Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

SCG62-P01 Room:Convention Hall Time:May 27 18:15-19:30

Detection of seismic anisotropy from low frequency earthquake

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Recently, members of family of slow earthquakes have been detected in a subduction zone by densely deployed seismic observation network. They occur at the plate interface, and the source regions of them delineate the rupture zone of a future mega-thrust earthquake in the southwestern Japan. Non-volcanic tremor is the most active phenomena within the family of slow earthquakes and has been found to correlate temporally and spatially with other slow earthquake (e.g., Rogers and Dragert, 2003). Therefore, there have been many studies on mechanism of non-volcanic tremor since the detection of the phenomena (Obara, 2002). However, the mechanism of the tremor has not been fully elucidated, although a lot of studies suggest a relationship between tremor and fluid rebated from the subducting slab. Thus, we examine the relationship between fluid and the behavior of non-volcanic tremor on the basis of special and temporal variations in seismic anisotropy, which is strongly related to the behavior of fluid.

In this study, we detected seismic anisotropy at the plate interface of the PHS slab from the isolated phase during non-volcanic tremor episode, which are categorized as low frequency earthquakes by the JMA (Nishide et al., 2000). The phases are regarded as S-wave and used by hypocenter determination. Therefore, in order to detect anisotropy, we utilized S-wave splitting method (e.g., Ando et al., 1983), in which seismic anisotropy is represented by polarization direction of fast S-wave (direction of anisotropy) and delay time between two S-waves.

Preliminary result of S-wave splitting analyses showed that the directions of anisotropy are tend to be orientated in the East-West trending direction and the delay times are 0.2-0.4 sec. In general, however, anisotropy obtained by S-wave splitting analysis is strongly affected by anisotropy near the receiver. In fact, the obtained anisotropy in this study is consistent with crust anisotropy in the study area. In order to rigorously discuss anisotropy around the source region, we have to remove the effect of the anisotropy in the crust.

Keywords: low frequency earthquake, seismic anisotropy, fluid

Japan Geoscience Union Meeting 2015
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SCG62-P02 Room:Convention Hall Time:May 27 18:15-19:30

Observation of the deep low-frequency earthquakes using deep borehole-seismograph network. Activity in Tokai area

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Tokai area is the eastern side of Southwest Japan subduction where great earthquakes and deep low-frequency earthquakes (LFEs) occur along the convergent plate boundary. Researching the LFEs, Tono Research Institute of Earthquake Science (TRIES) installed a seismic array with 10 stations in Toyota city, Tokai area. Geological Survey of Japan (AIST) also installed a seismic array of three borehole-type instruments with high-sensitive seismographs at three depths of 50m, 200m, and 600m in Toyota city. We used seismic data of those two arrays and SMYH station of Hi-net array of National Research Institute of Earth Science and Disaster Prevention (NIED) as 3D array data for investigating LFEs. We successfully detected not only S waves but also very weak P waves of LFEs using the 3D array data and the semblance method. We understood that 3D array observation was effective for researching LFEs. We, therefore, built the second 3D array in Tono region where located 30-40 km north from the source region of LFEs in Tokai area.

We applied the deep borehole-seismograph network and the high density network of seismic stations of TRIES in Tono region to the second 3D array. We called it Tono Juji array. Tono Juji array was constituted by two borehole stations of 1000 m depth, three borehole stations of 500 m depth and twelve shallow stations. Seismic wave data observed by acceleration seismographs were converted velocity data. All of the seismic wave data were unified to sample rate of 100Hz and filtered through a 2 to 10 Hz band pass filter. We selected a LFE with the maximum magnitude (M=0.6) among the 209 events from the JMA earthquake catalog and named it LFE108. The origin time of LFE108 was 2014/9/1, 15h26m40.77s. We found a slight signal of P wave of LFE108 in vertical component of each station. And we also found a slightly clear signal of S wave in horizontal component of each station. We could not find large difference in clear or unclear of the signals between borehole stations and shallow stations. It means that the cause of unclear LFE signals mainly depends on not ground noise but overlapping of P, S and Coda waves of many successive LFEs.

Acknowledgements: We thank to Japan Meteorological Agency (JMA) and National Research Institute for Earth Science and Disaster Prevention (NIED).

Keywords: deep low-frequency earthquakes, deep borehole-seismograph network, array observation, semblance analysis

Japan Geoscience Union Meeting 2015
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Automatic detection of low-frequency earthquakes in Southwest Japan using matched-filter technique

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The Japan Meteorological Agency (JMA) has distinguished a class of events marked as low-frequency earthquakes in the JMA's earthquake catalog since 1999 [Nishide et al.,2000]. LFEs have clear isolated S phase with dominant frequencies lower than ordinary earthquakes. The JMA's earthquake catalog has about 24,000 events of tectonic LFEs in the Nankai Trough under Southwest Japan from September 1999 to July 2014. Recent studies [Shelly et al.,2007] insist that tremor in the Nankai Trough consists of a swarm of LFEs that occur as shear faulting on the plate interface. It is thought that watching activity of LFEs is important for supposing the state of the plate interface. However, it is difficult to detect LFEs by STA/LTA ratio, because of the lack of impulsive phase arrivals, used to detect and locate hypocenters of ordinary earthquakes. Therefore, it takes time to locate their hypocenters in same procedure for ordinary earthquakes.

So, a matched-filter technique was used to detect events of tectonic LFEs in Southwest Japan automatically with the use of continuous three-component velocity seismograms at 75 stations. These stations belong to the integrated seismic network of Japan. 1,263 events which are listed in JMA's earthquake catalog are used as template events. In analysis, first 2-8 Hz bandpass filter was applied to templates and continuous seismograms, and these decimated to 20 samples per second. Template is 4 seconds time windows 1.5 seconds before the calculated S phase arrival. Next, the time window of template is shifted around the calculated S phase arrival in an increment of 0.05 second through coutinuous seismograms.At each time point, correlation coefficient value between templates and a part of continuous seismograms are computed , and the sum of correlation coefficient value for all stations is calculated. An event of LFEs can be detected when the sum of correlation coefficient value exceed a threshold. Finally, grid search method is used to make a hypocenter of detected event more precise. As a result of analysis, more events listed in the JMA's earthquake catalog have been detected after July 2014.

Keywords: low-frequency earthquakes, matched-filter technique

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SCG62-P04 Room:Convention Hall Time:May 27 18:15-19:30

Spatial inhomogeneity of deep low-frequency tremor activity evaluated from seismic radiation energy and duration

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Deep low-frequency tremor occurs associated with deep very low-frequency earthquake (VLF) and short-term slow slip event (SSE) on the interface of subducting Philippine Sea plate in southwestern Japan. Because they occur at the downdip part of the megathrust seismogenic zone, they are expected to be related to megathrust earthquake. Spatio-temporal distribution of tremor has been well investigated to get a whole picture of tremor activity. However, during very active tremor period, envelope correlation between stations becomes relatively poor because of complicated waveforms. Then, it is difficult to detect and locate tremor source during such active periods. On the other hand, radiation energy evaluated by squared velocity amplitude can be estimated robustly even if each waveform is complicated.

In this study, we developed a new tremor detection method with estimation of seismic radiation energy and centroid location. This method extracts at first tremor sequence defined as a continuous tremor activity with amplitude exceeding a threshold. Therefore, miss-detections of active tremor were reduced and it leads to more qualitative estimation of tremor activity. This method was applied to tremor data in the Nankai subduction zone in 10.5 years starting from 2004.

From spatial distribution of seismic radiation energy by tremor, we found that very large tremor energy is radiated from western Shikoku area compared to that of previous studies. Spatial distribution of total duration and energy rate of tremor shows that tremor zone can be classified into two types. One is an area which has high energy rate and long total duration such as western part of Shikoku or western part of Tokai. Another is an area which has low energy rate and short total duration such as central western part of Shikoku or central part of Kii. On the other hand, a region of western Shikoku area has low energy rate but has long total duration. Therefore, this part cannot be classified into two types. Comparison between distribution of tremor activity and epicenters of large VLF suggests that most of VLF epicenters were distributed on the area which has high energy rate and long total duration.

High energy rate indicates that the size of tremor is large. Therefore, tremor zone can be classified into area characterized by large size of tremor with long period or area characterized by small size of tremor with short period. On the other hand, a part of western Shikoku is characterized by small size of tremor with long duration. This suggests that the size and duration of tremor are independent each other and the tremor activity indicates spatial inhomogeneity.

Keywords: tremor, energy rate, duration

SCG62-P05 Room:Convention Hall Time:May 27 18:15-19:30

2014 Bungo channel slow slip event inferred from deep low-frequency tremor activity

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Episodic tremor and slip is a stick-slip phenomenon in the transition zone between locked and stable sliding zones on the plate interface in Southwest Japan. The tremor burst with duration of several days spontaneously occurs at interval of several months in each segment. On the other hand, in the Bungo channel region, the long-term slow slip event (SSE) occurs at every 6~7 years at the updip side from the tremor zone. During the long-term SSE, continuous tremor activity was observed for a few months in 2003 and 2010 at the updip part of the tremor zone which is neighbor to the source area of the long-term SSE. We expected the next long-term SSE in 2016; however, tiny long-term SSE was inferred from tremor activity in early 2014, then The Geospatial Information Authority of Japan reported the occurrence of the SSE (GSI, 2014). In this paper, we discuss the relationship between Bungo channel long-term SSE and triggered tremor.

Tremor activity seems to be quite different at its updip and downdip parts in the Bungo channel region. Tremor activity at the updip part is well correlated with the crustal displacement caused by the long-term SSE; however, tremor activity at the downdip part is constant with time irrespective to the occurrence of the long-term SSEs. The rate of the tremor number density which is the number of tremor per 1 km square is nearly the same in both parts except during the long-term SSE. This indicates that the standard rate of the tremor number density is independent from the depth. Because the triggered tremor by the long-term SSE is added on the standard tremor rate at only the updip part, anomalous increase of the updip tremor may indicate a proxy for SSE. Tremor activity at the updip part of the tremor zone in the Bungo channel seems to increase a little bit from the beginning of 2014. Then, small change in the crustal deformation was recognized from the middle of 2014 at southwestern Shikoku by using GSI GEONET GNSS data. Similar small change in both tremor and GNSS data had been observed in the late 2006 and the beginning of 2009. The 2006 small episode lasted for a few months. This is interpreted as the occurrence of very small long-term SSE. On the other hand, the 2009 small episode was identified by tiny increase of tremor activity, then gradually appeared in GNSS data, and finally evolved to the long-term SSE associated with significant slip and tremor activity from the beginning of 2010. According to these previous examples, we expect that the small change observed by tremor and GNSS data in 2014 might have stopped or will evolve to a regular long-term SSE before long.

After SSEs in 2003 and 2010, tremor activity seems to slightly increase in the inland region within 50 km from the triggered tremor region in the Bungo channel. Such 7-year period variation in tremor activity is observed at only the updip side of the tremor zone. Moreover, pattern of the long-term variation seems to slightly migrate from the Bungo channel to east during a few years. We might interpret that a tiny transient slip after the long-term SSE slowly propagates between the tremor zone and megathrust seismogenic zone.

Keywords: non-volcanic tremor, slow slip event, slow earthquake, interaction, subduction zone

SCG62-P06 Room:Convention Hall Time:May 27 18:15-19:30

Long-term ocean bottom monitoring for slow earthquakes on the shallow plate interface in the Hyuga-nada region

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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. Recently, ocean-bottom observation of offshore seismicity near the trench have succeeded to detect shallow tremor as a complete episode lasting for one month exhibiting similar migration property of deep tremor for the first time [Yamashita *et al.*, in revision]. This activity was also associated with shallow very-low-frequency earthquake (VLFE) activity documented by land-based broadband seismic network. The coincidence between tremor and VLFE and their migration pattern show strong resemblance with deep tremors during ETS episodes; this similarity suggests that the tremor activity in the shallow plate boundary may also be coupled with VLF and short-term slow slip events (SSEs) in this area. However, the shallow SSEs have not been detected to date, probably due to the lack of dense broadband seismic and/or geodetic observations in offshore. To clarify the relationship among these slow earthquakes is important to improve the assessments of the potential of tsunamigenic megathrust earthquake that is anticipated to occur at the Nankai Trough. Motivated by these issues, we started long-term ocean-bottom monitoring in this area from May 2014 using 3 broadband and 7 short-period seismometers. To detect the suspected shallow SSE, pressure gauges are mounted on the broadband ocean bottom seismometers for covering geodetic period range. In January 2015, we replaced the instruments and obtained the first data which includes minor shallow tremor and VLFE activity on June 1-3, 2014. Preliminary results of data analysis show that the shallow tremor activity occurred at the same area of the 2013 activity, but clear tremor migration has not been found yet. However, it is promising to detect the large short-term SSE with our dense and long-term observation including with pressure gauges in near future.

Keywords: shallow slow earthquake, Hyuga-nada, long-term ocean bottom monitoring

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Very low frequency earthquakes in the shallow Nankai accretionary prism, following the 2011 Tohoku-Oki earthquake

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A large number of shallow low frequency events were recorded after the 2011 Mw 9.0 Tohoku-oki earthquake by the cabled network of broadband ocean bottom seismometers (DONET) deployed in the eastern part of the Nankai trough. This low frequency event activity was intense for the first few days after the great earthquake and gradually decreased. Signals of the events are most clearly visible at the frequency range around 2-8 Hz. Some of the events are accompanied by a very long frequency (VLF) signal, which is clearly observed at around 0.02-0.05 Hz. The magnitude and source duration estimated by waveform analysis for one of the largest very low frequency earthquakes (VLFEs) was 3.0 ˜3.5 and 17 s. This source duration is extremely long compared to ordinary earthquakes of comparable magnitude. These newly detected VLFEs are likely to be normal fault earthquakes located at shallow depths within the accretionary prism, in contrast to the previously reported VLFEs that were explained by a low angle thrusting along the decollement zone. On the other hand, the low frequency events with no clear VLF signal were previously regarded as being low frequency tremors (LFTs). We show that events with and without the VLF signal likely represent the same phenomenon, and the VLF signal is only observed when a large magnitude event occurs near the station. The waveforms of VLFEs are characterized by the coexistence of long source duration and high-frequency radiation of signals, and such features were previously explained by the co-occurrence of shear failure and hydrofractures under the influence of fluid brought into the decollement zone. Our result indicates that the stress state and the mechanical environment, which promote the occurrence of VLFEs, exist not only along the decollement zone but also in the shallower part of the accretionary prism.

Keywords: Low frequency tremor, Very low frequency earthquake, Nankai trough, accretionary prism

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SCG62-P08 Room:Convention Hall Time:May 27 18:15-19:30

Low frequency earthquakes associated with a very low frequency earthquake in southern Ryukyu arc

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Southern Ryukyu arc is an island arc located at southeastern part of Eurasian Plate. Recent seismic and geodetic studies reported very low frequency (VLF) earthquakes near the Ryukyu trench (Ando et al. 2012) and slow-slip events beneath the islands in the southern Ryukyu arc (Heki and Kataoka, 2008). We have conducted seismic observation with 6 onshore stations and 30 ocean bottom seismograms (OBSs) to elucidate seismicity, lithospheric structure and seismic events associated with VLF earthquakes, as a part of "Research project for compound disaster mitigation on the great earthquakes and tsunamis around the Nankai trough region" funded by the Ministry of Education, Culture, Sports, Science, and Technology, Japan. Onshore stations are deployed at Miyako-jima, Tarama-jima, Ishigaki-jima, Iriomote-jima, Kuroshima, and Hateruma-jima islands. They are composed of broadband (STS-2) and/or short period (1Hz) seismometers. OBS equipped with 4.5Hz three component geophone were deployed around the onshore stations. When a VLF occurred at the southern Ryukyu arc during this observation, two different low-frequency events (events-A and B) are observed by several OBSs. Events-A were observed only at the beginning of the VLF event. They recurred at intervals of 100 - 120 sec for about 20 min. Predominant frequency of these events are less than 5Hz, and duration times of oscillation are about 60 sec. Events-B recurred for about 3 hours, and most of their duration times are longer than 100 sec. Predominant frequency is around 2~3Hz, and the amplitude at high frequency (>5Hz) are smaller than events-A. Spatial variations of amplitudes suggests that epicenters of Events-B would be located at north of Events-A. Hypocenters of Events-A were estimated by P- and S-wave arrival times of OBSs. The hypocenters were relocated at the southern end of the forearc basin, and their focal depths are about 15-20km. According to the seismic surveys in this area (Hsu et al. 2013; Arai et al. 2015, JpGU), these hypocenters are located near the plate boundary. In future, we will conduct envelope analysis with consideration of amplitude variation to clarify the detailed hypocenter locations.

Keywords: Low frequency earthquake, Ryukyu arc

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Development on a method for automatically detection and location of very low frequency earthquakes in Japan

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We have examined results of automatic detection and location of very low frequency earthquakes (VLFEs) in Ryukyu, southern Japan. In this system, three component seismograms recorded at the NIED F-net were analyzed by using waveform-correlation and back-projection techniques after processing a band-pass filter (0.02 to 0.05 Hz). Here we used known 6 VLFEs and 17 regular interplate earthquakes near the trench axis as template events. Time series of cross-correlation function (CC) at each station was calculated from continuous waveform data and triggered seismograms of template events. Assuming surface wave propagation, CCs are back-propagated onto possible origin times and horizontal locations. We obtained epicenters of VLFE candidates by performing a grid search in time and space domains to maximize the averaged CCs from all stations under the condition of high signal to noise ratios that was defined as amplitude ratios between two time windows before and after the surface wave arrivals from the VLFE candidates. We applied this method to the F-net data on November 29, 2014, when VLFEs occurred in Ryukyu, where only six stations are available for the analysis. Small number of stations easily causes errors in our detection and location of VLFEs probably due to aliasing in space domain. As the results of analysis, most of the VLFEs were detected and located off Ishigakijima Island. These epicenter locations are consistent with surface wave arrival from the VLFE candidates. However, some events were located between Okinawa Island and Miyakojima Island. This suggests that the present method needs additional development considering arrival times.

Keywords: very low frequency earthquake, automatic detection, automatic location

SCG62-P10 Room:Convention Hall Time:May 27 18:15-19:30

Detection and mechanism determination of VLF earthquakes in the Guerrero subduction zone

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Very Low Frequency (VLF) earthquakes have been observed with tremors in a few subduction zones suggesting a common source for the two phenomena. However to investigate more precisely the relation between these phenomena, VLF signal should be looked for in other subduction zones where tectonic tremor occurs. The Guerrero subduction zone is such an area where tremors have been consistently detected. Following the method of Ide and Yabe [2014], by stacking signals in the VLF band between 0.02-0.05 Hz at the time of occurrence of tremors, we confirm that VLF earthquakes are also observed.

MASE experiment data from 2005 to 2007 are used to determine the location of tremors and VLF earthquakes. They are found in two places tremors are detected, the southern transient cluster and the northern, more persistent, cluster. Both are located near the flat part of the subduction interface. This seems to confirm that VLF earthquakes are produced by shear failure near this interface. The VLF signals are then inverted to estimate the moment tensor of these events. Due to the linear geometry of the MASE experiment the mechanism is not well constrained but one of the nodal plane is generally nearly horizontal in accordance with the distinctive geometry of the subduction and the slip direction is globally coherent with the convergence direction. Moreover, the plunge of the P and T axis are well constrained with values of about 40 ^{o} adding a constraint on the principal stress directions.

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SCG62-P11 Room:Convention Hall Time:May 27 18:15-19:30

Broadband source spectrum of a slow slip event in the Cascadia subduction zone

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Slow earthquakes have been discovered in various time scales: non-volcanic tremor at high frequency range of 1-10 Hz, very low frequency earthquake (VLFE) at intermediate range of 10-100 s, and slow slip event (SSE) at geodetic time-scale longer than one day. Since these phenomena occur simultaneously, tremor and VLFEs can be regarded as the high frequency components of SSE. Based on this idea and to discuss the source time function of a SSE for the first time, we estimated source spectrum of Mw 6.8 episodic tremor and slip (ETS) event in the Cascadia subduction zone in 2010 from tremor band to the VLFE band. The source spectrum in the tremor band can be simply obtained by correcting the effect of attenuation and geometric spreading. The source spectrum in the VLFE band is more complicated because the signal-to-noise ratio is about one. We first improved the signal-to-noise ratio by stacking waveforms at a period range of 20-50 s with an assumption that the VLFEs coincide with peaks of tremor amplitudes. We then obtained source spectrum at 30-100 s by dividing the spectrum of stacked waveforms by the spectrum of synthetic waveforms corresponding to the obtained focal mechanism. The obtained source spectrum is proportional to inverse of frequency in both tremor and VLFE bands. In addition, the spectrum in both bands could be roughly fit by a synthetic source spectrum corresponding to a boxcar shaped source time function whose duration is about ten hours and the total moment release is Mw 6.8. The apparent duration of ten hours is shorter than the observed duration of the ETS, one month. This result indicates that the moment release during the one-month ETS consisted of slip pulses with typical durations shorter than a day.

Keywords: very low frequency earthquake, tremor, slow slip event, Cascadia

SCG62-P12 Room:Convention Hall Time:May 27 18:15-19:30

Basic study on detecting short-term SSE by using GPS and tiltmeter data

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We tried to detect short-term slow slip event by using both GPS and tiltmeter data. Detecting procedure for GPS-detecting is almost Nishimura's and titlmeter-detecting is similar to that of Kimura et al. However, we focus on spatial distribution of SSE.

Takeshi Kimura, Kazushige Obara, Hisanori Kimura and Hitoshi Hirose, Automated detection of slow slip events within the Nankai subduction zone, GEOPHYSICAL RESEARCH LETTERS, VOL.38, L01311, doi:10.1029/2010GL045899, 2011.

Takuya Nishimura, Takanori Matsuzawa, and Kazushige Obara, Detection of short-term slow slip events along the Nankai Trough, southwest Japan, using GNSS data, JOURNAL OF GEOPHISICAL RESEARCH: SOLID EARTH, VOL.118, 3112-3125, doi:10.1002/jgrb.50222, 2013.

Keywords: SSE, GPS, Tiltmeter, AIC

SCG62-P13 Room:Convention Hall Time:May 27 18:15-19:30

A test for detecting slow deformation around Japan based on seismicity data and statistical model

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Slow slips that occur at much slower slip rates than ordinary earthquake have been mainly detected by geodetic techniques such as GNSS. However, where there is no observation point in the vicinity of the source region or before dense GPS observation began, it is difficult to detect slow slips by the geodetic techniques. In this study, therefore, we apply the ETAS model (a type of statistical model) to the data of a seismic catalog, for detecting slow slips around Japan. Specifically, I focus on increase of values of a parameter called background seismicity rate after removing the effects of aftershocks. Results of the parameter estimation for known slow slip events showed that we can detect slow slips occurring over several days to weeks. Moreover, the results suggested that slow slip events around the north Izu-Ogasawara Trench and Kikai Island occurred, and slow deformation by a dike intrusion occurred around Mt. Fuji immediately after the 2011 Tohoku earthquake. In addition, around Okushiri island, Kikai island, Tanegashima island, and off Tohoku area, we possibly detect seismic quiescence or temporal attenuation of afterslip after large earthquakes.

Keywords: slow slip, ETAS model, earthquake activity, background seismicity rate

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Estimation of frictional parameters on the SSE fault throuth 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 frictional parameters on the fault related to SSE with GPS data through Ensemble Kalman filter (EnKF), a data assimilation method 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 velocity on the observation error. Then, we perform numerical experiments on estimation of frictional parameters through EnKF, verifying the estimated values and their errors.

In this paper, we focus on Yaeyama SSEs along the Ryukyu trench, southeast Japan. Around the Yaeyama islands, GPS observed southeast displacement related to SSEs recurrently. Heki and Kataoka (2008) reported the following features of Yaeyama SSEs; 1) there are few earthquake near affecting the SSE fault in the observation period ,2) SSEs recur on a plate interface at depths of 20-40km, 3) the average recurrence interval is 6.3 months, 4) its standard deviation is 1.2 months, 5) the slip rate released by SSEs is 11.0 cm/yr, in spite of the estimated convergence rate of 12.5 cm/yr.

We construct a simulation model which reproduces the above features of SSEs. 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 (Dietrich, 1979). 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 following Kato (2003). 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. We successfully reproduce the SSEs with the recurrence interval of about 6 months by setting a single asperity with the radius of about 30 km has frictional parameters of Vpl=12.5cm/yr, A=50 kPa, B=57.5kPa, and L=2.5 mm.

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 modifying the observations, simulated results and their variance-covariance matrix in a statistical way. The variance-covariance matrix are calculated by computing a lot of ensemble members which are generated by adding random numbers to initial values. As a first step, we generate the synthetic date as observed values by adding random noise to slip rate on the fault simulated on the above physical model and frictional parameters. Those parameters and calculated values are defined as true values on the experiments. We estimate slip rate, state variable and frictional parameters, A, A-B, and L thorough EnKF with the synthetic data and initial parameters with added offsets to true value, and verify the result by comparing the estimated values to true values.In this presentation, I show the verified result.

Keywords: slow slip events, Ensemble Kalman Filter

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Modeling various slow slip events along the Hikurangi subduction zone

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Recent high-resolution seismic and geodetic observations have revealed the occurrence of slow slip events (SSEs) along various subduction plate interfaces. Long-term SSEs with a duration of 1.5 years (e.g., Manawatu SSEs) occur at the deeper portion (25–60 km) of the Hikurangi subduction zone, and shallow (5–15 km) SSEs with a duration of 1–3 weeks occur along the northern and central parts of the subduction zone. Wallace et al. (2012) reported a sequence of simultaneous short-term and long-term SSEs at the Hikurangi subduction zone during 2010–2011.

We modeled short-term and long-term SSEs along the Hikurangi subduction zone using a rate- and state-dependent friction law and considered realistic configurations of the plate interface. We set the coupling region where a-b is negative based on the study of interseismic coupling by Wallace et al. (2009). By setting the effective stress and the critical displacement of shallow short-term SSEs to approximately 1.5 MPa and 2.4 mm, respectively, we could reproduce SSEs with a duration of 1–3 weeks and recurrence interval of 3 years. Additionally, by setting the effective stress and the critical displacement of the Manuatsu long-term SSEs to approximately 3.0 MPa and 7.2 mm, respectively, we were able to reproduce SSEs with a duration of 0.5 years and recurrence interval of 5 years. The effective stress of the Manawatu SSE zone is two times larger than that of the short-term SSE zones. However, the ratio of the effective stress to the critical displacement of the Manawatu SSE zone is smaller than that of the short-term SSE zones. We could also reproduce a sequence of simultaneous short-term SSEs and a long-term Manawatu SSE as observed by Wallace et al. (2009). The occurrence of the various slow slip events suggests heterogeneous distributions of constitutive law parameters along the Hikurangi subduction zone.

Keywords: modeling, slow slip events, Hikurangi subduction zone, a rate- and state-dependetn friction law, shallow short-term SSEs, Manuatsu long-term SSEs

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Earthquake cycles on the bumpy plate interface assuming subducting ridge chain : generation of SSE

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Recently the seismic and the geodetic observation networks have observed the slip events on the plate interface in subduction zones, in multiple scales in time and space. These slip events are densely distributed on the plate interface, and considered to interact to each other. And then, their interactions with large earthquakes are now starting to be investigated, using ECSs (Earthquake Cycls Simulations) (Ariyoshi et al., 2014; Matsuzawa et al., 2013).

When we consider the actual large earthquakes, the fault system such as the topography of the plate interface plays an important role on the occurrence of the earthquakes. However, the previous studies consider only the relatively large scale of the topography for the plate interface (e.g., Hirose and Maeda, 2013). In this study, we focus on the subducting ridge chains in Tokai regions, as the fault topography in the smaller scale. The ridge chain subducts under the Tokai region, central Japan. We can detect them in the bathymetry data (Hirose and Maeda, 2013). From the survey of velocity structure, we can also observe the ridges subduct with the oceanic plate (Kodaira et al., 2004). In the Tokai region, the next Tokai earthquake is anticipated to occur in the first half of this century. In the deeper part of the Tokai region, there have been observed also long-term slow slip events (SSEs) just beneath the Lake Hamana (Tokai SSEs). In this study, we set the bumpy plate interface assuming subducting ridge chain, and examined the slip cycles on the plate interface.

For ECSs, we often use the boundary integral elemental method and the quasi-dynamic scheme, which have smaller computational amount. Such ECSs always consider only the shear stress change but not the normal stress change due to the slip. However, the normal stress changes due to the slip on the fault interface when the fault interface is not flat but has topography. Therefore, in this study, we introduced the static normal stress change to the quasi-dynamic ECSs in BIEM, and examined the slip behaviors on the bumpy plate interface.

Now, as the fault, we set the flat plate interface of 200 km $\times$ 240 km for strike and dip directions, which subducts with the steady subducting velocity of 3.25 cm/year and the subducting angle of 15 degrees. We also set the bumpy plate interface as the fault, which has three bumps with the height of 5 km on the above flat plate interface. And then, we compare the earthquake cycles on the two plate interfaces to investigate the effect of the fault topography. We assume the laboratory derived rate- and state-friction law with the normal stress change (Linker and Dieterich, 1992). We set the uniform initial shear and normal stresses. The frictional parameters are set to be uniform at the region shallower than the depth of 40 km.

Then, even with the frictional condition that produces repeated normal earthquakes, the bumpy fault interface produced repeated slow slips and the earthquakes. A series of the tops and valleys of the ridges exhibit the increase and decrease in the normal stress during the interseismic period. This striped normal stress change can be the cause for recurring slow slip events around the valley of the ridge chain, because the change in the normal stress leads to the change in the friction. The Tokai SSEs are observed at the valley of the ridges. This study shows that the fault geometry can be one of the mechanism of generating the Tokai SSEs, in addition to the existence of high pore pressure.

Keywords: earthquake cycle simulation, normal stress, ridge chain, Tokai SSE

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Simulation of slow earthquakes affected by tide

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Slow earthquakes occur at the deeper extension from the seismogenic zone along subducting plate interfaces and may affect occurrence of large earthquakes. Therefore, it is important to understand the physical mechanism of slow earthquakes. On the other hand, the tides are one of important factors that affect slow earthquakes and possibly large earthquakes suggested by Tanaka[2012], who found increasing tidal sensitivity of seismicity toward a large earthquake.

In order to investigate quantitatively the influence of the tides on the recurrence process of earthquakes, we develop a physical model of slow earthquakes with the tidal effects.

In the primary model, we considered a 2-D fault embedded in the elastic half-space, mimicking as a subduction plate boundary. We divide the fault into the shallower coupling area and the deeper decoupling area. The coupling area has a frictional strength obeying the slip weakening law, associated with the velocity strengthening term to simulate slow slip events. The decoupling area obeys monotonic velocity strength, exhibiting steady slip by the tectonic loading and tidal stresses. We consider the following two cases in the tidal stresses: the simplified sinusoidal function that has the constant amplitude and the period, and the realistic case, in which we calculated the amplitude and the phases along the upper boundary of the subducting Philippine Sea plate in western Shikoku area. Both of the Earth and ocean tides are considered. The tectonic loading is assumed as the back slip model. We employ quasi-dynamic boundary element method for the numerical simulations.

As the results, we found that the tides actually modulate the timing of the slow earthquake occurrence. The migration velocity might also be modulated by tides. In addition, we confirmed that slow ”pre-slip” events occur in the small area at the bottom of the coupling area before large slip events, and they are modulated by the tides. The tides also seem to control the stoppage of slip events and further affect the distribution of the residual stress.

Keywords: slow earthquake, tide, source migration