S-P time. Fig.2 shows an example of hypocenter determination (red star) using estimated S-P time and propagation parameters, where we found 8.2 km difference in depth between the hypocenter in this study and that (green star) listed in Japan Meteorological Agency (JMA) catalogue. This example suggests that the inclusion of the S-P time strongly reduces the uncertainty on source depth, because the LFEs in the JMA catalogue were generally located using only S-arrival times. Choosing 4 LFEs with reliable results obtained from the semblance analysis, we located their hypocenters and found they distribute in the depth range from 28 km to 35 km approximately along the plate interface inclining in depth from 30 km to 32 km.Because a single array inherently has a limitation in the precise location estimate, especially for epicenter, we also tried to locate hypocenters (for example, a blue star in Fig.2) of LFEs using 3D array data together with arrival times (in many cases, S-arrivals) of surrounding stations that listed in JMA catalogue. For the LFE in Fig.2, we found 4.5 km difference (between a blue star and a red star) in the epicenter by combining the arrival times of surrounding stations, which is not always negligible for better understanding the spatial and temporal distribution of LFEs.

Keywords: deep low-frequency earthquake, 3D array, P- and S-waves, semblance analysis, plate boundary



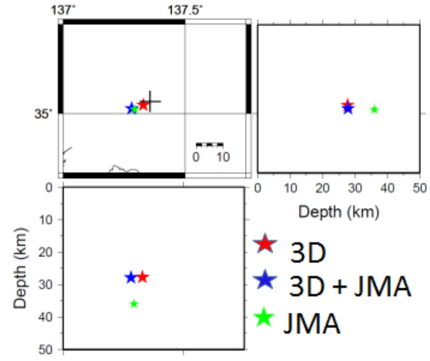


Fig. 2. An example of the difference in depth of hypocenter of LFE (LFE13) between 3D, 3D+JMA, and JMA. The 3D and 3D+JMA hypocenters were located using not only S-arrival times but also P-arrival times, while the JMA hypocenter was located using only S-arrival times.

Fig. 1. Map of seismic stations comprising the 3D array of SMY in the Tokai area, located in the central part of Japan. A: Index map of the central part of Japan. Red lines represent the depth contours of the Philippine Sea plate boundary (Hirose et al., 2008). Green areas show the source regions of expected Tokai and Tonanki interplate earthquakes. B: Epicenter distribution (black points) of LFEs occurring in November 2010 derived from the JMA earthquake catalog. The epicenters were located mainly by using some of the seismic stations (blue small triangles) of Hi-net (Obara et al., 2005) operated by NIED. A thin red cross shows the central location of the 3D array of SMY. C: Distribution of four SMC stations (red diamonds) of a medium-sized array and SMYH station (blue triangle) of Hi-net. D: Distribution of six stations (red triangles) of a small-sized array and three borehole stations (black squares). Numbers followed by m show the depths of the boreholes.

Interaction between slow earthquakes in and around Bungo channel, Nankai subduction zone

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Slow earthquakes occur at transition zones from locked to stable sliding zones along megathrust faults at both shallow and deep parts. So far, various types of slow earthquakes with different characteristic time scales have been detected in many subduction zones along the Pacific Rim. In each subduction zone, the activity style, combination and interaction of slow earthquakes are different. Therefore, the slow earthquake is considered as an index to characterize each subduction process. Interaction between long-term slow slip event (SSE) and downdip tremor has been observed in southwestern Japan, Mexico, and Alaska even though detailed relationship is slightly different. In Bungo channel near the western edge of deep tremor belt-like source region along the Nankai subduction zone in southwest Japan, the long-term SSE occurs at a recurrence interval of about six years. During the 2003 and 2010 long-term SSEs, tremor activity increased at the shallower part of the tremor zone, which is the adjacent region of the SSE source fault. On the other hand, the deeper tremor activity is stable irrespective of the SSE. Takagi et al. (2016) detected tiny crustal deformation and estimated a sequence of long-term SSEs with eastward migration through the gap between locked and tremor zones. Associated with the migrating long-term SSE, the long-term variation of tremor activity seems to migrate eastward at speed of a few 10 km per year in western Shikoku. These observation suggest that the long-term SSE may trigger the downward neighboring tremor activity.
On the other hand, shallow tremor has been recently detected associated with shallow very-low-frequency earthquake near the Nankai trough (Yamashita et al., 2015). This shallow slow earthquake activity shows along-strike variation. At the updip side of the 1946 Nankai earthquake rupture fault, shallow slow earthquake seismicity is quite low. On the other hand, slow earthquake frequently occurs at Hyuga-nada where the quasi-stable sliding zone with many repeaters exists at the downdip side of the shallow slow earthquake region. The slow earthquake seismicity is usually limited at the southern part from the Kyushu-Palau ridge. However, slow earthquake region extended eastward with a length of 100 km from the Kyushu-Palau ridge at the beginning stage of the Bungo channel long-term SSEs in 2003 and 2010. This might suggest that the shallow slow earthquake seismicity is an indicator for the coupling status at the downdip portion of the plate interface.

Keywords: slow earthquake, Subduction zone

Constraints on source parameters of low-frequency earthquakes in Parkfield, CA

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Low-frequency earthquakes (LFEs) are small repeating earthquakes that occur in conjunction with deep slow slip. Like typical earthquakes, LFEs are thought to represent shear slip on crustal faults but when compared to earthquakes of the same magnitude, LFEs are depleted in high frequency content and have lower corner frequencies, implying longer duration. Here we exploit this difference to estimate the duration of LFEs on the deep San Andreas Fault (SAF). We find that the M<1 LFEs have typical durations of ~0.2 s. Using the annual slip rate of the deep SAF and the average number of LFEs per year we estimate average LFE slip rates of ~0.24 mm/s. When combined with the LFE magnitude this number implies a stress drop of ~10^4 Pa, two to three orders of magnitude lower than ordinary earthquakes, and a rupture velocity of order 0.7 km/s, 20% of the shear wave speed. Typical earthquakes are thought to have rupture velocities of ~80-90% of the shear wave speed. Together the slow rupture velocity, low stress drops, and slow slip velocity explain why LFEs are depleted in high frequency content relative to ordinary earthquakes and suggest that LFE sources represent areas capable of relatively higher slip speed in deep fault zones.

High-speed migration of tremor along the Nankai subduction zone, Japan

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As an underlying source physics of episodic tremors and slip (ETS), a diffusion process of stress or fluid along plate boundary fault has been proposed as one of plausible mechanism [e.g., Houston et al., 2011]. Most rapid migration phenomenon is categorized as high-speed tremor migration features, where the propagation speed of tremor-front rises up to ~ 100 km/h. However, there is little constraint on spatio-temporal evolution of high-speed tremor migration features. To reveal spatio-temporal evolution of high-speed tremors migrations, we applied a matched-filter technique to continuous seismograms during 6 years, using relocated template low-frequency earthquakes (LFEs) at the western part of Shikoku Island. We newly detected about 60 times the number of template LFE events, which is fairly larger than ones obtained by conventional envelope cross correlation method. We identified hundreds of repetitive sequences of high-speed tremor migrations, which evolve in a diffusional manner with diffusion constant to be 10^5 m2/s. The length scale of the fast diffusion is relatively short, up to ~20 km. Most of the rapid migrations seems to be triggered by ocean and solid Earth tides. As a fundamental elements for diffusive propagation of ETS, stress diffusion on the background ductile shear zone [Ando et al., 2012] or slip and fluid diffusion [Shelly, 2015] is considered to be a likely explanation of the high-speed tremor migrations.

Universality of very low frequency signals from slow earthquakes

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The scaling law for slow earthquake [Ide et al., 2007] provides a unified view of deep tectonic tremors, low frequency earthquakes, and slow slip events (SSE). This view has been strengthened by several kinds of evidence and explanations using theoretical models. One of the strongest evidence is the detectability of intermediate phenomena between seismically observed tremor above 1 Hz and geodetically observed SSE longer than several hours. The signals are especially clear in the very low frequency (VLF) range from 0.02 to 005 Hz, where Ito et al. [2007] first discovered signals accompanied with tremors. Since their discovery, similar phenomena have been found in many places, with simultaneous tremor observation. This fact suggests the universality of VLF signals behind tremors, and we can enhance the signal amplitude in the VLF range to overcome environmental noises, by stacking broadband seismograms relative to tremor timing.

We arrange many reference points in a tremor zone, extract VLF signals by stacking broadband seismograms, and determine moment tensor corresponding to the underground deformation. This method was first applied to a wide tremor zone in the Nankai subduction zone [Ide and Yabe, 2014], and then to a small tremor cluster in Taiwan [Ide et al., 2015], the Guerrero tremor region in Mexican subduction zone [Maury et al., 2016], around southern Vancouver Island in Cascadia subduction zone, and the Parkfield section of the San Andreas Fault. In every region, moment tensor solutions consistent with regional plate motion were determined. These solutions will constrain tectonic interpretation in each region. The reliability of solution is not homogeneous: we can constrain solutions with only 500 tremors in Nankai, while noises are too large after stacking 5000 tremors in Parkfield. This is partially due to the different quality of seismic networks, but the size of source is not the same everywhere. Average moment magnitudes corresponding to VLF processes are Mw 2.2-3.0 in Nankai, Guerrero, and Cascadia, but less than Mw 2 in Parkfield. The similarity and difference for these results will provide keys to understand physics that govern these slow deformation processes.

Keywords: slow earthquake, deep tectonic tremor, very low frequency

The detection of shallow very low frequency earthquake in Hyuga-nada

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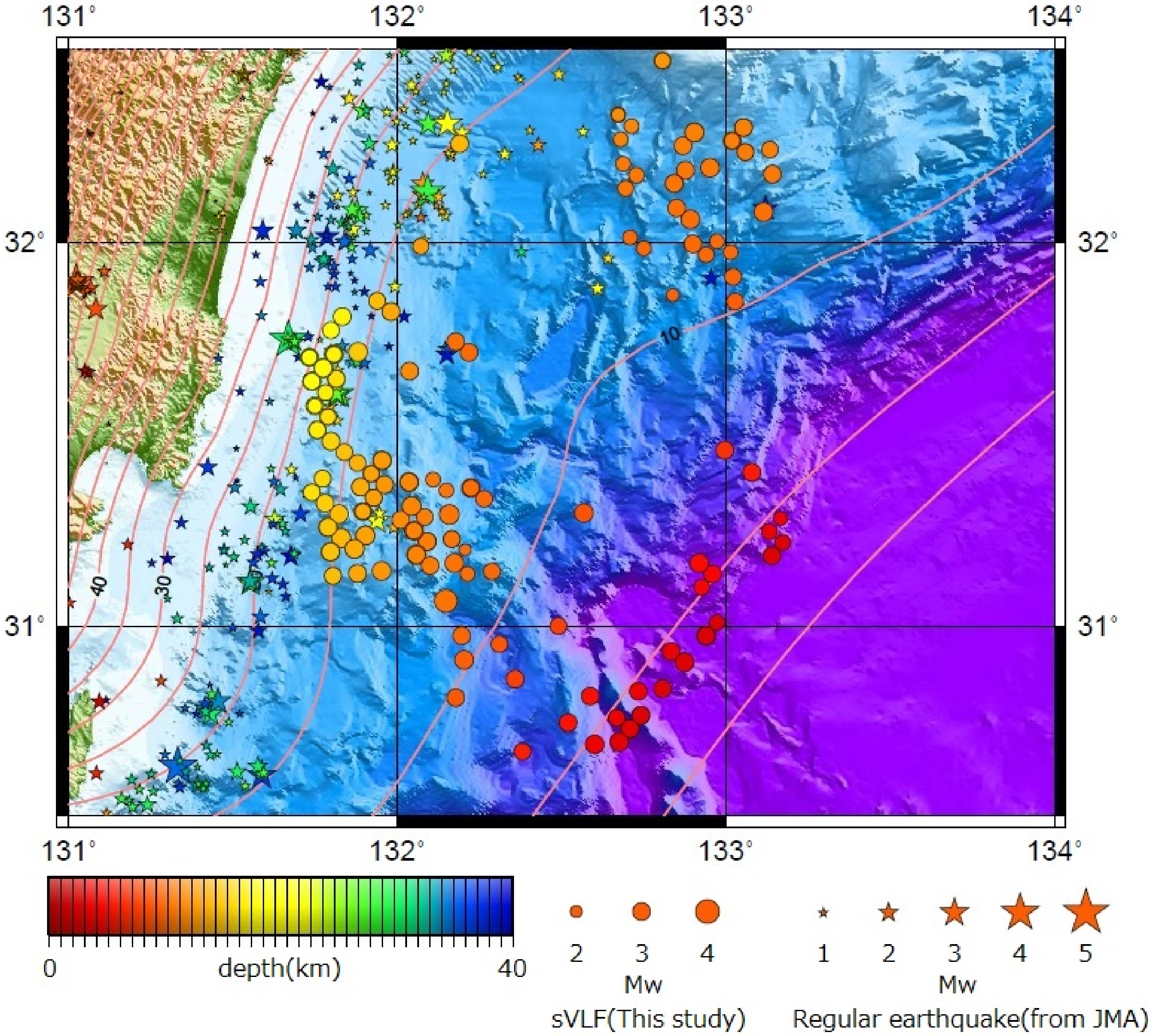
GPS continuous observation system of Geographical Survey Institute, Hi-net and F-net of National Research Institute for Earth Science and Disaster Prevention have been nationally developed. Thanks to these seismic network systems that “Slow earthquake” exceling normal earthquake on a long period is discovered in southwest Japan for these 10 years [e.g. Obara, 2002]. The slow earthquake is a generic name of the different multiple phenomena of the time scales. These phenomena are classified by frequency, e.g. Slow Slip Event (SSE), Non volcanic tremor (tremor), Very Low Frequency earthquake (VLF) [Ito et al, 2007]. Tremor and VLF are observed due to earthquake vibration and these signals are in 2-8Hz and 0.02-0.05Hz respectively [Ito et al, 2007]. It is shown that tremor and VLF are activated by SSE and the relationship with the giant earthquake is pointed out. In Hyuga-nada that is located in the west end of an area that is expected to have a major earthquake along Nankai trough, understanding the seismic activity including the slow earthquake and exactly sliding properties of plate are the purpose of this study.

The analysis in this study is carried out on data between September 1, 2006 and September 30, 2006 in the same area as that of Asano et al, [2014]. It is supposed that shallow VLFs are activated by SSE, so the analysis is carried out in a period when tremor are used occurred frequently, and also before and after the period. 21 points observation data of F-net in west japan are used. The data of each observation point are comprised of horizontal north and south direction east and west direction and up-and-down motion.

The result of analysis shows that shallow VLF occurred in the area where asperity of the regular earthquake did not exist. This result indicates that the frictional force at the plate boundary shows different behavior by depth. Similar to a prior study, this study shows that after the shallow VLF’s migration towards the east, the migration to the opposite direction started. Thus, the migration direction of the shallow VLF is almost same in the different period. This result suggests that destruction origin and destruction spread direction of SSE considered to activate the activity of VLF are approximately same irrespective of duration period. In addition, the result shows the possibility that in the shallower part (shallower than 15km) of study area where the regular earthquakes do not occur, the unknown slow slip event occurs and activates shallow VLFs.

Keywords: shallow Very Low Frequency earthquake, Slow Slip Event


131°
132°
133°
134°
32°
31°
10
30
40
0
depth(km)
40
2
3
4
Mw
sVLF(This study)
1
2
3
4
5
Mw
Regular earthquake(from JMA)

Spatio-temporal distribution of very low frequency earthquakes in the eastern Nankai accretionary prism revealed by hierarchical clustering analysis of ocean bottom seismometer records

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Many low frequency tremors (LFTs) occurred in the eastern Nankai accretionary prism in October 2016 through a period of about one week and were recorded by the 20 broadband ocean bottom seismometers of the DONET1 ocean floor network. We detected more than 900 tremors at the frequency range of 2-8 Hz. Among these, 144 events were accompanied by signals at lower frequency range (> 0.1 Hz). In this study, the events with the low frequency signal are referred to as very low frequency earthquakes (VLFEs).

The observed waveforms of the entire network suggest that many of the events are spatially clustered. However, due to the large errors introduced during the travel time measurement processes, the estimated location of each event is spatially scattered, which makes it difficult to evaluate the distribution of the clustered events.

Here, we introduce a hierarchical clustering algorithm to group some of the closely located events. The degree of similarity between any two events is defined by comparing the arrival times of the peak amplitude obtained by a set of stations at which the signals of both events were observed. The peak amplitude at each station is measured from the root-mean-square envelope of two horizontal components filtered at 2-8 Hz, and then smoothed by a low-pass filter with a cutoff frequency of 0.059 Hz.

Thus far, the algorithm has been applied to only the VLFEs, although we intend to eventually cluster all of the events, including the LFTs. Among the 144 VLFEs, 121 events grouped with at least one other event, and a total of 27 groups appeared.

Finally, the horizontal location of each cluster was determined by using the median of the measured differential travel times between stations obtained for individual events within the cluster. The differential travel times were calculated from the previously described peak amplitude arrival times. This procedure also allowed us to detect and remove outliers of measured times, which are caused mostly by noise. The locations were estimated by assuming a constant shear velocity structure.

The results showed that the cluster locations are largely divided into two groups. The clusters in the first group (Group 1) are distributed around a major reverse fault in the northern part of DONET1. They occurred within the first 3 days of the total activity. The cluster locations of the second group (Group 2) are distributed form around the major reverse fault of the southern part of DONET1 and slightly toward the trench axis side. Many of the events in the trench axis side seems to have occurred in the latter part of the total period of activity.

The waveforms of events in Group 1 tended to show somewhat discernable S wave onsets compared to events in Group 2. Furthermore, we were able to identify systematic P arrivals for many events in Group 1 by aligning the waveforms within the individual clusters. By using manually picked P and S arrival times, we relocated some clusters by a grid search through a 3-D velocity model. The results showed that the depth of the clusters varies from ~8 km to ~2 km beneath the seafloor. Whereas many events are located near the major reverse fault, some are located ~5 km landward of the fault. Our result suggests that the stress state that promotes the occurrence of VLFEs is not limited to the narrow range along the major fault, but exists through a broader range in the shallow accretionary prism.

Keywords: Very long frequency earthquake, BBOBS, hierarchical clustering analysis , accretionary prism

Tremor location in Guerrero, Mexico from catalog comparison: identification of new clusters

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Tectonic tremor are known to occur in two areas in the Guerrero subduction zone, one updip of the other. However these locations are obtained from only 29 months of recording and more precise location is needed. To do this we used two datasets, the previously used MASE dataset and the GGAP dataset. The MASE network is a linear network that allows good along dip resolution. The GGAP network is located around the downdip cluster and is better able to locate the events in this area. We generate a tremor catalog by envelope correlation method for the two time periods. In a second step we estimate their moment tensor from stacking broadband seismograms in the VLF band (0.02-0.05 Hz).
Results shows two different tremor distributions depending on the time period. From MASE data we detect the previously known two clusters, one southern transient cluster and one northern more active cluster. The second dataset reveals that the northern cluster is in fact formed of two clusters in the strike direction. Analysis of the error of the first dataset shows the lack of resolution in the strike direction due to the linearity of the network explaining the difference between the two catalog. To confirm these results our tremor locations are also compared to other catalogs obtained with the tremor energy and polarization (TREP) method [Cruz-Atienza et al, 2015] and the cross station cross correlation method [AGU abstract Peng and Rubin, 2015]. Results from these methods agree globally with our result. The comparison of these three different catalogs underlines the complexity of determining tremor location.
Moment tensor inversion reveals low angle thrust mechanism with slip direction in agreement with TREP results and close to the convergence direction. Additionally the depth of the VLF events is coherent with the depth of the subduction interface highly suggesting that these events represent shear slip on the plate interface.

Keywords: tremor location, moment tensor of slow earthquakes

The fluctuation of the slip accumulation rate of long-term SSE and its relation to VLFE beneath the Iriomote Island, southwest Ryukyu Arc

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37 slow slip events (SSEs) beneath the Iriomote Island, the southwestern Ryukyu Arc, were detected in the GEONET F3 solution GNSS data 1997-2015. Their average moment magnitude (Mw) is 6.6, and the average recurrence interval is ~6 months, which are in accord with Heki and Kataoka (2008). However, the recurrence interval was found to vary in time during the 18 years time span. During 2005-2009, the interval remained as short as ~4 months, and then returned to ~7 months after that. Moreover, the SSE slip rate (cumulative slip/ lapse time) increased from 9 to 11 cm/y and from 6 to 11 cm/y during two time periods, 2003-2006 and 2013-2015, respectively. Heki and Kataoka (2008) and Nakamura (2009) suggested that the slip rate could increase due to occurrences of large thrust earthquakes near the Ryukyu trench. However, no noticeable events occurred in this region prior to the trend increase around 2013. Conversely, two earthquake swarms occurred in the Okinawa Trough during these periods. In addition, southward motion of the Yonaguni Island, to the west of the Iriomote, has accelerated together with the SSE slip accumulation rate. From these results, we hypothesize that both the spreading at the Okinawa trough and the subduction at the Ryukyu trench could modify the SSE slip accumulation rate beneath the Iriomote Island.
In additions to SSEs, very low frequency earthquake (VLFE) is another kind of slow earthquakes that occur along the Ryukyu subduction zone. To understand the relationship between SSE and VLFE activities, we analyzed the broadband seismic data of the F-net in Japan and the BATS in Taiwan in order to identify VLFEs in southwestern Ryukyu Arc. During 2005-2010, we detected 2575 VLFEs there, and most of them were found to be thrust events in the shallow part of the plate boundary. According to the distributions of SSEs and VLFEs, we found VLFEs are often activated by SSEs 10-30 days after the SSE onsets. We also found that the VLFE activity becomes higher during the periods of the enhanced SSE slip accumulation rate.

Keywords: slow slip events, very low frequency earthqaukes, The Ryukyu subduction zone

Repeating Slow Slip Events in the Bonin/Ogasawara Islands Observed by the Continuous Global Navigation Satellite System (GNSS)

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Slow slip events (SSEs) are the episodic movement across a fault, characterized as a slow fault deformation that releases energy on timescales of hours, to weeks or even years, which is much longer than seconds to minutes timescales of regular earthquakes. Numbers of SSEs has been recognized from various subduction zones around the world. The character of SSE was first recognized in Cascadia subduction zone in the Northwestern of United States and Canada. These studies were followed by some reports of similar event including Japan.
The dense geodetic observation by Continuous Global Navigation Satellite System (GNSS) station operated by Geospatial Information Authority of Japan (GSI), also widely known as GPS, contribute a big impact on observing such events in Japan. It has been used as a way to measure the motion of Earth’s crustal plates. In Japan, from the starting of their installation in 1996, various SSEs have been recorded to have occured.
We have been conducting the same study of this event and reporting the possibility of this occurence in other part of Japan which is never reported before. The area of this newly found SSE is in the remote islands of Japan, Bonin (Ogasawara) islands, which lies along the convergent boundary where the Pacific Plate subducts beneath the Philippine Sea Plate. These islands are located at the southern part of Japan, very close to the edge of Mariana arcs.
The events are detected by using GNSS data from GSI together with additional supporting data from National Astronomical Observatory of Japan (NAO) to confirm the occurence of these events. GNSS stations on Bonin Islands recorded the plate deformation and reveals the possible existence of Slow Slip Events (SSEs) near the boundary between the Philippine Sea plate and Pacific plate. The Slow Slip Events (SSEs) together with other crustal deformation in this area has been observed since the beginning of GNSS installation in two islands, Chichijima and Hahajima from 1996 until now. This ~20 years of observation contribute the result of finding of repeating SSEs.
Using data from this dense geodetic network, we focus our study on the repeating SSEs in the latest decade, reporting that there are at least 5 SSEs have occured within 10 years with the recurrence interval of ~2 years, detected by stations in Hahajima and Chichijima islands. These 5 SSEs have uniform characters in the time constants as well as the recurrence interval, and we modeled the rupturing due to these SSEs by using rectangular fault plane model. This study is giving the result of slip approximately 8-10 cm for each event or 4-5 cm/yr. These events have magnitude from 6.8 to 6.98, varies especially from the size of the fault rupture, with the seismic moment of 2×10^{19} Nm - 3.75×10^{19} Nm.

Keywords: Bonin Islands Arc, Fault Rupture, GNSS, GPS, Ogasawara, Slow slip event (SSE)

Analysis on Crustal Deformation of Slow Slip Events Occurred in the Southwestern Ryukyu Arc in 2010-2014

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In the last 20 years, various types of slow earthquakes have been reported mainly on the plate boundary. For example, Slow Slip Events (SSEs) are one of the slow earthquakes. They don’t radiate seismic wave and last for a few days to years. Discovery of slow earthquakes encourage us to examine about strain accumulation and release on plate boundaries.

In the southwestern ryukyu arc, SSEs were reported by Heki and Kataoka (2008). They estimated a simple rectangular fault model from displacement data at 8 GNSS stations. And they reported that SSEs are repeatedly occurred beneath Iriomotejima island. Though, we think faults which cause SSE are probably more complicated, and there is a difference on slip distribution between SSEs.

In this study, we estimate slip distribution of each SSE by using 13 GNSS stations including new stations (one station in Miyakojima island and four stations in and around Iriomotejima island). We adopt a station in Irabujima island as a reference. Then, we analyze GNSS daily coordinates from Apr. 1, 2010 to Jan. 31, 2015, and estimate crustal deformation by fitting a function to the time-series data. We estimate displacement of SSE and earthquake, linear velocity, and initial offset by least square method, and estimate SSE occurrence time and time constant for duration of SSE by grid search method. We assume temporal evolution of SSE is expressed by an exponential decay function proposed by Heki and Kataoka (2008). Then, we obtain horizontal and vertical displacement for eight SSEs.

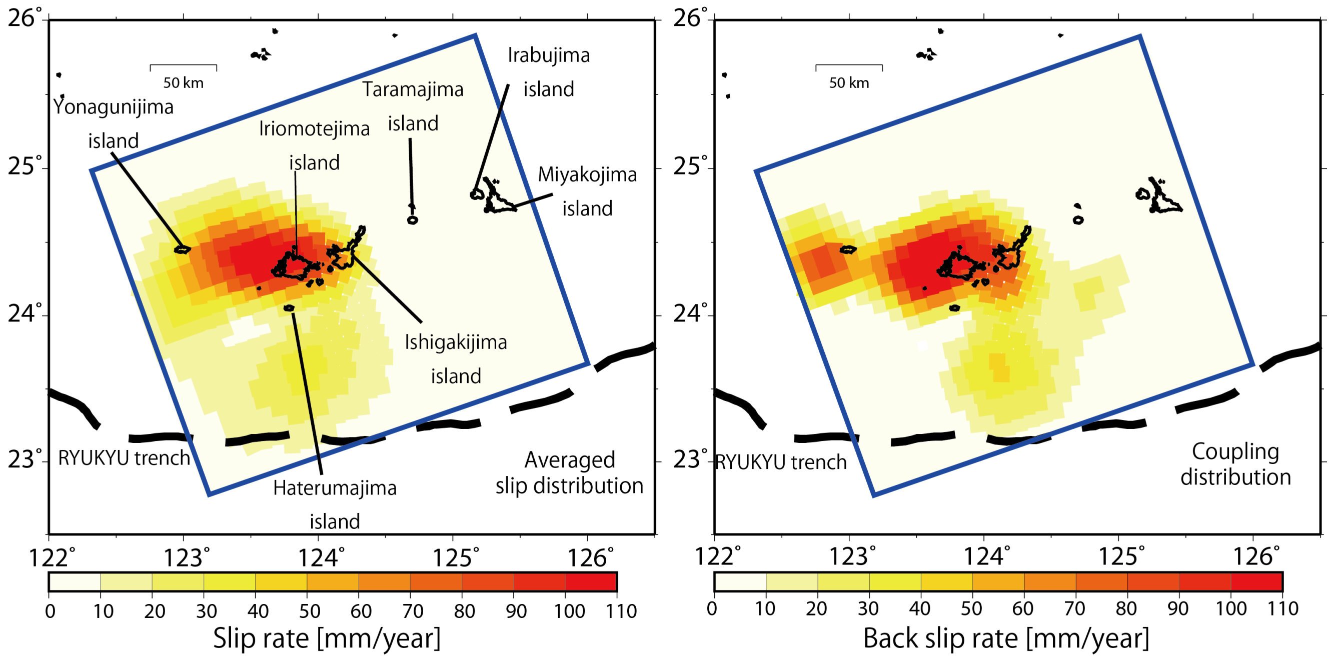
We estimate slip distribution of SSE by inversion analysis from displacement data. We estimate dislocation on each patch in an elastic half-space (Okada, 1985). We decide fault patches as follows. First, we divide a slip area to small patches, whose size is 10 km square. Then, we set rectangular fault lying on the plate interface on each patch. We adopt constraints on smoothness of slip distribution and non-negative slip. Slip azimuth and weight between data and smoothness are determined by minimizing ABIC. The geometry of the plate interface is based on the Slab 1.0 model (Hayes et al., 2012).

As a result, average moment magnitude, recurrence time, and slip azimuth are estimated to 6.90, 7 month, and 155 degree, which is clockwise angle from north, respectively. Heki and Kataoka (2008) successfully estimated characteristics of SSEs in the southwestern ryukyu arc. However, we found more complicated slip distribution which is varied among SSEs. We introduce obtained results. The slip region is biased to the west on the SSE occurred on Aug. 9, 2010. In case of the SSE occurred on Apr. 30, 2012, slip is also estimated in the region south off Yonagunijima island, besides the slip region on the SSE occurred on Aug. 9, 2010. And south off the Yaeyama islands at a depth of 15~20 km is commonly suggested as a slip area from some SSEs. The depth of the slip area around Iriomotejima island and Yonagunijima island are estimated to be 35~50 km, which is deeper than that in the previous study, mainly because of the adopted geometry.

We also estimate coupling distribution from average velocity data during inter-SSE period. The result suggests strong coupling region. This region is almost the same as slip region of SSE. In this region, coupling rate is calculated to be 75 %. Because back slip rate is almost equal to the average slip rate of SSEs in this region, most strain is released by the SSEs. Furthermore, we estimate weak coupling south off Taramajima island, although this region has poor resolution. We propose the hypothesis that strain may be accumulated over a long time in this region, and that

this region has a potential of a future megathrust earthquake. To examine this hypothesis, we must continue geodetic observation for a long time, and set new stations including ocean bottom pressure gauges.

Keywords: Slow Slip Event, Coupling, Southwestern Ryukyu Arc



Slow slip events response to tidal stress in western Japan

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Slow slip events (SSEs) often occur in the Nankai subduction zone, Japan, within a band-like zone extended from the center of Honshu to western Shikoku. SSEs are believed as shear slip on the plate interface, where the frictional property changes from velocity weakening to strengthening in the dip direction. Therefore the dynamics of SSEs may give some hints on the processes related with the depth dependent friction.

The tidal modulation of SSEs has been identified by statistical analysis using strain data of Plate Boundary Observatory, in the Cascadia subduction zone [Hawthorne & Rubin, 2010]. Here, we show the results of similar statistical analysis using strain data recorded at borehole stations maintained by National Institute of Advanced Industrial Science and Technology. Target SSEs were selected from the catalog of short term SSEs detected by using GNSS [Nishimura et al., 2013].

For each SSE, we calculated shear stress by ocean and solid earth tide in the slip direction on the plate interface, assuming focal mechanism determined by Nishimura et al. [2013]. The ocean tide is calculated by convolving the spatial distribution of theoretical ocean height for NAO.99b [Matsumoto et al., 2000] and theoretical Green’s functions [Okubo & Tsuji, 2000] for PREM. The solid earth tide is calculated using tide-generating potential of Tamura [1987].

We estimated tide components due to regional deformation from raw strain data before and after an SSE period, and removed them from the raw strain data to make processed strain data. The processed data show transient deformation related with the SSE, accompanied with oscillation in phase with the calculated tidal shear stress on the plate interface. The correlation between the oscillation in SSEs and tidal stress was confirmed statistically. Moreover, the oscillation is clearly visible without statistical processing during the period of some SSEs, providing strong evidence of tidal modulation.

The processed strain rate is consistent with slip rate predicted by a velocity strengthening friction law and tidal shear stress on the plate interface. This suggests a possibility to constrain frictional parameters at SSE locations. Our results suggest that even a small (~kPa) disturbance of shear stress may control slip speed to some extent in the transition zones of the subducting plate.

Keywords: strain data, slow slip, tidal modulation

Earthquake swarms along the Oaxaca segment of the Mexico subduction zone and relationships to slow slip phenomena

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Earthquake swarms are thought to differ from traditional mainshock-aftershock sequences due to a separate driving processes such as slow slip or fluid flow. Several recent studies have suggested that tracking earthquake swarms may provide an indication of broader fault movement, which could eventually result in triggering of larger earthquakes. We utilize waveform correlation techniques to enhance the detection and characterization of earthquake swarms. We focus on the Oaxaca region of the Mexico subduction zone where a locally deployed joint seismic-GPS network has been maintained for 10 years. This network has previously been used to identify and locate many episodes of slow slip and nonvolcanic tremor across the study region. The improved temporal and spatial characterization of the earthquake swarms will be compared with the patterns of slow slip and nonvolcanic tremor to investigate the potential physical relationships between these different aspects of fault slip.

Frictional property of rocks in the Izu forearc: implications for the Boso slow slip events

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As different from the Nankai and Tohoku subduction zones, island-arc components composing the Izu arc subducts beneath the Kanto region. The collision and subduction of the Izu arc into the Kanto region could result in occurring the different type of earthquakes, including seismic slip (e.g., the 1923 great Kanto earthquake) and aseismic creep (i.e., the Boso slow slip events). Based on a source location map of the Kanto earthquake and the Boso SSEs (e.g., Hirose et al., 2014), the seismic and aseismic slip at the Kanto region seems to generate side by side at almost same depth, probably nearly same P-T conditions. We thus hypothsis that the different types of slips arise from different materials of the Izu arc.

To address this hypothesis, we have performed friction experiments on five types of rocks from the Izu forearc at temperature of 300oC (nearly seismogenic condition), confinig pressure of 156 MPa and fluid pressure of 60 MPa using a high P-T gas medium apparatus at AIST. Rock types used in this study were marl, boninite, andesite, antigorite and chirysotile serpentinites that were recoverd by Leg 125, Ocean Drilling Program from the Izu forearc. Considering the direction of plate motion, igneous rocks composing the arc is expected to be subducted into the hypocentral area of the Kanto earthquake, while serpentinite appeared as a diaper in the forearc is to be subducted into the area where the Boss SSEs occur. In the experiments, we fixed the temperature and pressure conditions to investigate the difference in slip behavior between the rock types.

In the experiments we conducted velocity-stepping tests at slip rates of 0.1-1 μm/s. At the experimental condition, serpentinites exhibited velocity strengthening behavior. In contrast, marl, boninite and andesite characteristically showed a periodic stick-slip behavior. Slip duration of the stick-slip events was an order of seconds, three orders of magnitude longer than the ideal slip duration of stick-slip event as expected from the stiffness and mass of the apparatus. We thus called such slip behavior as “slow stick-slip”. Linear relationship between the slip duration and the stress drop of slow stick-slip hold for the observed slow stick-slip events, except for the event of marl sample of which the relationship shifted from linear to cubic with displacement. The linear relationship between the duration and the stress drop is consistent with that between the duration and the seismic moment of slow earthquakes in nature (Ide et al., 2007), as the stress drop is proportional to the seismic moment. The result implies that the Boso SSEs may be hosted by igneous rocks (e.g., boninite or andesite) composing the Izu arc, rather than serpentinite which is often considered as a source material for slow earthquakes. However the result should be taken carefully, because whether slow sticks-slip occurs or not depends on the balance between the stiffness of fault surrounding mdedium and the critical stiffness which is defined by effective normal stress and friction parameters of fault materials. To connect the slow stick-slip observed in laboratory with slow earthquake in nature, it is necessary to consider the coupling between the stiffness components.

Keywords: slow stick slip, the Boso SSEs, friction

Constraints on friction, dilatancy, hydraulic diffusivity, and effective stress from low-frequency earthquake rates on the deep San Andreas Fault

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Similar to their behavior on the deep extent of some subduction zones, families of recurring low-frequency earthquakes (LFE) within zones of non-volcanic tremor on the San Andreas fault in central California show strong sensitivity to stresses induced by the tides. Taking all of the LFE families collectively, LFEs occur at all levels of the daily tidal stress, and are in phase with the very small, ≤~200 Pa, shear stress amplitudes while being uncorrelated with the ~2 kPa tidal normal stresses. Following previous work we assume LFE sources are small, persistent regions that repeatedly fail during shear within a much larger scale, otherwise aseismically slipping fault zone and consider the constraints on two different models of the fault slip: 1) that the correlation of LFE occurrence reflects modulation of the fault creep rate by the tidal stresses, and 2) that creep occurs episodically, triggered by the tides. With these models we examine the predictions of laboratory-observed rate-dependent dilatancy associated with frictional slip. The effect of dilatancy hardening is to damp the slip rate, so high dilatancy under undrained pore pressure reduces triggering of slip and modulation of slip rate by the tides. The undrained end-member models produce: 1) no sensitivity to the tidal normal stress, as first suggested in this context by *Hawthorne and Rubin* [2010], and 2) fault creep rate or earthquake rate in phase with the tidal shear stress. For these models, the observed tidal correlation constrains the hydraulic diffusivity to be less than about 1 x 10^{-6} /s and the product of the friction and dilatancy coefficients to be at most 5 x 10^{-7} in the LFE source region. The product is more than an order of magnitude smaller than observed at room temperature for talc, an extremely weak and weakly dilatant material. This may reflect a temperature dependence of the dilatancy and friction coefficients, both of which are expected to tend towards zero at elevated temperatures at the brittle-ductile transition. Alternatively, in the absence of dilatancy the ambient effective normal stress would be no more than about 50 kPa. In summary, for friction models that have both rate-dependent strength and dilatancy rate-dependence, the observations require intrinsic weakness, low dilatancy, and lithostatic pore fluid pressures.

Keywords: low frequency earthquake, friction, tremor

Two effects of slow earthquakes on large megathrust earthquakes: Triggering and facilitating of coseismic slip

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We propose that slow earthquakes may have two effects on ordinary megathrust earthquakes, especially in the shallow subduction zone. The first effect is triggering of coseimic rupture by slow slip events; this is well modeled in previous work. The second is facilitation of coseismic slip on a fault which is experiencing slow slip. The fault hosting ongoing slow slip may be more easily induced to slip coseismically if a dynamic rupture from a large earthquake propagates onto the fault.
Before the 2011 Tohoku-Oki earthquake, two shallow episodic tremor and slip events (ETS) were observed in the same area of the 2011 mainshock near the Japan Trench, where the huge coseismic slip exceeding 30 m occurred. The first ETS event occurred over a week in November 2008 and included a slow slip event that exhibited an equivalent moment magnitude of 6.8. Shortly prior to termination of the slow slip, a M6 earthquake was induced by the slow slip event at the down-dip edge of the slow slip rupture area. The second ETS event was observed from the end of January 2011 until just before the 2011 Tohoku-Oki earthquake and exhibited an equivalent moment magnitude of 7.0. This slow slip event induced the largest foreshock (M7.3 on March 9) and probably triggered the March 11 mainshock of the 2011 Tohoku-Oki earthquake. Both of the ETSs clearly trigger interplate earthquakes on the plate interface.
The difference between 2008 and 2011 ETSs is whether they continued or ceased before they induced large interplate earthquakes. To investigate the effect of ETS on coseismic slip occurring on the same fault, we performed laboratory friction experiments on simulated fault gouges. We observed that increases in sliding velocity could induce slip-weakening behavior, which overwhelms the velocity dependence resulting in large overall weakening. Therefore, a fault which is experiencing a transient slip or slow earthquakes may be more easily induced to slip coseismically if a dynamic rupture from large earthquake propagates onto the fault.

Keywords: slow earthquake, Megathrust event, rock experiment

The Hydrologic, Metamorphic, and Frictional Habitat of Shallow Slow Earthquakes

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Slow slip events (SSE) and very low frequency earthquakes (VLFE) in the outermost forearc of subduction zones demonstrate that unstable slip nucleates at shallower depths and nearer the trench than previously recognized. These events provide an opportunity to unravel the physical processes governing the nature of slip on subduction megathrusts; their source regions are accessible by drilling and well-imaged by geophysical surveys, enabling investigation of the properties and state of the plate interface. Here, we describe recent drilling, modeling, and laboratory results that, collectively, advance our understanding of the habitat of these events.
Estimates of in situ pore fluid pressure obtained by combining laboratory measurements on core samples with P-wave velocities from regional geophysical surveys show that the slow earthquake source regions are highly and locally overpressured, with pore pressures 75–90% of lithostatic. Kinetic models of smectite-illite transformation show that the reaction and peak fluid release occur mostly updip of the slow earthquake source areas; this may contribute to fluid overpressure, but is unlikely to be the primary driver. Laboratory frictional experiments on samples from subduction faults document primarily velocity-strengthening behavior, suggesting that nucleation of unstable slip is unlikely. However, a minimum in friction rate dependence (*a-b*) occurs at sliding velocities of ~1-10 μm s^{-1}, and we note increasing rate weakening with increased quartz content. Additionally, slip-weakening trends in these materials occur over larger distances (several mm) than commonly used to define frictional rate dependence, and are quantitatively consistent with several characteristics of slow earthquakes.
The emerging picture is that VLFE occur in a zone of highly overpressured fluids, low stress, and transitional frictional behavior. Although illitization is largely complete updip of the events, clay dehydration may augment fluid overpressures generated by disequilibrium compaction, and the accompanying release of SiO_2 may lead to greater tendency for unstable slip. Taken together, elevated pore fluid pressure and low effective normal stress, coupled with a minimum in frictional rate dependence at slow slip rates likely produces a fault zone with transitional frictional stability and reduced rigidity, favoring long rise times and slow rupture.

Keywords: Slow Earthquakes, Pore Pressure, Friction

3D migration of fluid and its implications for the spatial variation of slow earthquakes

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In recent years, slow earthquakes have been studied extensively because of its importance for better understanding of interplate slip behavior in the subduction zone. At least in southwest Japan and Cascadia where relatively dense seismic and geodetic observations are available, we can clearly see the spatial variation of the activities of slow earthquakes. In southwest Japan, non-volcanic tremor may not be active around Kii Channel and Ise Bay, where the geometry of subducting Philippine Sea Plate changes significantly. In Cascadia, the amount of slip due to slow slip events is largest beneath Port Angeles where we can see the bend of the subducting Juan de Fuca Plate. These observations suggest a possible relationship between slab geometry and the activities of slow earthquakes. Considering that fluid may play an important role in generating slow earthquakes, one explanation for it is that fluid released from the subducting slab migrates in 3D due to complex slab geometry and it leads to the along-arc variation in porosity.

To investigate 3D fluid migration due to complex slab geometry, we construct 3D subduction zone models based on finite element approach. The model domain is divided into crust, subducting slab, and mantle wedge. Mantle wedge is subdivided into a thin serpentinite layer just above the slab and the remaining part. We assume that the serpentinite layer has permeability anisotropy so that the fluid can move nearly parallel to the slab surface and reach the region where slow earthquakes occur. We first compute matrix flow and temperature. Matrix flow is computed only in the mantle wedge and temperature is computed for the whole model domain. Next, we compute fluid migration in the mantle wedge. We assume that fluid migrates as porous flow. 3D fluid migration arises from the combined effects of permeability anisotropy and complex slab geometry.

For a simple oblique subduction case, we find that fluid moves nearly parallel to the maximum-dip direction of subducting plate, not subparallel to the direction of plate motion. For the case with slab geometry similar to that of Cascadia, the fluid concentrates around the bend of the slab, which results in the increase of porosity there. This may help explain the observed along-arc variation in the slow slip events in Cascadia. Our results show that 3D fluid migration may have a strong impact on the spatial variation of slow earthquakes.

Keywords: 3D fluid migration, subduction zone, slow earthquakes

Toward unified source model of seismic phenomena

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Seismic phenomena on the plate interface are diverse, including ordinary earthquakes, shallow and deep slow earthquakes, and stable slip. Ordinary earthquake, which is characterized by power-law statistics, and slow earthquake have different scaling relation between seismic moment and duration of the event. The M9 Tohoku earthquake in 2011 provides us interesting observation about the hierarchical structure of ordinary earthquakes. Foreshocks and aftershocks on the plate interface occurred only at the area where seismicity has been observed so far. This observation suggests that hierarchical structure is stick to space. This view of seismic source is similar to the model by Ando et al. (2010, 2012) and Nakata et al. (2011), which reproduce the behavior of slow earthquakes. In their model, brittle patches are distributed on the ductile background.
Nakata et al. (2011) showed that their model could reproduce both ordinary earthquake and slow earthquake with different density of brittle patches. However, Nakata et al. (2011) did not show the detail condition how slip behavior of the fault transit from ordinary earthquake to slow earthquake. This study will investigate how this boundary is determined. For easy understanding, we use a 2D model space (line fault) with rate and state friction, which can explain the slip behavior of rock at slow slip speed, although Nakata et al. (2011) used slip-weakening law with Newtonian rheology as friction law. We calculate quasi-static elastic stress interactions between sub-faults with a cyclic boundary condition and radiation damping at a prescribed seismic speed. Frictional parameter (a and b) was set heterogeneously on the fault as either velocity weakening (VW, $a-b < 0$) or velocity strengthening (VS, $a-b > 0$), but characteristic length (Dc) was distributed uniformly. We tested bimodal distributions of frictional parameter. The distribution of frictional parameter is characterized by the length of cyclic unit L and the ratio h of VW region within the fault. The stress loading by the plate is characterized by stiffness k. We have tested many sets of h and k, and have investigated the slip behavior. As a result, three types of slip behavior are observed, (i) stable slip, (ii) seismic slip in VW regions and afterslip in VS regions, and (iii) entire seismic slip. When h is small, the size of a VW region is smaller than the nucleation size of constant-weakening regime ($a/b=5/6$ in our study, Rubin and Ampuero, 2005), and slip occurs stably. Stable slip also occurs with a sufficiently large k. When k is below a critical stiffness, slip in VW regions is accelerated to the seismic speed. The boundary between (ii) and (iii) is determined by whether slip in VS regions exceeds Dc, accelerated by seismic slip in the adjacent VW regions. When h is small, slip in VS regions does not reach Dc and the decrease of state variable is small, before the termination of the seismic slip in the VW regions. Later, relatively slow slip occurs in VS regions as an afterslip. When h is large, slip in VS regions exceeds Dc and state variable decreases rapidly, before the termination of seismic slip in the VW region. Therefore, the slip in VS regions is also accelerated to the seismic speed, and the entire fault slips seismically at the same time. The boundary between the regimes (ii) and (iii) shifts to smaller h when k is decreased. Given that small randomness exists in the bimodal distributions in the regime (ii), seismic slip in VW regions occurs independently separated by slowly slipping VS regions. These successive slip events occurring in a short period appear to be a single event with almost constant moment rate function, which looks like a slow earthquake. On the other hand, the entire seismic slip in the regime (iii) is considered as an ordinary earthquake. Thus the boundary between regimes (ii) and (iii) separates two modes of seismic slip.

Keywords: Heterogeneity, Earthquake, Source model

Modeling long- and short-term slow-slip events and their interaction with large earthquakes along the Hikurangi subduction zone

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Recent geodetic observations revealed the occurrence of various slow slip events (SSEs) along the Hikurangi subduction plate interfaces (Wallace and Beavan, 2010). Long-term SSEs with a duration of 1.5 years (e.g., Manawatu SSEs) occur at the deeper portion of the Hikurangi subduction zone, and shallow short-term SSEs with a duration of 1-3 weeks occur along the northern and central parts of the subduction zone. One of the fundamental questions is how SSEs interact with large earthquakes. In the present study, we performed quasi-dynamic modeling on short-term and long-term SSEs and their interaction with large earthquakes along the Hikurangi subduction zone. We used a rate- and state-dependent friction law with a cut-off velocity to the evolution effect (Shibazaki and Shimamoto, 2007). We investigated a realistic configuration of the plate interface. On the basis of the study on interseismic coupling by Wallace and Beavan (2010), we set the seismogenic zone where a-b is negative. The long term average relative slip velocity of each element was fixed at 4.5 cm/year for simplicity.
We set both the Manawatu and Kapiti SSE regions at the deeper extension of the seismogenic zone. The activity of Kapiti SSEs changes significantly during a cycle of large earthquakes. When large earthquakes approach, slip velocities increase at the deeper extension of the seismogenic zone. Consequently, slip velocities of the Kapiti SSEs at the deeper extension of the seismogenic zone increase. During a large earthquake, coseismic slips occur at the Kapiti SSE zone, but the occurrence of SSEs is subsequently restrained for some time. We also developed a model which investigated subducting seamounts in the northern segment of the Hikurangi subduction zone. The effective stress is assumed to be very high in the region of seamounts. The seamounts act as barriers of slow slip but between seamounts slips propagate to the shallow fault zones. Comparison between our results and observations will be necessary to develop a more realistic model of SSEs in this region.

Keywords: Long- and short-term slow slip events, The Hikurangi subduction zone, Modeling, Large earthquakes

Numerical experiments on estimation method of frictional parameters on the SSE fault -Through Ensemble Kalman Filter-

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Slow slip events (SSEs) occur repeatedly on the plate interface beneath the source regions of the interplate large earthquakes. The activity of SSE possibly changes before the occurrence of large interplate earthquakes (Peng and Gomberg, 2010). Hence, it is essential to know the frictional properties for producing SSEs to predict the occurrence of large earthquakes. Our final goal is to optimize slip evolution and frictional parameters on the SSE fault related to SSE with GPS data through Ensemble Kalman filter (EnKF), one of data assimilation methods which combines the observational data and the forecast values derived from a simulation model, and then to give some insight on the occurrence of large interplate earthquakes. In this paper, we construct the synthetic data from simulated slip velocities with the observation errors. Then, we perform numerical experiments on estimation of frictional parameters through EnKF, verifying the estimated values and its errors.
We set a dipping fault embedded in a homogeneous elastic half space. The friction on the fault is assumed to obey a rate-and state-dependent friction law, and the slowness law of state evolution. We set an asperity at depths of 20-40 km on a stable sliding plate interface, whose frictional properties are characterized by frictional parameters A, B and L. The asperity has the velocity weakening frictional property of A-B<0 and its radius is nearly equal to or less than the nucleation radius determined by frictional parameters. Then, we successfully reproduce the SSEs with the recurrence interval of about 6 months.
We perform numerical experiments on estimation of frictional parameters on the fault through EnKF with the constructed model. EnKF is the method for estimating optimum values by sequentially updating the observations, simulated results and their variance-covariance matrix in a statistical way. The variance-covariance matrix is calculated by computing a lot of ensemble members which are generated by adding random numbers to initial values.
The experimental results in the cases using the synthetic data on the fault show that retrieving frictional parameters requires the appropriate arrangement of observation points which can resolve the spatiotemporal evolution of the SSE slip. We perform the experiment using the synthetic data on the ground surface to discuss possibility of application to the actual SSE faults. It seems to be possible to apply the Bungo channel SSE and the Tokai SSE regions, though this should be confirmed by performing numerical experiments assuming the models and the arrangements of observation points appropriate for these regions.

Keywords: Ensemble Kalman Filter, slow slip event

Total energy of deep low-frequency tremor in the Nankai subduction zone

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Deep low-frequency tremor was first discovered in the Nankai subduction zone of southwest Japan, and is now known to occur in other subduction zones along the Pacific Rim. Because tremor usually occurs simultaneously with short-term slow slip events spatially and temporally, clarifying tremor activity is considered to be an important role to understand the slip process on the megathrust plate interface.
In this study, we estimated the total seismic energy of deep low-frequency tremor in the Nankai subduction zone, southwest Japan, over an 11-year period from 2004 to 2015. For precise estimation of the energy, continuous time sequences of tremor activity were carefully detected using a new procedure designed to minimize false-negative detections. By the result of spatial distribution of accumulated total energy of tremor, we found high-energy area in the western Shikoku region. Tremor activity rate, defined as the yearly average of total tremor energy per unit square, was investigated in each area throughout the Nankai subduction zone. Tremor activity rate averaged in 11 years is very high in near Bungo channel region compared to other regions. In the Bungo channel, the long-term SSE is known to occur at every six or seven years and activate nearby tremor activity. During the analyzing period, the long-term SSE occurred in 2010 and 2014. The tremor activity rate in this region in these two years increases to at least two or three times higher than that of quiescent period without the occurrence of long-term SSEs. This may indicate that external stress perturbations from the source of long-term SSEs in the Bungo Channel increased tremor activity by a factor of two to three. Slip on the plate interface in the tremor source region may be accelerated by nearby long-term SSEs. The relationship between tremor activity and nearby long-term SSEs in the Bungo Channel is consistent with the characteristics of tremor energy. We also note that tremor activity rate in this region is higher than that of other region even in the quiescent period.
In general, the tremor activity rate is high and low in areas west and east of the Kii Channel, where the plate geometry is complicated, respectively. In this comparison, tremor activity rate during quiescent period is used for Bungo channel region. The plate convergence rate shows the same spatial pattern as that for tremor activity. We infer that tremor activity is influenced by accumulated strain due to plate convergence. Strain at the plate boundary may be well accumulated where the plate convergence rate is high; tremor activity begins as a result of accumulated strain. In some areas in eastern Shikoku, the tremor activity rate is extremely low, although the plate convergence rate is relatively high. This may occur because the dip and convergence directions differ. Another possibility is that heterogeneous structures reduce the coupling between subduction rate and strain accumulation. Further investigation of this region is needed to constrain the tremor source mechanism.

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Keywords: tremor, energy, Nankai

Detection of deep low frequency tremor triggered by teleseismic surface wave based on matched filter technique

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Deep low frequency tremor in subduction zone is sometimes triggered by surface waves of teleseismic earthquakes. The triggered tremor can be easily recognized because of its correspondence to each phase of the surface wave whose period is about 30 seconds. The frequency of the triggered tremor is about 1-10 Hz. In Nankai subduction zone in southwestern Japan, triggered tremor was firstly reported for the 26 Sep. 2003 Mw8.3 Tokachi-oki earthquake, and the 26 Dec. 2004 Mw9.0 Sumatra-Andaman earthquake (Miyazawa and Mori, 2005; 2006). Such triggered tremors were observed in subduction zones where ambient deep low frequency tremor occurs associated with short-term slow slip events. However, the triggered tremor is not distributed in all source area of ambient tremor, but is concentrated in several fixed spots. In addition, recent studies have detected triggered tremor in some inland areas within the continental plate away from the subducting plate interface in Hokkaido, Kanto, and Kyusyu area. The triggered tremor and ambient tremor have difference in their activities. In this study, we investigated the relationship between triggered tremor and ambient tremor in detail, using the seismic waveform data.
We first compared the spectrum of tremor triggered by the 11 Apr. 2012 Mw8.6 Sumatra earthquake and that of ambient tremor that occurred at almost the same location in Mie prefecture, Central Japan, by using the waveform data recorded by densely distributed high-sensitivity seismograph network in Japan (Hi-net) operated by National Research Institute for Earth Science and Disaster Prevention. As a result, triggered tremor and ambient tremor showed almost the same spectral property.
Next, we applied the matched filter technique to waveform data with a passband of 2–8 Hz. As template events, we used low frequency events (LFEs) detected by Japan Meteorological Agency in 2014 with the epicentral distance from the triggered tremor of shorter than 30 km. The time length of each template event is five seconds including the arrival of S wave. The cross correlation between 355 template events and three-component waveform data recorded at 10 Hi-net stations including the surface wave of teleseismic earthquake were calculated. Then, we detected similar events to templates by using a threshold for the summed cross correlation coefficients.
We applied the matched filter technique for one hour-length data at 2012 Sumatra earthquake. Although the triggered tremor corresponding to each phase of the surface wave were clearly observed at the beginning part of the arrival of the surface wave from the band-pass filtered seismograms, no event having high cross correlation to the LFE templates was detected. On the other hand, after about 400 seconds from the beginning of triggered tremor, events with high cross correlation were detected. This result may suggest the change in waveform of triggered tremor due to migration during a sequence of triggered tremor.

Keywords: slow earthquake, deep low frequency tremor, triggered tremor, matched filter technique

Estimated the apparent released energy of shallow low-frequency tremor occurred Southeastern Kyusyu through frequency scanning at a single station

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Slow earthquakes, such as tectonic tremors and very-low-frequency earthquake (VLFE), share a common mechanism as shear slip on the plate interface and occur at both ends of updip and downdip of coseismic slip areas. Shallow low-frequency tremors have been observed in the subduction zone off southern Kyusyu [Yamashita et al., 2015].

Yamashita et al. (2015) have detected the shallow low-frequency tremors off southern Kyusyu from ocean-bottom seismometer (OBS) data. Although the seismicity has been documented, the released energy of these tremors has not been calculated. Here we calculate the released energy of tremor sequences off southwestern Kyusyu with applying the frequency scanning analysis [Sit et al., 2012] to OBS data.

Sit et al. (2012) proposed “the frequency scanning analysis” to detect tectonic tremors by calculating ratios of the envelope waveforms through different bandpass filters of broadband data at a single station in the Cascadia margin. We apply this method to the seismic data recorded at 12 short-period OBS stations deployed off southeastern Kyusyu, Japan. Three types of bandpass filters with frequencies of 2-4 Hz, 10-20 Hz, and 0.5-1.0 Hz, corresponding to the predominant frequency band of tectonic tremors, local earthquakes, and ocean noises, respectively, are adopted. When ratio value is over the threshold, we define that the tremor signal is detected in the time window. We estimate the apparent released energy as an approximation that is calculated from the squared amplitude of the median of absolute amplitude within the time window.

We have successfully detected the some sequences with large radiated energy, which correspond to the tremor events reported in Yamashita et al. (2015). In addition, we have also identified other possible sequences of tremors, which have occurred at the further southward that has been reported in Yamashita et al. (2015). The most largest released energy of tremors observed around the southern part of the tremor swarm.

Long-term ocean bottom monitoring of slow earthquakes on the shallow plate interface in the Hyuga-nada region (3)

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The Hyuga-nada region, nearby the western end of the Nankai trough in Japan, is one of the most active areas of shallow slow earthquakes in the world. We have started long-term ocean-bottom monitoring of them in this area from May 2014 using three kinds of sensors: broadband seismometer with pressure gauge (BBOBSP) and short-period seismometer (LTOBS). During the first observation (March 2014 to January 2015), we already reported minor shallow tremor and very-low-frequency earthquakes (VLF) activity and very-low seismicity of ordinary earthquakes within the focal area of shallow earthquakes in the Hyuga-nada. The second observation started from January 2015 using 3 BBOBSPs and 10 LTOBSs, and all sensors were retrieved in January 2016. From the monitoring using land-based seismic observation, many shallow tremors and VLFs occurred just under the OBS network during second observation period, which started from early in May and continued approximately 2 months. We confirmed the existence of these signals in the data recorded by each OBSs. Though the detailed hypocenter determination is still being performed, the observed records strongly suggests that the shallow tremor migrated within the OBS network, which reached at off Cape Ashizuri area where shallow VLFs have been occurred every 6-7 years associated with long-term SSE at Bungo channel. This off Cape Ashizuri’s activity (tremor and VLF) started at the end of May, especially increased activity after the large deep-focused earthquake at Ogasawara region (Mw7.8, 30 May 2015). In the presentation, we will introduce the preliminary result of second observation, in particular focus on the migration of shallow tremor.
Acknowledgements: This study is part of Research project for compound disaster mitigation on the great earthquakes and tsunamis around the Nankai trough region.

Keywords: shallow slow earthquake, Hyuga-nada, Ocean bottom observation

A tentative investigation to detect past activities of deep low-frequency tremor from the paper recording of the Kanto-Tokai observation network for crustal observation

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In the Nankai region, episodes of deep low frequency tremor recur at the intervals of several months. The activity of tremor is detected and monitored by NIED, using Hi-net seismic data. However, other recordings are required to reveal the activity before 2000, as the Hi-net data is available after Oct. 2000. NIED operated the Kanto-Tokai observation network for crustal observation (Okada et al., 2000) from 1979. Seismic stations of this network gradually increased after 1979. Continuous data of vertical component of seismograms has been stored as paper recordings in NIED. At first, we examined whether the recordings are useful to reveal past activities of deep low-frequency tremor. Then, we scanned paper image, and examined the setting to convert the paper recordings, as the paper recordings now causes a trouble in the storing space.
Short-term slow slip events (SSEs) in the Tokai region from 1984 are detected and reported by Kobayashi et al. (2006), using a tiltmeter. We checked the recording around the period of the reported SSEs, and found signals dominant in several Hz with the amplitude of several hundreds of nm/s at some stations (e.g., SMY, KSH, and TOE) in the Tokai region. This is characteristic to the deep low-frequency tremor detected from Hi-net data. For example, the signal is found in SMY, from 13 to 16, Aug., 1984, from 4 to 5, Dec., 1986, and from 8 to 10, May, 1987, while SSEs are reported from 13 to 14, Aug., 1984, from 3 to 4, Dec. 1986, and from 8 to 10, May, 1987, respectively. The several-days difference of the activities between tremor and SSE may be attributed to the spatial migration of tremor and SSE, as the SMY station is about 20 km north from the tiltmeter station.
We examined the digitization of paper recordings. We need to choose appropriate settings (e.g., resolution) in the conversion to image files. Paper feeding speed is 4 mm/s and amplitude of 336 nm/s is scaled to 1 mm on the paper of the recording of SMY. If the resolution is 300dpi, one pixel is about 0.085 mm. This means that temporal resolution is about 47 samples/s, and minimum resolution of velocity is about 28 nm/s. This is sufficient to recognize low frequency tremor. We note that this value is not common in this network, as the settings are different at each station.
In terms of color, even the black and white color is sufficient, as the outline of pen is clear.
It takes five minutes to convert images of 1 day. As the observation at SMY started from May 1980, it takes more than 600 hours to convert 20-years data. Much work is required to convert all of paper recordings, as the number of stations is 66 even in 1985, while this data is significant and cannot be replaced.

Keywords: deep low-frequency tremor, paper recording, slow slip event

Detection of shallow very low-frequency earthquake using a grid-based, fixed focal-mechanism method

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Recent observations of shallow very low-frequency earthquake (sVLFE) show the large-scale migration of activity and the simultaneous occurrence with shallow tremor, indicating sVLFE and shallow tremor are induced by background shallow slip event as is the case with the deep slow earthquakes (Asano et al. 2015; Yamashita et al. 2015). Understanding the relationship between the shallow slow earthquakes along the Nankai trough is important in view of occurrence of the future Nankai great earthquake.

In September 2006 a major activity of deep very low-frequency earthquake (dVLFE) and deep tremor occurred in the Bungo Channel and western Shikoku region. This activity is considered to be induced by a small long-term Bungo Channel slow slip event (SSE) because small surface displacements were also observed in GPS records. It is known that large long-term Bungo Channel SSE induces high sVLFE activity in the Hyuganada region (Hirose et al. 2010). Therefore sVLFE activity is expected to be observed also in Sept. 2006.

In this study we applied the grid-based, fixed focal-mechanism method (Suda et al. 2014) to detection of sVLFE in the Hyuganada region. We analyzed the F-net data from 33 stations between August 20 and September 30, 2006. We used only the F-net data because one purpose of this study is to check the feasibility of real-time monitoring of sVLFE using JDXnet data, which include no Hi-net accelerometer data.

We detected over 90 events in the analysis period. The main activity occurred in August 28-31 and only a small number of events occurred in September 7-21 when the activity of dVLFE and deep tremor occurred. This observation is in contrast to that the 2010 sVLFE activity in the Hyuganada region occurred in the acceleration stage of dVLFE and deep tremor activity in the Bungo Channel and western Shikoku region. The present observation suggests that a possible SSE that induced dVLFE and deep tremor in September 2006, if any, was not large enough to induce the high sVLFE activity in the Hyuganada region. The sVLFE activity observed in August might be due to a local shallow SSE.

Keywords: slow earthquake, shallow very low-frequency earthquake, Hyuganada

Distribution of low frequency earthquakes accompanied with very low frequency earthquakes along the Ryukyu Trench

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We investigated the long-term distribution of low frequency earthquakes (LF) which are accompanied with very low frequency earthquakes (VLF) in the Ryukyu Trench. The VLFs occur regularly by the accumulation of short-term burst-type swarms (about 1-4 days) along the Ryukyu Trench. Takahashi et al. (2015) detected the LFs accompanied with the VLFs using ocean bottom seismometers in the southwestern Ryukyu Trench. However, the long-term distribution of the LFs has not been known along the Ryukyu Trench. Then we detected the LFs for long-term and determined the hypocenter distribution in the Yaeyama and Okinawa region.
First we analyzed the long-term appearance of LFs accompanied with the VLFs. We hi-pass-filtered (1 Hz) to the waveforms of F-net (NIED) seismograms. Then we checked manually whether the LFs are found in the seismograms. The results showed that the appearance of the LFs is from 2 (Amami area) to 16% (Yaeyama area) along the Ryukyu Trench from 2004 to 2013. The LFs were successfully detected when the magnitudes of the VLF is over 4.0, whereas they were not found when the magnitude of the VLF is less than 3.7. Small amplitude of LF would be obscured by noise if magnitude of the VLF is small though LF would be always accompanied with VLF.
Next we determined the hypocenter of the LFs. For the hypocenter determination, we used the short-period seismometers by Japan Meteorological Agency (JMA) in the Ryukyu arc. First we selected the swarm of VLFs using the VLFs catalogue by Nakamura and Sunagawa (2015). Then we analyzed the waveform of the JMA seismometers. The surveyed period is from 2004 to 2013. We analyzed the data in the Yaeyama and Okinawa region where is near the cluster of the VLFs (Nakamura and Sunagawa, 2015). We picked the relative arrival time difference among the stations automatically using envelope cross-correlation method (Obara, 2002). We composited the horizontal waveforms and computed the RMS amplitude with 10 s average. We computed the cross-correlation for each network and we determined the hypocenters when the at least 4 stations satisfy the cross-correlation over 0.85. We used the S-wave velocity structure for the hypocenter determination because the phases are dominant with S wave.
The results show that the epicenters are distributed between south of Yonaguni Island and south of Iriomote Island in the Yaeyama area. Almost events are located between the Ryukyu Trench and Ryukyu arc. Since hypocenters are located out of the seismic network and only S phases are used for the calculation, estimation errors for the NS and EW direction are 70 km and 30 km, respectively. However, the distribution of the LF along the trench direction are similar to those of the VLFs which is estimated using semblance method (Nakamura and Tu, 2015). This suggests that the LFs occur in the similar region as VLFs in the Yaeyama. The LFs are found with accompanied with the occurrence of the large VLFs. The occurrence of the isolated LFs is rare. Moreover, the hypocenters of the LF concentrate at the southeast of south Okinawa Island and southeast of Okinoerabu Island in the Okinawa island area.
The hypocenters of the swarm of LF concentrate at the diameter of approximately 40 km in the Okinawa and Yaeyama areas. The migration of the hypocenters of the swarm activity was not found in the Okinawa and Yaeyama areas. This suggests that the distance of the migration of large LF was limited within 40 km if the hypocenters of the LF swarm migrate.

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

Swarm of shallow very low frequency earthquakes in the Bungo channel region in 2015 observed by temporal broadband seismic stations in the Shikoku island, southwest Japan

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The Bungo channel region in southwest Japan is one of regions where various types of slow earthquakes are observed at the top surface of subducting Philippine Sea plate. The slow earthquakes includes (i) long-term slow slip events (SSEs) at depths around 30 km and short-term SSEs at deeper depths recorded by geodetic instruments, (ii) shallow/deep low frequency tremor recorded by short-period seismometers at 1-10 Hz, (ii) and shallow/deep very low frequency earthquakes (VLFEs) recorded by broadband seismometers at 10-100 s. Although the coincidence of long-term SSEs and shallow VLFEs indicates relationship between them, there still exists a gap area between their estimated source areas without detection of any slow earthquake at this moment. For further understanding of slip distribution at the plate interface, we installed one Guralp CMG-3T (100 s) broadband seismometer and two Nanometrics Trillium (120 s) broadband seismometers in the southwestern part of the Shikoku island in February 2015 and June 2015, respectively. The observation plan at least continues to 2020.
The preliminary records showed seismic waves from shallow VLFEs activated in early June 2015. The data quality of vertical components was comparable to that of permanent stations of F-net broadband seismograph network operated by National Research Institute for Earth Science and Disaster Prevention at a period range of 20–50 s. We first applied the GRiD MT method (Tsuruoka et al. 2009) to records of 18 F-net stations as well as three new stations on June 8th filtered at a period range of 20–50 s for determining location and focal mechanism of each VLFE. We then applied the matched filter technique (Shelly et al. 2007) to detect similar events for eight months from May to December in 2015 by using a Mw4.1 event as a template event. The total number of detection is 1,476. We also determined the amplitude and location of each event with respective to the template event by grid search and waveform fitting.
The space-time plot of detected events showed two migrationg sequences of shallow VLFEs from southwest to northeast for two times, and several rapid reversal movements in June 2015. The cumulative number plot of time interval between adjacent events shows power-low distribution, which is different from exponential distribution for normal earthquakes and may characterize the swarm-like activity of VLFEs. The cumulative number of amplitude could be explained by both exponential and power-low functions due to limited range of amplitudes. Further discussion about the detection level for small amplitude is needed to conclude which function better explains the obtained distribution.
We also applied various band-pass filters to the waveforms at the time-windows aligned by the origin time of detected events. As a result, we could observe coherent signals between each time-windows at a period range of 10–100 s. Since the data quality was limited especially at periods longer than 50 s, we improved the signal-to-noise ratio by calculating station-averaged waveforms for each event. The averaged waveforms showed constant phase shifts between each time-windows at least at a period range of 20–100 s. This result indicates that the moment release function of each VLFE has a typical duration less than ~20 s.

Keywords: Very low frequency earthquake, Southwest Japan, Broadband seismic observation

Shallow very-low-frequency (VLF) earthquake activities along the Nankai trough in 2015

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In 2015, we observe shallow very-low-frequency (VLF) earthquakes along the Nankai trough by DONET, a permanent ocean-floor observation network. The activity started off the Shiono-misaki in August, which is followed by the activity off the Kii channel in September. In October the activity moved beneath the Kumano fore-arc basin. I investigated their source location and mechanism. Previous VLF activities along the Nankai trough are observed in 2004 (Obara and Ito, 2005), 2009 (Sugioka et al., 2012), and 2011 (To et al., 2015).
I determined the source location and mechanism of the VLF events by a waveform inversion using the SWIFT system (Nakano et al., 2008). Bband-pass filtered waveforms between 20 and 30 s, of which VLF signal is dominant, are used for the inversion.
Obtained CMT solutions show that the VLF sources are concentrated in several clusters located off the Kii channel, off Shiono-misaki, and Kumano fore-arc basin. These clusters well overlaps those reported by Obara and Ito (2005). The sources in the Kumano fore-arc basin can be divided into two clusters, which are located east and west of the previous major activity reported by Sugioka et al. (2012).
The source depth is between 7 and 10 km, corresponding to the base of the accretionary prism. The focal mechanism solutions represent low-angle thrust; one of the nodal planes is almost horizontal and the slip direction is almost perpendicular to the dip of slope of the sedimentary wedge. These results infer that the VLF events are caused by a slip along the plate boundary beneath the accretionary prism. We note that the dip of slope of the sedimentary wedge above the cluster off the Kii channel rotates about 60 degrees eastward due to the subduction of a seamount, but the rake angle of the obtained focal mechanism is very similar to those in the other clusters.
The obtained magnitude is at most about 4. The b-value obtained from the frequency-magnitude distribution is 2.4, inferring low stress level at the source.
I found that the occurrence of each event corresponded to minimal (not always the minimum) of ocean-bottom pressure caused by the ocean tide observed at DONET stations. This feature is evident in the activities off the Kii channel and off the Shiono-misaki. The correspondence to the low pressure was not evident in the activity beneath the Kumano fore-arc basin because of the swarm activity, although several events before the swarm activity corresponded to minimal of ocean-bottom pressure.
Assuming almost horizontal fault plane for the VLF sources, unclamping the fault by the decrease of hydrostatic pressure would promote VLF events. The tidal pressure change is about 10 kPa, comparable to the stress drop estimated for VLF earthquakes (Ito and Obara, 2006), which would be enough to perturb the state of stress at the source. But the truth would not be as simple as this because several of VLF events did not occur at minimum of the pressure. Combined effect of tidal force and external loading, a proposed model for deep non-volcanic tremor (e.g. Nakata et al., 2008; Ide and Tanaka, 2014), would be necessary to model the trigger of VLF earthquakes.

Keywords: DONET, off Kii channel, off Shiono-misaki

Investigating the relationship between slow-slip events and tremor in the Shikoku region, Southwest Japan

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In the subduction zone of Southwest Japan, Obara (2002) discovered nonvolcanic tremor, which is characterized by longer duration than regular earthquakes. After this discovery, other new slip phenomena at the plate boundary, characterized as well by longer durations, have been discovered in subduction zones around the world. These phenomena are collectively known as “slow earthquakes”. Understanding of slow earthquakes is an important issue for understanding the physics of subduction zones and may help the risk assessment of huge earthquakes. Fortunately, by the strengthening in recent years of the observation networks, the routine analysis of slow earthquakes is becoming possible and open observation data are being made available.
In this study we analyze and discuss the characteristics of slow earthquakes by using catalog data which have been newly developed in the recent years in the Shikoku region. This area has a new catalog of SSEs (Nishimura *et al.*, 2013; Nishimura 2014) and tremor (Idehara *et al.*, 2014).
Our results show that in the Shikoku region, almost all of the short-term SSEs (S-SSEs), which were detected by Nishimura (2013, 2014), synchronize with tremor activity. Assuming that tremor activities reflect the destruction of small patches on the SSE fault, we observe a consistent relationship of linear increase in the duration of the activation of tremors with the moment of SSEs. This result is in agreement with the scaling law of SSEs (Ide et al., 2007) and observation case of long-term SSEs (L-SSEs) (e.g., Miyazaki *et al.*, 2006). In addition, the calculation of the magnitude of L-SSE by using the tremor activation period during the periodic L-SSEs at Bungo Channel and the scaling law obtained in this paper is consistent with geodetic observations (Yoshioka *et al.*, 2015).
The obtained results suggest that the space-time pattern of tremor is well explained by SSEs characteristics and that the tremor can be used as a proxy for the detection of SSEs.

Keywords: ETS, tremor, scaling law of SSEs

Relationship between coupling and tremor rate in the region adjacent to the Bungo Channel SSE area

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In the Bungo Channel area, southwestern Japan, repeating long-term slow slip events (SSE) occur every several years. The recent events before 2011 occurred in 1997, 2003 and 2010 in almost the same area. Along the Nankai subduction zone, which contains the Bungo Channel area, deep low-frequency tremor activities occur on the subjecting plate interface. Hirose et al. (Science, 2010) shows the relationship between the tremor and SSE that the tremor in the northern part of the SSE area was activated by the SSE.
Ochi (EPSL, 2015) analyzed daily GNSS coordinates from 1997.0 to 2011.0 and inferred temporal evolution of the interplate coupling and long-term SSE. According to the results, the interplate coupling in the region on the east of the 2010 Bungo Channel SSE area strengthened in synchronization with the SSE. On the other hand, AIST makes the tremor catalog in this area after July 2008 using envelope correlation method (Maeda and Obara, JGR, 2009). According to the tremor catalog, the tremor active rate in this region increased after 2011 when the long-term SSE terminated. The increased active rate continues around mid-2014 and decreased to the level that was almost the same as before 2011. Because the long-term SSE occurred again after mid-2014 (GSI, Report of CCEP, 2015), decrease of the tremor active rate seems to coincide with the long-term SSE in the adjacent area. We will discuss the relationship between coupling rate after 2011 and the tremor active rate in this region.

Keywords: Slow earthquake, deep low-frequency tremor, interplate coupling

Short-term Slow Slip Events in the Kanto Region, Central Japan Detected Using GNSS Data

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The Kanto region, central Japan is situated under complex tectonics where the Philippine Sea and the Pacific plates subduct from the Sagami Trough and the Japan Trench, respectively. Several large earthquakes including the 1923 M7.9 Kanto earthquake historically damaged the Kanto region. Shallow short-term slow slip events (SSEs) were observed by continuous GNSS east off the Boso Peninsula in 1996, 2002, 2007, 2011, and 2014 [e.g., Ozawa *et al.*, 2014]. These Boso SSEs with M_w ~6.6 occurred on the Philippine Sea plate in a depth of 10-20 km. Some studies reported that SSEs occurred on the Pacific plate. However, spatiotemporal distribution of SSEs remains unclear in the Kanto region. In this study, we accomplish systematic searches for SSEs along both the Sagami Trough and the Japan Trench using GNSS data.

An operation of a continuous GNSS network was started in 1994 in the Kanto region. We estimate daily coordinates at all available stations operated by the Geospatial Information Authority of Japan and the Japan Coast Guard using GIPSY 6.2 software. We apply the method of Nishimura *et al.* (2013) and Nishimura (2014) to detect a jump associated with short-term SSEs in GNSS time-series and estimate their fault models from observed displacements. A rectangular fault on the Philippine Sea or the Pacific plates is assumed for each SSE. The stacking of GNSS time-series based on the displacement predicted by the fault model [Miyaoka and Yokota, 2012] enable us to estimate duration of SSEs. For SSEs on the Philippine Sea plate, five Boso SSEs are detected with duration of 9-13 days. Although the largest SSE with M_w6.7 is detected far east off the Boso Peninsula, no apparent seismicity is observed. The duration of the SSE is estimated to be 23 days, which is longer than the Boso SSEs. The longer duration may be a cause of no seismicity related with the SSE. For SSEs on the Pacific plate, we found 24 SSEs. Their moment magnitude ranges between 6.0 and 6.4. Many SSEs are clustered near the eastern rim of the overriding Philippine Sea plate. This may reflect on a difference of interplate coupling controlled by geology of the overriding plate [Uchida *et al.*, 2009]. It is also suggested that the SSE cluster corresponds to a subducted seamount induced from a bathymetry.

Keywords: Slow Slip Event, GNSS, Kanto region

Long-term slow slip events beneath the Kyushu Island

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A transient deformation in the Kyushu Island from January to April 2014 was detected by GNSS observation network in Japan. We estimated slip distributions at the plate boundary between the subducting Philippine Sea Plate and the continental plate from that GNSS data. Two slipped areas were estimated beneath the Kyushu Island. The south slip area corresponds to the Hyuga-nada SSE area. The north slip area corresponds to the gap area between the Bungo-channel SSE and the Hyuga-nada SSE, that has not been reported long-term SSE previously. We also found that long-term SSEs occur in the gap area repeatedly before the 2014 event.

Keywords: long-term SSE, Bungo-channel, Hyuga-nada

Comparison of the spatio-temporal evolution of slow slip events in the Yaeyama Islands, southwestern Japan

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Along the Ryukyu Trench, the most southwestern part of Japan, no historical records of large thrust type earthquakes (Mw > 8.0) exist for the last 300 years (Ando et al. 2009) and therefore it is assumed that subduction zone in this region are aseismic. However, a tsunamigenic normal fault type earthquake occurred in 1771 around the Yaeyama Islands and its source region was estimated in the shallower part of the Ryukyu Trench from the tsunami heights (Nakamura 2009a). Recently, very low frequency earthquakes (VLFEs) were detected from a broadband seismic network along the trench (Ando et al. 2012). On the other hand, Heki and Kataoka (2008) reported that slow slip events (SSEs) had repeatedly occurred with a recurrence interval of about six months along the southwestern Ryukyu Trench. They estimated simple time-independent fault model for the SSEs assuming a planar rectangular fault with spatially uniform slip around the Iriomote Island by analyzing GNSS data at eight GEONET stations. However, the spatio-temporal evolution of SSEs has not been investigated.
We have developed four GNSS stations in the Yaeyama Islands in 2010 in addition to eight GEONET stations to clarify the characteristics of the subduction zone along the southern part of the Ryukyu Trench. Because no large earthquakes recently occurred in this region, it is expected that the GNSS observations contain signals of SSEs that are not contaminated by earthquakes although some meteorological phenomena such as typhoon may affect the observations. In this study, we apply a geodetic time-dependent inversion scheme to these GNSS data to clarify the spatio-temporal evolution of the SSEs and its relation to VLFEs.
Data period used in this study is between March 2010 and July 2013. GNSS data from the 12 stations are processed with the GIPSY-OASIS II software. As a result, 5 SSEs were detected during the period. First of all, we remove the trend from each time-series. Then we conduct a geodetic time-dependent inversion using the detrended time-series to infer the spatio-temporal evolution of slip during each event. For this purpose, we employ a modified Network Inversion Filter (NIF) which is based on the Monte Carlo mixture Kalman Filter (MCMKF, Fukuda et al. 2004, 2008). This method is an improved version of the standard NIF (Segall & Matthews, 1998) and is able to extract slow slip signals without oversmoothing or undersmoothing of estimated slip.
The estimated temporal evolution of moment rate suggests that the first event initiated around 10 August 2010 and lasted for about 40 days and the moment magnitude is estimated as about 6.75. The main slip region locates at the northwestern part of the Iriomote Island and the maximum magnitude of slip is about 10 cm, which is consistent with Heki & Kataoka (2008). The resolution of slip below the Iriomote Island is improved by adding the four new observations, and hence no slip is inferred at the southeastern part of the Iriomote Island at depths of about 30 km where some amount slip is inferred without the four new stations. We find that the passage of a typhoon in the summer of 2010 affected the GNSS position estimates. We thus removed the data during that period to avoid the estimated slip to be affected by the typhoon. In the presentation, we will also show the results for the four other SSEs between 2010 and 2013 and compare the spatio-temporal evolution among the five SSEs.

Keywords: slow slip event, Ryukyu Trench, time-dependent inversion, GNSS

Automated detection of slow slip events from tilt and strain data

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In subduction zones such as Nankai and Cascadia, various types of slow earthquakes have been detected using dense geodetic and seismic observation networks. Kimura et al. [2011] developed an automated detection method for the identification and location of short-term slow slip events (SSEs) within the Nankai region using continuous tilt data observed at NIED Hi-net stations. Recently, AIST has constructed a borehole strainmeter network around the Shikoku and Kii peninsula regions, and these strainmeters are generally more sensitive to short-term SSEs than the Hi-net tiltmeters [Itaba, et al. 2010]. In this study, we apply the automated detection method of SSEs not only to the tiltmeter data but also to the strainmeter data in order to enhance the detection capability and improve the accuracy in the SSE model.
We evaluated the capability of detecting short-term SSEs in Shikoku using the strength of the white and random-walk noises estimated for each geodetic time-series data [Kimura et al. 2011]. The comparison between the capability using tiltmeter data and that using both the tiltmeter and strainmeter data indicated that the addition of the strainmeters enhances the detection limit by 0.1-0.2 in the magnitude of SSEs in the Bungo channel and western and central Shikoku regions. On the other hand, in the eastern Shikoku region, the detection capability does not change significantly because strainmeter stations are relatively far from short-term SSE source area.

Keywords: Slow slip event, strainmeter, tiltmeter

Magneto-telluric monitoring for probing changes in crustal resistivity associated with slow earthquakes

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In southwest Japan, various slow earthquakes such as deep low-frequency tremor, deep very-low-frequency earthquake, and short-term slow slip events occur at the subducting plate interface (e.g. Obara, 2002, Scinence; Ito *et al*., 2007, Science; Hirose and Obara, 2005, EPS). To understand their mechanisms by probing the associated structural changes around the plate interface, we have been carrying out continuous magneto-telluric (MT) observations in western Shikoku, Japan since 2008. MT survey along the dip direction of subducting Philippine Sea plate revealed an existence of low-resistivity structure in the lower crust in this region (Yamashita and Obara, 2009, AGU). Two observational sites KBN and SGW were installed on the survey line. The observation at SGW terminated and representative observation at IKT, which is about 10 km away from the survey line, has started in 2010. Qualities of the data recorded at these sites are relatively fine. However, to further improve the quality, we are applying a data processing method same as Honkura *et al*. (2013, Nat. commun.); we use only data whose coherency between electric and magnetic field is higher than a threshold. Using the high-quality data, we estimate daily MT parameters, apparent resistivities and phases at nine frequencies from 0.00055Hz to 0.141Hz. As a result of the careful data analysis, we found some temporal changes in MT parameters. They should not be originated from a noise but the structural change in crust, because amounts of the changes in apparent resistivity and phase over nine frequencies are consistent with the theoretical relation in MT method. In addition, those temporal changes are common among two observational sites. We further found that the changes in the MT parameters looked correlated with the activity of the deep low-frequency tremor beneath the observational sites. Based on the surveyed resistivity structure, we will further investigate amount and location of the resistivity changes.

Keywords: Slow earthquake, Crustal resistivity, Magneto-telluric monitoring

Continuous measurements of S-wave splitting parameters for monitoring of seismic anisotropy

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In this study, we approach an unsolved question with respect to mechanisms of triggering and synchronization among members of a family of slow earthquakes using seismic anisotropy. The study area is the Nankai trough subduction zone, southwest Japan. In this presentation, we mainly focus on a tremor activity from 2015/12/26 to 2016/01/05 beneath eastern Shikoku.

Features of seismic anisotropy are attributed to characteristics of stress state, structure, and physical properties of the medium. A study of seismic anisotropy using slow earthquakes can, therefore, provide physicochemical, geometrical and mineralogical information in their source regions and along the ray paths. In our previous study, we focused on one of a slow earthquake, deep low frequency earthquakes (DLFEs), reported by JMA. Ishise & Nishida (2015 JpGU) investigated S-wave polarization anisotropy using DFLEs and tried to detect temporal variation of seismic anisotropy in the source region of DLFEs in the Nankai trough subduction zone: S-wave splitting analysis (Ando et al., 1983 JGR) was applied to S-phases of DFLEs picked by JMA. However, the seismicity of DLFEs was too low to show the temporal variation of anisotropy. Ishise & Nishida (2015 SSJ), then, applied S-wave splitting analysis continuously to continuous waveform data including DLFEs analyzed in our previous study and continuously measured S-wave splitting parameters in order to detect temporal variations of seismic anisotropy during the tremor activities. Since tremor signals are inferred to be composed of S-waves primarily, we can obtain S-wave anisotropy during the tremor activity. A similar analysis provided crustal anisotropy beneath northern Cascadia (Bostock and Christensen, 2012 JGR).

In this study, we applied the S-wave splitting analysis to filtered seismograms (2-8 Hz) and determined the polarization direction of fast S-wave and the delay time between fast and slow S-waves. The time window and time step of the continuous analysis were 60 and 30 seconds, respectively. Together with the anisotropy monitoring, we performed polarization analysis to estimate the incoming wave. Following Bostock and Christensen (2012 JGR), assuming S-wave incidence, we estimate back azimuths and incident angles.

The continuous measurements of splitting parameters showed the relatively smaller variability of the parameters and high reliability of the estimated anisotropic parameters when strong tremors were recorded. In a similar manner to splitting analysis, polarization analysis provides reliable estimation when strong tremors are recorded because it assumes S-wave incident during the polarization analysis. Actually, we found a number of clear temporal variations of back azimuth of the incoming waves that were synchronized between more than one stations. Judging from the intensity of the tremor signals, the temporal variations suggest processes of tremor migration.

As for characteristics of anisotropy, we found that polarization directions of fast S-wave tend to fluctuate around the strike directions of geological lineaments (from SW–NE to NW–SE). It suggests that the surface anisotropy would prevent from detection of deeper anisotropy. At the same time, we observed clear temporal variations of anisotropic parameters at stations near the center of tremor activities. The temporal variations of anisotropy tended to synchronize with those of parameters of incoming waves. The temporal variation of anisotropic parameters can, therefore, be explained by spatial variations of seismic anisotropy. In order to achieve our purpose to detect temporal variation of seismic anisotropy in tremor source region, we need more case studies through retrospective analyses.

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Keywords: monitoring of seismic anisotropy, deep low frequency tremor

Laboratory-observed slow frictional slip instabilities in Tohoku plate boundary fault zone samples

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The plate boundary megathrust at the Japan Trench has exhibited remarkable slip behavior that has drastically changed our understanding of fault slip behavior. The 2011 Tohoku-Oki earthquake produced an extraordinarily large amount of coseismic slip (several 10’s of meters) up to the seafloor, on a portion of the megathrust previously thought to be aseismic. Additionally, this region is also known to generate slow earthquakes. One of these slow earthquakes occurred with the rupture area of the 2011 Tohoku earthquake; this event was observed one month before the 2011 earthquake and was likely ongoing during the earthquake. This shows that the Japan Trench megathrust does not exhibit strictly stable slip and thus failure can occur in a variety of styles. During Integrated Ocean Drilling Program Expedition 343, the Japan Trench Fast Drilling Project (JFAST), samples of the plate boundary fault zone in the Tohoku region were recovered ~7 km from the Japan Trench axis, within the region of largest coseismic slip during the 2011 Tohoku earthquake. We sheared these samples in laboratory friction experiments utilizing a slip velocity of 2.7 nm/s, equal to the convergence rate between the Pacific and North American plates (85 mm/yr). One key observation is that infrequent strength perturbations occurred which are interpreted to be laboratory-generated slow slip events (SSE). For intact samples, these events have stress drops of ~50-120 kPa that occurs over several hours. The stress drop matches the estimated stress drop of the SSE that occurred prior to the 2011 Tohoku earthquake. Peak slip velocities of the laboratory SSE reach 10-25 cm/yr, comparable to observations in natural subduction zone SSEs worldwide. Displacement records indicate a slip deficit accumulation prior to the laboratory SSEs which is recovered during the subsequent stress drop. The laboratory SSEs tended to occur more frequently in intact samples rather than powdered samples, suggesting that the intense scaly fabric is favorable for the SSEs. Velocity-stepping tests also reveal velocity-weakening frictional behavior, suggesting that the laboratory SSEs are slip instabilities or quasi-instabilities. This is supported the observation that in powdered samples, very large SSEs appear at 16 MPa effective normal stress whereas they are mostly absent at 7 MPa. This is consistent with critical stiffness theory, in which increased effective normal stress is associated with an increased likelihood of slip instability.

Keywords: Slow slip, rock experiment, The 2011 Tohoku-Oki Earthquake

