Japan Geoscience Union Meeting 2014
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SCG64-01 Room:501 Time:April 30 11:00-11:15

Spatial and temporal evolution of slip and seismicity during the 2013-2014 Boso slow slip event

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GPS time series data show that transient crustal deformation has been occurring in the Boso peninsula, central Japan, since December 2013. Observed spatial and temporal patterns of surface displacements suggest the occurrence of transient aseismic slip on the subducting Philippine Sea plate. In addition, an increased rate of seismicity was observed from 31 December 2013 to 9 January 2014 off the east coast of the Boso peninsula. The location of the increased seismicity partly overlaps with the areas of seismic activity during the past Boso slow slip events.

To estimate spatial and temporal evolution of aseismic slip, we use GPS data from 71 stations of the GEONET in the Kanto region and data from 6 stations located along the east coast of the Boso peninsula, which are operated by Earthquake Research Institute of University of Tokyo and Tohoku University. The data are analyzed with GIPSY-OASIS II software to obtain daily coordinate time series at the 77 stations. Secular velocities, seasonal variations, and postseismic deformation following the 2011 Tohoku-oki earthquake are removed from the time series. We use a modified version of the Network Inversion Filter to estimate spatial and temporal evolution of daily cumulative slip and slip rate on the Philippine Sea plate. Slip slowly started around 20 December 2013 off the east coast of the Boso peninsula and then slip rapidly accelerated around 28 December and propagated to the west. Slip continued to accelerate until 3 January and then rapidly decelerated until 9 January.

To investigate spatial and temporal correlation of slip and seismicity, we use a matched-filter technique to detect earthquakes in the area of increased seismic activity. The detected earthquakes are located along the northern edge of the large aseismic slip and migrated from east to west during the period of rapid aseismic slip (31 December to 9 January). This migration pattern is consistent with the propagation of rapid aseismic slip, suggesting that the earthquakes are triggered by stress loading due to the propagation of aseismic slip. We do not identify significant seismic activity before 28 December, indicating that the slow slip event started well before the initiation of the seismic activity.

Keywords: slow slip event, seismic activity, GPS

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A slow slip event near the Boso Peninsula immediately triggered by the 2011 Tohoku-Oki earthquake

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It has been recognized that a series of slow slip events, accompanying with ordinary earthquakes, take place with recurrence intervals from 5 to 7 years near the Boso Peninsula along the plate interface of the subducting Philippine Sea plate [e.g., Hirose et al., 2012]. Immediately after the 2011 Tohoku-oki earthquake, intensive afterslip have been detected to start along the plate interface of the Pacific plate from off Tohoku region to southward Kanto region [e.g., Munekane et al., 2012; Fukuda et al., 2013]. It is well known that both the Pacific and the Philippine Sea plates are subducting beneath the Kanto region, and interacting with each other. Therefore, it is expected that the Philippine Sea plate might be dragged by the speeding Pacific plate during the intensive afterslip. We hypothesize that the dragging of the Philippine Sea plate by the Pacific plate leads to triggering of a slow slip event near the Boso Peninsula immediately after the Tohoku-Oki earthquake.

In order to verify the above hypothesis, we analyzed the seismicity including small repeating earthquakes, applying the matched filter technique to continuous waveforms. We used all available earthquakes associated with three sequences of slow slip events in 2007, 2011, and 2014 as template events. Then, we searched for events those have similar waveforms to ones of each template event from continuous waveforms. Based on the new earthquake catalog, we found out an abrupt increase in the swarm-like seismicity at the slow slip source area from March 12 to 14, 2011. In addition, some repeating earthquakes were extracted in the swarm, indicating aseismic slip transient. We, thus, interpret that the seismic swarm were linked to a newly detected slow slip event, which has not been previously recognized. However, based on the amount of aseismic slip deduced from the repeating earthquakes, moment released by the slow slip event is estimated to be smaller that by previously recognized slow slip events. We thus conclude that a small slow slip event might be triggered through the dragging of the Philippine Sea plate by the Pacific plate immediately after the Tohoku-Oki earthquake.

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG64-03 Room:501 Time:April 30 11:30-11:45

Tidal correlations of earthquake swarms associated with slow slip events off Boso Peninsula

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We investigated statistical correlations between Earth tides and earthquakes in the four swarms associated with slow slip events (SSEs) off Boso Peninsula in 2002, 2007, 2011, and 2014. Following Hirose et al. (2012), we selected the SSE-related events from the Hi-net earthquake catalog. For each event, we assigned the tidal phase angle at the origin time by theoretically calculating tidal Coulomb failure stresses with a frictional coefficient of 0.2. For the fault plane, we assumed a landward-dipping reverse fault from the F-net moment tensor solution of the largest earthquake (Mw 4.9) in the 2014 swarm. Based on the distribution of tidal phase angles, we statistically tested whether they concentrate near some particular angle or not by using the Schuster test. In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the earthquakes occur randomly irrespective of the tidal phase angle. The result of analysis shows the 2014 swarm was strongly correlated with tidally-induced stresses ($p = 0.01\%$). The distribution of tidal phase angles exhibited a peak near the angle 0, which corresponds to the time of the maximum tidal stress promoting fault slip. We suggest that tidal stress fluctuations can trigger earthquakes when superimposed on stress buildup caused by nearby slow slip. On the other hand, the other three swarms show insignificant correlations with tides. The resultant p-values are 87%, 16%, and 14% for the 2002, 2007, and 2011 activities, respectively. Geodetic observations indicate larger slow slip in these three episodes than in 2014 (Hirose et al., 2013; Kimura, 2014). It is highly likely that the swarm earthquakes in those activities were fully triggered by stress perturbations imparted by large slow slip. Tides appear to have exerted little or no influence on triggering in that case.

Keywords: Boso Peninsula slow slip events, Earth tides, earthquake triggering

SCG64-04 Room:501 Time:April 30 11:45-12:00

Interplate coupling and SSE in the Tokai region after 1981 using leveling data

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The long-term SSE in the Tokai region, central Japan, from mid-2000 to mid-2005 [Suito and Ozawa (2009)], had continued five years, which was much longer than other SSEs around the world [e.g. Schwartz and Rokosky (2007)]. After the termination of the SSE in 2005, no obvious long-term SSE has been detected and that makes difficult to discuss a recurrence interval of the events. In order to reveal whether the event repeats or not, and if it repeats, in order to clarify the interval and a temporal and spatial change of the interplate coupling and the slow slip, I analyzed a leveling data before the era of GEONET.

Various types of geodetic observations have been conducted in the Tokai region and there are some previous works about the temporal change of the crustal deformation using the data of these observations. For example, Kimata and Yamauchi (1998) analyzed EDM data and Kobayashi and Yoshida (2004) analyzed tidal data to detect irregular feature in the crustal deformation. In this study, I analyzed leveling data in the Tokai region from 1981 to 1999 and reveal spatially the temporal change of the vertical deformation velocity. Leveling observations have been conducted four times a year along the route from Kakegawa City to the Omaezaki Cape and once a year along the others around the Omaezaki Cape. I used all the data from these observations and inferred two-year-averaged vertical deformation rate using the time-dependent network adjustment [Fujii (1991)]. The estimated error of the rate is about 2 mm/yr, which is twice as much as the error of GNSS vertical data in this region [Ochi and Kato (2013)]. Comparing with the other geodetic data, the biggest advantage of the leveling data is that it can produce a spatial view of the crustal deformation with small error.

From the results of the analysis, two patterns of the crustal deformation that may correspond to existence and non-existence of the SSE appear alternately. The pattern that resembles that of in the 2000-05 was detected around 1982-83, 1988-90 and 1997. The duration of the event in 1982-83 is shorter than that of 1988-90, which is again shorter than that of 2000. Summing up these results, it is clear that there are various durations in the SSEs. In addition, if the small event in 1997 is taken into account, small and large events occur alternately and the intervals after the large event may tend to get longer. However, as the 1997 event is temporally close to the large long-term SSE after 2000, the SSE would affect the analysis of 1997 data and it should be considered further.

I also inferred the temporal change of the interplate coupling and slow slip using the results. In order to overcome the lack of temporal resolution, I fixed the distribution center of the slow slip to the same place by the results by Ochi and Kato (2013), the northwestern part of the Lake Hamana with the depth around 30-40 km. According to the forward modeling, the pattern of the crustal deformation in the 1982-83 and 1988-90 require somewhat smaller amount of SSE. On the other hand, the interplate coupling beneath the Omaezaki Cape constantly continues whether the SSE occurs or not.

Keywords: leveling data, interplate coupling, slow slip event, the Tokai region

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SCG64-05 Room:501 Time:April 30 12:00-12:15

A shallow slow-slip-event in northern Hokkaido in 2012-2013: An event triggered by seismic waves.

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GNSS (Global Navigation Satellite System), as represented by GPS (Global Positioning System), enabled us to study SSE (Slow Slip Event), slow displacement of fault without exciting seismic waves. In this study, we report that baseline length between the Horonobe and the Nakatombetsu GNSS stations (part of the GEONET, GNSS Earth Observation Network) in Northern Hokkaido, shortened by ~2 cm over 4-5 months period from 2012 summer to the early 2013. We assumed that an SSE is responsible for this change, and inferred fault parameters of this unique SSE. There have been lots of reports on repeating SSE at plate boundaries, e.g. off the Boso Peninsula, the Nankai Trough, and the Ryukyu Trench. In the Northern Hokkaido, a block boundary is considered to run north-south (Loveless and Meade, 2010) with the convergence rate of about 1 cm/year. This shallow SSE we report here is considered to have occurred at this boundary.

At first, we analyzed time series of the distance change between Horonobe and Nakatombetsu, together with a few additional GNSS stations nearby and estimated the fault parameters of this SSE by grid searches. The estimated slip was about 10 cm (Mw was ~5.9), which suggests that a similar SSE recurs every decade. However, these GNSS stations started in 2002, and we do not have information on the previous SSE. We modeled the time series using lines with two breaks, and we constrained the onset time and the ending time of the SSE by minimizing the root-mean-square of the post-fit residuals. The optimal onset and termination was 2012.64 and 2013.08, respectively. Around the onset time, there was a deep earthquake beneath Sakhalin (M7.7) on August 14, 2012, and there were four M4 class earthquakes close to the Horonobe station in July, 2012. Seismic waves generated by these earthquakes may have triggered this SSE. At the termination time, there was an M4.8 earthquake on 3 Jan. 2013 at the depth of 24 km on the westward extension of the SSE fault. From mechanical point of view, it is difficult to consider that this earthquake encouraged the termination of SSE.

Keywords: GPS, Slow Slip Event, Northern Hokkaido, seismic waves

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(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG64-06 Room:501 Time:April 30 12:15-12:30

Seismicity and pressure changes observed around DONET at the same time

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The Philippine Sea plate is subducting to northwest below the Eurasian plate along the Nankai trough in southwestern Japan at a convergence rate of about 65 mm/year. In this region mega-thrust earthquakes have repeatedly occurred along the Nankai trough and caused serious and widespread damages in central and western Japan. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) installed permanent ocean bottom observation stations named as Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) off the Kii Peninsula to monitor earthquakes and tsunamis and to decrease damage due to those. Because several kinds of continuous data have sent to JAMSTEC in real time, we can discuss continuous seismicity and other seismic/geodetic information. It is important for considering occurrence of large earthquakes to judge seismicity of small earthquake and to monitor crustal deformation.

Suzuki et al. (2013) has reported that quiescence of seismicity and ocean bottom pressure changes around DONET have occurred almost at same time from Feb. 2013 to Sep. 2013. In this study we extended observational period until Jan. 2014. As a result of investigation by using similar method with Suzuki et al. (2013), these changes seem to have continued after Sep. 2013. Quiescence of seismicity has not finished yet; seismicity is lower than one predicted from ETAS model (Ogata, 1989) represented by five parameters fitted by using data between 2012. Although pressure changes have been observed at only three stations (KMB05, KMB06 and KMB07) on Sep. 2013, pressure change at KMB08 was also observed on extended time series in addition to the three stations. We will try to estimate fault slip model that can cause these pressure changes and investigate how that fault slip influence to seismicity.

Keywords: seismicity, ocean bottom pressure gauge, DONET, ETAS model

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Detection of short-term slow slip events along the Nankai Trough by observations of groundwater level or pressure

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Non-volcanic deep low-frequency (DLF) tremors are detected on plate boundaries along many subduction zones around the world [Obara,2002; Ide, 2012]. Short-term slow slip events (S-SSEs), which cause small crustal deformation with no usual seismic waves, are also detected in subduction zones [Rogers and Dragert, 2003; Schwartz and Rokosky, 2007; Sekine et al., 2010]. There is a close spatial and temporal correlation between DLF tremors and S-SSEs. However, S-SSEs do not always occur in areas where DLF tremors occur and vice versa. Therefore, it is important to clarify the detailed spatial and temporal correlations in order to know what occurs on the plate boundaries along subduction zones. In general, detecting S-SSEs via crustal deformation is more difficult than with DLF tremors when using a seismograph. One major reason for this is that the decay of crustal deformation by distance is much larger than that of seismic waves. Therefore, it is necessary to develop new tools or techniques to detect S-SSEs. For this purpose, we attempted to detect S-SSEs in the Nankai Trough, Japan by conducting groundwater pressure observations at ANO station in Mie Prefecture, Japan. The ANO is a groundwater observation station operated by the Geological Survey of Japan, AIST, for earthquake prediction research. The groundwater pressures changed due to six S-SSEs that occurred near ANO from June 2011 to April in 2013. The fault models of these S-SSEs, which were estimated mainly by observing the crustal strains and tilts, explained the changes in the groundwater pressures. We also considered the conditions for detecting S-SSEs via groundwater observations. The volumetric strain changes caused by the S-SSEs along the Nankai Trough were 10-20 nstrain/day at most [Kobayashi et al., 2006], where nstrain means 10^{-9} strain. Therefore, the strain-converted noise level should be 5 nstrain/day or smaller to detect the S-SSEs. Taking the actual conditions of groundwater observation into consideration, it is necessary that the noise level should be smaller than 50 mm/day and that the strain sensitivity of the groundwater pressure or level should be larger than 1 mm/nstrain for the required strain-converted noise level.

Keywords: Slow slip event, Deep low-frequency tremor, Groundwater, Poroelastic theory, Strain, Earthquake forecast

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG64-08 Room:501 Time:April 30 14:15-14:30

Time evolution of non-volcanic tremor episode

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Non-volcanic tremor in subduction zones like as Nankai is one of slow earthquake phenomena in the transition zone between the seismogenic zone and the stable sliding zone on the subducting plate interface (Obara, 2002). Major tremor episodes with duration longer than several days are always accompanied by short-term slow slip events (SSEs). The space-time correlation of tremor and SSE suggests that the time evolution of tremor episode reflects the rupture process of SSE. Based on the similarity, studying the mechanism of slow earthquakes is important to understand the activity style of megathrust earthquake. Therefore, we investigate the time evolution of tremor episode based on the clustering catalog (Maeda and Obara, 2009, Obara et al., 2010) because the tremor is well-detected compared to other slow earthquakes.

Tremor belt-like zone is divided into some segments based on their spatial extent and recurrence interval (Obara, 2010). Each segment includes some sub-segment as units of tremor activity (Obara et al., 2013). Tremor episode usually initiates from the deeper part of the tremor belt-like zone. If the episode reaches to the updip part of the tremor zone, it becomes a major episode associated with detectable SSE (Obara et al., 2011). We sometimes observe major episodes initiated from the shallower part. The time evolution of tremor energy at the beginning stage of the tremor episode depends on the location of initiation point. If the episode starts from the deeper part, the evolution velocity is small for a while then increases rapidly after the tremor migration front reaches to the updip edge. On the other hand, the evolution velocity is high if the episode starts from the shallower part. This suggests that the tremor patches radiating high energy concentrate at the updip side. The time evolution of tremor energy at the beginning stage of each episode is not related to the final size of the episode. The size of episode may be controlled by the strain energy accumulation at each portion on the way of migration. This is the same for along-strike evolution of tremor episode. The propagation of tremor episode depends on the slip deficit in each sub-segment ahead of the rupturing sub-segment. We observed temporal deceleration of migration speed in front of the small gap as the sub-segment boundary. On the other hand, we detect acceleration of the migration speed at a common spot during passage of the major tremor episode several times. This spot is considered as a sweet spot where tiny tremor activity continuously occurs in the shallower part of the tremor zone. This spot frequently generates tremor episodes and is considered to be strongly inhomogeneous. Such variation on the plate interface may control the rupture process of SSE.

Keywords: non-volcanic tremor, slow earthquake, source migration, segmentation

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(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

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Fundamental properties of non-volcanic low frequency tremor catalogues

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Since a discovery of non-volcanic low frequency tremor (NVT) in the subduction zone of southwest Japan (Obara, Science, 2002), the NVT has been found in various subduction zones or bottom of faults all over the world, and has been studied by many researchers. In these studies, an envelope cross-correlation technique for NVT detection and making a catalogue of NVT is important to discuss spatial and temporal activity of NVTs (e.g.; Maeda & Obara, JGR, 2009; Ide, Nature, 2010; Nakata et al., Nature Geoscience, 2008; Imanishi et al., GRL, 2011). There are some differences in NVT catalogues in the same region, since each study developed an original program for NVT catalogue. Furthermore, in some cases, even if they use a same program, parameters to detect NVT in the program were changed depending on a scope of the study. Consequently, there are some different features of NVT activity between the catalogues. In this report, we compare three catalogues, made by Japan Meteorological Agency (JMA), National Research Institute for Earth Science and Disaster Prevention (NIED) and Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), regarding a resolution of location and a NVT scale-sensitivity property as fundamental properties of the NVT catalogue.

Based on the method to estimate the resolution of location from a standard deviation of relative location (Ide, Nature, 2010), we calculated the resolution of location in each catalogue using several standard deviations of relative location. The estimated epicentral resolutions in three catalogues are almost 2-3km.

The NVT scale-sensitivity was estimated by a ratio of NVT counts in catalogues. For example, the sensitivity of the NIED catalogue for magnitude (M) based on the JMA catalogue was defined as $N_{nied-jma}(M)/N_{jma}(M)$. Here, $N_{jma}(M)$ is total counts of low frequency earthquakes (LFEs) with M listed in the JMA catalogue, and $N_{nied-jma}(M)$ is total counts of NVT in the NIED catalogue which is also listed in the JMA catalogue. To examine the relationship between the scale and the sensitivity in the catalogues, we used magnitude and NVT energy as the scale in the JMA and the other catalogues, respectively. By comparison of the NVT scale-sensitivity properties, it is found that these catalogues have characteristic scales in the sensitivity. Furthermore, the sensitivities of all catalogues decrease for large scale NVT. This is attributed to the increase of lost counts due to complex waveforms of highly active NVT. In our presentation, we show some examples of different features of NVT activities arising from different scale-sensitivity properties.

We conclude that these fundamental properties are useful not only for a comparison of catalogues, but also for an optimization of parameters in the programs of NVT detection.

Acknowledgments: We use the earthquake catalogue reported by JMA, and seismic waveform data provided by NIED (Hi-net), AIST, JMA, University of Tokyo, Kyoto University, Kyushu University, Kochi University, and Nagoya University.

Keywords: non-volcanic low frequency tremor, catalogue, position resolution, NVT scale-sensitivity property

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(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

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Determination of focal mechanisms of non-volcanic tremors using S-wave polarization: Correction for shear wave splitting

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Non-volcanic tremors (NVTs) have been found at various plate boundaries during the last decade. Focal mechanisms of NVTs are important for better understanding physical mechanisms of tremor generation. Stacking of many similar event waveforms greatly enhances the signal to noise ratio of tremor signals, which enables us to use conventional focal mechanism determination methods based on P-wave first motion polarities and/or waveforms (Ide et al., 2007; Bostok et al., 2013). However, the stacking approach cannot resolve spatio-temporal variations of focal mechanisms, so a new method is needed.

Imanishi and Takeda (2010) conducted a polarization analysis to continuous seismic data and showed that the scatter in the particle motion directions becomes small in accordance with a period of NVT activity. The same conclusion was reported for Cascadia tremors by Bostock and Christensen (2012). Because NVTs are primarily composed of shear waves (e.g., Obara, 2002), our observed particle motions contain information regarding focal mechanisms. However, the shear wave particle motion should be treated in caution, since shear-wave splitting may distort the particle motion excited by a seismic source (e.g., Zhang and Schwartz, 1994).

In this study, we first explored the existence of seismic anisotropy using tremor signals. A standard shear-wave splitting analysis (Silver and Chan, 1991) was used to determine the fast polarization direction (LSPD) and the lag time between fast and slow shear waves (DT). The analysis detected clear split arrivals separated by about 0.1 s, indicating the need of the correction for splitting effects to recover radiation pattern of S-wave. The LSPD shows two major directions which are normal or subparallel to the strike of the plate margin. These results are consistent with previous studies using regular earthquakes (e.g., Saiga et al., 2011), demonstrating that tremor signals are also available to investigate seismic anisotropy.

We then determined focal mechanisms of NVTs by correcting for splitting effects on particle motions. The actual procedure is as follows:

(1) We rotate two horizontal seismograms to the fast and slow directions, advance the slow wave by the lag time, and rotate back to NS and EW directions.

(2) A polarization analysis is subject to 1 minute windows to determine S-wave polarization angles.

(3) Average and standard deviation of polarization angles are calculated at each hour.

(4) A grid search approach is performed at each hour to determine the best double-couple solution using polarization angles of multiple stations. Here the epicenter is determined by an average of locations using our ECM catalogue. The depth is assumed to be 35 km.

(5)Uncertainty is estimated based on a bootstrap approach.

We applied the above method to a tremor sequence at northern Mie prefecture that occurred at the beginning of April 2013. Most solutions show NW-dipping low-angle planes or SE-dipping high-angle planes. Because of 180 degrees ambiguity in polarization angles, the present study alone cannot distinguish compressional quadrant from dilatational one. Together with the observation of very long frequency earthquakes near the present study area (Ito et al., 2007), however, it is reasonable to consider that they represent shear slip on low-angle thrust faults. It is also noted that some of focal mechanism solutions contain large strike-slip component. We will present the spatial and temporal characteristics of focal mechanism solutions based on the analysis of more tremor sequences.

Acknowledgements: Seismograph stations used in this study include permanent stations operated by NIED (Hi-net), JMA, and Earthquake Research Institute. This work was supported by JSPS KAKENHI Grant Number 24540463.

Keywords: Non-volcanic tremors, Focal mechanism, Polarization analysis, Shear wave splitting

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SCG64-11 Room:501 Time:April 30 15:00-15:15

Improved estimation of seismic energy radiation from deep low-frequency tremor

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Deep low-frequency tremor occurs associated with slow slip event on the subducting plate interface at the downdip part of the megathrust seismogenic zone. Studying these phenomena is considered to play an important role to understand the mechanism of the megathrust earthquake. Until now, spatio-temporal distribution of tremor has been well investigated to get a whole picture of tremor activity. In this paper, we proposed a method for assessing energy radiation of tremor more quantitatively.

The Hybrid Method (HM) [Maeda and Obara, 2009] is a technique which determines epicenter and seismic energy of tremor simultaneously by using relative arrival time and amplitude distribution of the tremor envelope. To avoid false event detection, the " HM selected catalog " constructed with a threshold of a high Variance Reduction (VR>90) has been used for tremor study. However, when tremor activity is very high, envelope correlation between stations is relatively poor because of complicated waveforms. Then the VR generally becomes low and some parts of tremor during the active stage are not included in the HM selected catalog [Takeda et al., 2014]. Therefore, in order to investigate the energy release of tremor activity precisely, we have to re-evaluate it by using the waveform data.

Here, we developed a method for estimation of tremor energy by using measurement of tremor duration time from envelope waveform and the HM catalog. We started to search the duration around an origin time of tremor in the HM selected catalog. Then we determined the tremor duration when the amplitude is higher than noise level at each station simultaneously. At each tremor duration, we determined epicenter using centroid location of hypocenters of HM selected catalog within corresponding time and determined energy radiation by summing up of energy of tremor epicenters with VR of larger than 60.

As a result, we found characteristic spatial distribution of energy. It has been already known that there are two peaks of the number of tremors in the dip direction [Obara et al., 2010]. In this study, we found that high-energy region is distributed in the shallower part of the source area of tremor along the strike of the subducting Philippine Sea plate. This biased distribution of high-energy radiation suggests that the shallower part is more brittle in the brittle-ductile transition zone where tremor occurs. This brittle part may radiate higher seismic energy when shear slip occurs. This research will lead to quantitative assessment of the role of tremor in the stress relaxation process in the subduction zone.

Keywords: tremor, Nankai trough, slow earthquake

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The role of tectonic tremor in slow earthquake

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Since the discovery of the slow earthquake, tectonic tremors, very low frequency earthquakes (VLFs), and slow slip events (SSEs) are thought to have close relation. Although the tremor activity is often regarded as a proxy of SSEs, the degree of proximity is yet unclear due to the lack of detailed quantitative comparison between them, especially for tectonic tremors. Here, we develop a method to estimate the seismic energy of tremors and apply it to tremors in four subduction zones (Nankai, Japan; Cascadia, USA-Canada; Jalisco, Mexico; South Chile). This method estimates the seismic energy of tremors, after evaluating the regionally averaged seismic attenuation and the site amplification factors, which has not been considered enough in previous studies estimating the seismic energy of tectonic tremors. Then the catalog of the energy rate, which is the seismic energy divided by the tremor duration, is compared with some characteristics of tremors, VLFs, and SSEs.

We have observed three types of spatial distributions in terms of energy rate; heterogeneous, homogeneous, and isolated. In regions where the energy rate is heterogeneously distributed on the plate interface, such as Nankai and northern Cascadia, tremor activities almost always initiate from where the energy rate is low. Sometimes the initial tremors trigger more energetic tremors nearby, which are further followed by a long-distance tremor migration along the strike of the subducting plate. These energetic tremors tend to have longer recurrence intervals, and seem to control the onset of a large-scale tremor migration, which probably corresponds to a SSE. In Nankai, the energy rate of tremors estimated between 2-8 Hz is large where VLFs have been detected in the frequency range of 0.02-0.05 Hz. These observations suggest that the characteristics of tremors are regionally various, but similar in different frequency ranges. In the region where tremor activities are isolated, such as East Shikoku, Jalisco and South Chile, each tremor activity has occurred independently, and the relations between the energy rate and the recurrence intervals cannot be seen. In the region where the energy rate is homogeneously distributed on the plate interface, such as a part of southern Cascadia, tremor activities have occurred spontaneously in the entire tremor zone.

Our observation suggests a possibility that the spatial distribution of the energy rate of tectonic tremors might control the behavior of slow earthquakes in the region. When the energy rate is distributed heterogeneously, some energetic tremors seem to control the activity of SSEs, as a switch that ignites a large-scale migration. When tremor patches are isolated, they are passively controlled by the tectonic loading. When it is homogeneously distributed, minor tremor activities, which rupture the only part of the tremor zone, cannot occur.

Keywords: Slow Earthquake, Tectonic Tremors, Seismic wave energy

SCG64-13 Room:501 Time:April 30 15:30-15:45

Effect of long-term SSE and megathrust earthquake on tremor activity

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Tremor activity migrates with a velocity of $\sim$10 km/day along the strike of subducting plate boundary. Recently it has been shown that migration front draws a parabolic pattern in spatio-temporal distribution of tremors, indicating that tremor migration is diffusional process [Ide 2010]. We analyzed activities from 2001 to 2013 in western Shikoku, and obtained diffusion coefficients on the order of 10^4 m^2/s for all the activities. Relatively large values ($>1.5\times10^4$ m^2/s) were obtained for the activities during long-term slow slip events (SSEs) in the Bungo Channel region or just after the 2011 Tohoku earthquake (SSJ2013). In this study we investigate the relation between these activiteis and external stress perturbations.

To evaluate perturbations due to these events, we calculated Coulomb stress changes (ΔCFF) using Coulomb 3.3 [Toda et al. 2011]. The long-term SSEs in 2003 and 2010 produced ΔCFF of 28.7 and 5.4 kPa, respectively. These values are large enough to affect tremor occurrences because they are on the same order of magnitude as the tidal effect, which modulates tremor occurrences. The Tohoku earthquake produced ΔCFF of 0.4 kPa. Although it is smaller than the tidal effect by an order, a long-time stress change due to possible viscoelastic response would give some effect on tremor occurrences. Since such a stress perturbation is widespread on the plate interface, it could accelerate tremor migration observed as high diffusion coefficient. We also compare tremor activities with the seismicity calculated with a rate- and state-dependent friction law.

Keywords: deep non-volcanic tremor, tremor migration, Coulomb stress change, long-term slow slip event, megathrust earthquake, subduction zone

Japan Geoscience Union Meeting 2014
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SCG64-14 Room:501 Time:April 30 15:45-16:00

Improvement of tectonic tremor detecting and locating methods: Case study in Shikoku and Kanto

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Obtaining accurate tremor sources in time and space is important because it provides essential information that reveals the mechanism of tremor activity. Recent findings of triggered tectonic tremor in recently discovered regions in Hokkaido (Obara, GRL, 2012), Kyushu, and Kanto (Chao and Obara, AGU Meeting, 2012) provide an ideal dataset with which we can test the clock-advanced model, which predicts the occurrence of triggered tremor in regions where ambient tremor occurs. In this study, we improve upon two existing tremor detecting and locating methods: 1) the WECC (Waveform Envelope Correlation and Clustering) auto-detecting algorithm (Wech and Creager, GRL, 2008), which auto-detects tremor episodes, and 2) the improved conventional envelope cross-correlation technique (Obara, Science, 2002; Chao et al., BSSA, 2013), which accurately pinpoints the locations of short duration tremor sources in space. Using WECC, we detected tremor episodes in western Shikoku and compared the results with existing NIED tremor catalogs (Maeda and Obara, JGR 2009; Obara et al., GRL, 2010). Our preliminary results indicate that during testing period (i.e., tremor episodes between 2012/05/25 and 2012/06/02), the WECC was able to successfully auto-detect the same ambient tremor episodes listed in the NIED tremor catalogs. The tremor detections by WECC show similar tremor migrations pattern as the features from the NIED tremor catalog. In addition, the WECC is able to capture more small tremor episodes that are not included in the NIED catalog. Our next step will be to apply the WECC to the entire dataset to determine whether it can successfully detect all tremor episodes while minimizing noise. Using the modified envelope cross-correlation technique, we plan to conduct a 3D grid search to locate accurate triggered tremor sources in Kanto following several teleseismic earthquakes. This modified technique has been used to locate micro-earthquakes ($M<=0.5$) in western Shikoku, and a comparison of the hypocenter of these micro-earthquakes with those from the JMA earthquake catalog showed that they were located within 5km of one another.

Keywords: ambient tremor, Shikoku, Kanto, tremor auto-detection technique

SCG64-15 Room:501 Time:April 30 16:15-16:30

Volcanic Deep Low-Frequency Earthquakes and Cooling Magma

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Deep low-frequency earthquakes (LFEs) are deep earthquakes that radiate low-frequency seismic waves. While tectonic LFEs on plate boundaries are thought to be slip events, the physical mechanism of volcanic LFEs around the Moho beneath volcanoes is not well understood. For initial brittle failure to be produced at these temperature-pressure conditions, high strain rates should exist there.

Since an ascending magma diapir tends to stagnate near the Moho, where there is a density discontinuity, we suspect its thermal contraction acts as a driving force of volcanic LFEs. In the present study, we estimated thermal strain rates caused by a cooling magma near the Moho beneath volcanoes.

We calculated thermal evolution after an initial perturbation of 400K uniformly within planar and cylindrical magma intrusions. Then, we estimated thermal strain rates within the region of δT $<$200K, where the medium can be treated as a Poissonian elastic body. We assume a thermal diffusivity of 6×10^{-7}m^2/s and a thermal expansion coefficient of 2×10^{-5}/K, taking into account latent heat release and the density change caused by a phase change of partially molten material.

As a result, strain rates larger than the effect of tectonic loading ($>5\times10^{-14}$/s) is observed for planar magmas of width of $<$200m and cylindrical magmas of radius of $<$160m. Even if the initial crack were not observed because of small amplitude and high attenuation, an exited larger-scale deformation such as a resonance would be observed as an LFE.

The orientation of produced strain rates differs between planar intrusions and cylindrical intrusions. Assuming that magma shape and strain rate correspond to source distribution and source mechanism, respectively, we expect a correlation between source distribution and source mechanism for volcanic LFEs. Although a part of this relationship has been recognized for the LFEs in eastern Shimane in western Japan [Aso and Ide, 2014], more mechanism analyses are needed to verify our model.

Keywords: volcanic low-frequency earthquakes, cooling magma, CLVD

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SCG64-16 Room:501 Time:April 30 16:30-16:45

Spatiotemporal Distribution of Shallow Very Low Frequency Earthquakes along the Nankai Trough and the Ryukyu Trench

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We have investigated spatiotemporal distribution of shallow very low frequency earthquakes (sVLFEs) along the Nankai trough and the Ryukyu trench. Three component seismograms recorded at 40 broadband stations of 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 sVLFEs 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 sVLFE epicenters 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 epicenters. As the result of this analysis for the last decade, we detected infrequent activity of sVLFE episodes at a few clusters adjacent to the locked zone related to the megathrust earthquakes along Nankai trough: in 2004 and 2009 of Kii peninsula, in 2003 and 2009 off cape Muroto, and in 2003 and 2010 off cape Ashizuri. On the other hand, sVLFE episodes in Hyuga-nada and areas along the Ryukyu trench are frequent. Such a variation of seismicity of sVLFEs revealed from this study based on the same detection capability may suggest the difference of the plate coupling in the seismogenic zone.

Keywords: Very Low Frequency Earthquakes, Nankai Trough, Ryukyu Trench

SCG64-17 Room:501 Time:April 30 16:45-17:00

Relationship between very low frequency earthquakes and repeating slow slip events in the south Ryukyu Trench

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The repeating slow slip events (SSEs) occur on the upper interface of subducted Philippine Sea plate at the depth from 30 to 50 km in the south Ryukyu Trench region (Heki & Kataoka, 2008). The afterslip of the March 2002 earthquake (Mw=7.2) is distributed at the west of the fault of the repeating SSEs. This afterslip continued from March 2002 to 2005 (Nakamura, 2009).

Recently, very low frequency earthquakes, which occurred continuously along the Ryukyu Trench, were detected (Ando et al., 2012). The occurrences of SSEs, afterslip, and very low frequency earthquakes reflect the state of slip in the plate interface.

Then we investigated the relation between the SSEs with very low frequency earthquakes.

We employed the broad-band seismometer network of NIED (F-NET) and IRIS. We used the station of Ryukyu Islands, Kyusyu, SSE (Shanghai), and TATO (Taipei). The used the waveforms of vertical component for the analysis. The period we used are from January 1, 2002 to September 30, 2013. We filtered the band-pass range of 0.02-0.05 Hz to the waveforms, and detected the low-frequency events and picked the arrival times of surface waves manually. The local and teleseismic earthquakes were eliminated using the earthquake catalogue. The local events were also eliminated with checking the high-pass filtered record. Then we determined the location of low frequency events assuming that the observed waves were Raleigh waves.

We determined the 6299 low frequency events for 12 years. Almost events are distributed along the Ryukyu Trench axis. The low frequency events are clustering at the south Iriomote Island, south of Okinawa Island, and near Amami Island. The events are also distributed near the Okinawa Trough. However, the events in the Okinawa Trough would be the apparent distribution by miss-location of hypocenter determination which is caused by the linear distribution of seismic stations along the Ryukyu Arc.

Next we investigated the cumulative number of low frequency earthquakes in the clusters. The activity of the low frequency events at the cluster of the south of Iriomote Island decreased from 2005 to 2010, and increased since late of 2011. The activation of very low frequency events occurred after the occurrence of repeating SSEs. The 24 SSEs had occurred since 2002, and the 14 activation of the low frequency events occurred after the SSEs. The occurrence rates of the VLFEs during the SSEs increased about 2-3 times than the averaged ones. However, the activation of usual earthquakes during the SSEs occurred only two times. These suggest that the SSEs would trigger the VLFEs.

Keywords: very low frequency earthquake, slow slip event, Ryukyu Trench

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SCG64-18 Room:501 Time:April 30 17:00-17:15

Activity characteristics of deep very low frequency earthquake and asperity structure

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Deep very low frequency earthquake (VLF) and deep nonvolcanic tremor (NVT) concurrently occur with short-time slow slip event (SSE) in the Nankai subduction zone. Among them VLF is least known since seismic records are usually noisy at dominant periods of VLF signals (20-50 sec). We have developed a new grid-based method for monitoring VLF activity in the Nankai subduction zone. In this method we assume that VLF occurs at equally-spaced grids on model plate boundary, and that VLF at each grid has a fixed source mechanism predetermined from plate boundary model and observed plate convergence direction. Previous studies have used the grid moment-tensor method in which depth and source mechanism are freely determined. These parameters are predetermined in the present method, so that it is expected that small VLFs can be detected even from low S/N records.

As a preliminary study we analyzed Hi-net accelerometer records for two activities in western Shikoku in September 2006 and March 2007. We detected a large number of VLFs compared with previous studies, and observed the following characteristics: (1) Some VLF occurrences were rapidly activated than NVT occurrences, and VLF activity highs were sometimes delayed relative to NVT activity high, (2) There was an NVT cluster with or without VLF depending on activity, (3) Rapid tremor reversals are associated with VLFs, (4) Clusters with maximum moment release were different between VLF and NVT, (5) The cluster of maximum VLF moment release was located in the updip portion next to the region of maximum SSE moment release. Some of these characteristics can be explained by a nested or fractal asperity model, in which small NVT asperities are contained in a VLF asperity.

Keywords: Nankai subduction zone, slow earthquake, very low frequency earthquake, nonvolcanic tremor, automatic detection, asperity

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(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG64-19 Room:501 Time:April 30 17:15-17:30

Preseismic behaviors involving slow slip in rate-state earthquake sequence models with a hierarchical asperity concept

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Understanding preseismic phenomena before large earthquakes is of critical importance in assessing possibility of disaster mitigation by detecting and recognizing them. The 2011 Tohoku-Oki earthquake has long recorded geophysical data for tens of years prior to it. Since the earthquake, multiple studies have reported potentially important phenomena involving slow slip which may be particular to ripe asperities. It is our mission for modelers to see if they are consistent with, or appear naturally without fine tuning of numerical models of earthquake sequences accounting for interseismic processes, as well as earthquake ruptures.

The off-Miyagi to off-Fukushima region was locked at least from Apr. 1995 to Mar. 2002 [Nishimura et al. 2004], with the shallower region not being able to be constrained by on-land GPS stations [Loveless and Mead, 2011]. The region started creeping from 2005 [Ozawa et al., 2012]. Recently, Katsumata [2013, JpGU] pointed out that seismic quiescence [Katsumata, 2011] correlates with the locked period, and inferred that this region may have been creeping at least from 1980 to 1988. In the shallower region near the hypocenter of the Tohoku-Oki earthquake, a couple of slow slip events were reported by Ito et al. [2013], one in Nov. 2008 and the other in Feb. 2011. This interval is much shorter than that for the larger scale events inferred by Katsumata [2013].

Suito et al. [2011] reported that M7-class earthquakes along the Japan Trench after 2005, including the Mw 7.3 preshock 2 days before the Tohoku-Oki earthquake, had unusually large amount of afterslips. The postseismic moment releases are comparable to or even larger than the coseismic ones, with the centroid being located close to the epicenters, not deeper than them.

In the present talk, we present that qualitatively similar behaviors to those observations are recognized in numerical models reported by Noda et al. [2013, JGR]. They presented rate-state earthquake sequence simulations accounting for a hierarchical asperity concept [Ide and Aochi, 2005]; a large tough patch has a small fragile patch in it. Importantly, those simulations were not meant to mimic the Tohoku-Oki earthquake through fine tuning of the model, and are representing general behaviors characteristic to the rate-state (aging law) earthquake sequence with a certain kind of heterogeneity in the parameter distribution.

In those simulations, interseismic penetration of a creep front into a locked velocity-weakening patch often becomes non-steady and accompanied by aseismic transients before nucleation. This is because the critical length scale for impossibility of coherent steady-state slip [Rice et al., 2001] can be smaller than the nucleation size [Rubin and Ampuero, 2005]. In the simulation, the transients take place both in the large tough patch and in the small fragile patch when a creep front penetrates inwards to a certain extent. A transient does not necessarily, but may lead to nucleation. In addition, such an elevated aseismic slip rate in the large patch seems to be a necessary condition for cascade-up rupture growth from the small patch if it is smaller than the nucleation size of the large patch.

A small event which only ruptures the small patch is sometimes followed by a large event before the afterslip smearing out. Such small events are classified as precursory events, since clear causality is recognized between them and the following large ones; the large ones are initiated either by delayed cascade-up or by large nucleation hosted by the afterslip. The precursory small events tend to have larger afterslip than non-precursory ones.

In the rate- and state-dependent friction law, logarithmic slip rate is, by definition, proportional to stress minus strength which correlates with fracture energy. Therefore temporal changes in the aseismic slip rate in a so-called asperity, if detectable, could be used to infer the ripeness of it.

Keywords: Earthquake sequence, Preseismic phenomena, Hierarchical asperity, Numerical simulation

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SCG64-20 Room:501 Time:April 30 17:30-17:45

Numerical simulation of slow slip events before the 2011 Tohoku-Oki Earthquake

NAKATA, Ryoko[1*] ; ARIYOSHI, Keisuke[1] ; HYODO, Mamoru[1] ; HORI, Takane[1]

[1]JAMSTEC

In the Japan Trench, the M9.0 great interplate earthquake occurred on 11 March 2011, off the coast of Tohoku, Japan. Before this earthquake, two slow slip events (SSEs) were observed on 2008 and 2011. The second SSE occurred on February 2011 at the downdip end of the huge-coseismic-slip region, and it continued at least until the occurrence of the M7.3 largest foreshock on March 9 [Ito et al., 2013]. In addition, following the largest foreshock, postseismic slip propagated to the location of the mainshock hypocenter and triggered the dynamic rupture there [Ando & Imanishi, 2011].

In this study, we numerically simulated cycles for occurrences of seismic and aseismic events along the Japan Trench with the 3D geometry of the Pacific plate. We model the M9 2011 Tohoku-Oki Earthquake, the largest foreshock of the M9 earthquake, and the SSE before the foreshock using the slowness law, which is a type of rate- and state-dependent friction law. We set frictional properties at source area of earthquakes and SSEs to satisfy a condition of unstable slip and slow slip, respectively. We evaluated simulation results achieved using different values of frictional parameters with respect to characteristics such as the slip history leading to the 2011 Tohoku-Oki earthquake and crustal deformation before and after the Tohoku-Oki earthquake.

As a result, we quantitatively reproduced the observed scenario. Temporal characteristics of the resultant scenario were sensitive to both sizes and locations of the circular fault patches. Now, we are improving our model to reproduce various characteristics qualitatively. Based on some of the reasonable results achieved, we will discuss frictional conditions for the pre-seismic process of the 2011 Tohoku-Oki earthquake.

SCG64-P01 Room:Poster Time:April 30 18:15-19:30

Deep Triggered Non-Volcanic Tremor in the Slow Earthquake Active Regions in South Chile and Ecuador

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Deep non-volcanic tremor has been observed at many major plate-boundary faults and intraplate faulting systems. Recent studies have shown that the tremor triggered by surface waves of teleseismic earthquake occurs on the same fault patches as the spontaneously occurring ambient tremor. The observations suggest that the triggered tremor can be used as a proxy to estimate the background tremor activity. Here we search for tremor triggered by teleseismic earthquakes in south Chile and Ecuador where the ambient tremor and slow slip event have been observed respectively. In south Chile, we analyzed a temporal array data between 2004 and 2006 and observed clear triggered tremor following the 2004 Mw9.0 Sumatra, 2005 Mw8.6 Nias, and 2006 Tonga earthquakes. Triggered tremor sources are located at the central of the ambient tremor zone. The results indicate both Love and Rayleigh waves promote the tremor triggering potential. The tremor triggering threshold is around 2 kPa, similar to which in Parkfield. In Ecuador, we can only use single station to infer the existence of triggered tremor due to lack of seismic stations in this region. During the period between 2004 and 2012, we observed triggered tremor following the 2010 Mw8.8 Chile and 2007 Mw8.0 Peru earthquakes. Since there is no other station within 500 km near that station, we roughly estimate that the triggered tremor sources are located within 50 km from the station based on the attenuation of tremor from previous studies and the estimation of the time difference between P- and S-waves of triggered tremor. We infer that the triggered tremor source might be located at the region where the slow slip event has been observed. The apparent tremor triggering threshold in Ecuador is about 40 kPa. The high threshold infer a low background tremor rate or simply due to the network capability.

Keywords: non-volcanic tremor, triggered tremor, south America

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(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SCG64-P02 Room:Poster Time:April 30 18:15-19:30

Shallow low-frequency tremor activity in the Hyuga-nada, revealed by ocean bottom seismographic observation

YAMASHITA, Yusuke[1*] ; YAKIWARA, Hiroshi[2] ; UCHIDA, Kazunari[1] ; SHIMIZU, Hiroshi[1] ; HIRANO, Shuichiro[2] ; MIYAMACHI, Hiroki[2] ; UMAKOSHI, Kodo[3] ; YAMADA, Tomoaki[4] ; NAKAMOTO, Manami[1] ; FUKUI, Miyo[1] ; KAMIZONO, Megumi[1]

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In order to reveal the detail of microseismicity from the shallower part of the plate boundary to seismogenic zone in the Hyuga-nada region, we have conducted Ocean Bottom Seismographic observation from May 19 until July 6, 2013. We used 12 Ocean Bottom Seismometers (OBSs) with a three-component short-period seismometer. During this observation, we observed many low-frequency tremors (SLFT) which mainly occurred from end of May to end of July 2013 [*Yamashita et al*., 2013 AGU fall meeting]. We report the detail of SLFT activity in the Hyuga-nada region based on the semi-automatically analysis using envelope correlation method (ECM)[*Obara*, 2002].

The differential arrival times between OBS stations using ECM were obtained from the lag times with maximum cross-correlation coefficient between the pair of the root mean square (RMS) envelopes which were converted from composite horizontal components waveform with applying a 2-8 Hz bandpass filter. RMS envelopes were smoothed by using 5 s window and performed down-sampling with a 20Hz. The length of RMS envelops for calculating of cross-correlation coefficients was set for 150 s. If the maximum cross-correlation coefficient for a pair was larger than 0.85, and more than or equal to 6 pairs, we searched minimum RMS residual position by a grid search algorism. These processing were performed automatically for the continuous RMS envelope records every 75 s (i.e., overlapping two moving window for 75 s). After the calculation, we carefully examined the candidate tremor events to distinguish "regular" earthquakes, T-phase signals, or background noise.

Based on the result of SLFT location by ECM, we identify two migration episode of the SLFT: 1st episode started in east off Tanegashima Island from end of May, 2013, migrated northward along strike of subducting plate, veered away to the north-west in the around S08 station, then reached under the S06 station on July 12 - 14. 2nd episode started in the south of S08 station on July 17, migrated northward and veered away to the north-west in the around S08 station, reached around the S07 station, veered away to the east, reached around the S09 station.

These migration episodes suggest that undetected short-term slow-slip event may have occurred at the same time in the shallow part of the Hyuga-nada region. Around the focal area of SLFT, the Kyushu-Palau ridge is subcudting: the SLFT activity was only found on the south side (i.e., Ryukyu arc side). In particular, the depth of plate boundary around the S08 station is southwestward deepening down to 10 km depth [*Park et al*., 2009]. Therefore, the episodic slow-slip extended to northward with SLFT activity, and shifted to northwest-ward caused by the Kyushu-Palau ridge which act a segment boundary to controle the interplate slip phenomena.

Acknowledgements: We thank the crews of T/S Nagasakimaru (Faculty of Fishers, Nagasaki University) for OBS observation.

Keywords: Shallow low-frequency tremor, Ocean Bottom Seismographic observation, Hyuga-nada

SCG64-P03 Room:Poster Time:April 30 18:15-19:30

The Slow Slip Event off the Boso Peninsula on January 2014 and the associated earthquake swarm

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Introduction

Off the Boso Peninsula, at the southeastern Kanto, central Japan, slow slip events (SSE) accompanied with earthquake swarms recurs with time interval of 4-7 years. SSEs have occurred in 1983, 1990, 1996, 2002, 2007, and 2011 and the latest SSE recurred from Dec. 2013 to Jan. 2014 with interval of 2 years and 2 months. In this study, detailed activity of the earthquake swarm and a fault model of the Boso SSE were determined.

Data and Methods

High precision hypocenter distribution was determined for earthquakes shallower than 30 km off the Boso Peninsula, from Jan. 1, 2005 by Double Difference method incorporating waveform correlation analysis. Hypocentral parameters determined by NIED Hi-net (automated hypocenters were partly included) were used as initial hypocenters.

A rectangular fault model with uniform slip was determined using genetic algorithm inversion for fault location and geometry and the weighted least squares method for slip amounts, following a method of Obara *et al*. (2004) based on tilt data recorded by high sensitivity accelerometer co-installed in NIED Hi-net station. In this analysis, slip direction was fixed to the direction of relative plate motion.

Results

Most earthquakes occurred around the northern edge of the seismic region where seismic swarms associated with the previous Boso SSEs occurred. Seismic swarms first occurred at the eastern offshore area and then migrated to the western onshore area. Migration from offshore to onshore regions is common feature among the previous Boso SSEs. Distribution of earthquake swarms is similar to that of the 2007 SSE, although spatial distribution and number of events are slightly smaller than the 2007 SSE.

The maximum crustal tilting of about 0.4 μ radian with northwestward direction was observed at KT2H station and the fault model was determined to be located off the Boso Peninsula with size of M_W6.1. Location of SSE slip overlaps with locations of the 2007 (Sekine *et al*., 2007) and initial stage of the 2011 (Hirose *et al*., 2012) SSEs. Tilting direction is similar to tilting direction of the 2007 SSE, however, its amount is about a half of the 2007 SSE (M_W6.4) and the SSE size is also smaller. Smaller number of earthquakes is likely to reflect smaller size of the SSE. In the 2011 SSE, west-northwestward tilting of about 0.3 μ radian was observed for the first two and a half days and size for this period was estimated as M_W6.2. Its direction and amount are similar to those of the 2014 SSE and the SSE size is also close.

Discussion

Recurrence interval of the 2014 SSE was shortest for the last about 30 years. The size of the 2011 SSE was estimated to be comparable to previous SSEs and a possibility that the 2011 SSE was hastened by the stress increase caused by the 2011 Off Tohoku Earthquake and its afterslip has been proposed (Hirose *et al*., 2012). On the contrary, size of the 2014 SSE is likely to be smaller than previous SSEs. This result infers that the SSE slip is smaller supposing the same source area and the SSE recurred with shorter interval with smaller stress accumulation. Further analysis is necessary to reveal the detailed source process of the Boso SSE for monitoring of the stress accumulation.

Acknowledgements:

In this study, seismic data obtained by Earthquake Research Institute (ERI) and Japan Meteorological Agency (JMA) were used.

Keywords: Slow Slip Event, plate boundary, earthquake swarm, Kanto region

SCG64-P04 Room:Poster Time:April 30 18:15-19:30

A long-term slow slip event in central Shikoku in 2013

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A long-term slow slip event in central Shikoku is investigated using the GEONET GNSS data. We estimated the steady deformation rate at each GNSS station from the daily coordinates for the period from January to December 2012. Then the steady deformation rates were subtracted from all the coordinate data. The artificial offsets of the coordinate were corrected using data set shown on the web site of the Geospatial Information Authority of Japan. We can see south-eastern displacements less than 1 cm at GNSS stations in central Shikoku for one year from October 2012. These unsteady displacements are also seen in the time series of the baseline lengths between central Shikoku and Chugoku district.

We estimated slip distribution on the plate boundary, assuming the unsteady displacements were caused by a slip on the plate boundary. The estimated slip is distributed in central Shikoku. Center of the slip is located slightly southeast of the belt of deep low-frequency earthquakes. The size of the slip is equivalent to Mw 6.2, which is smaller than other long-term SSEs along the Nankai Trough.

Keywords: long-term slow slip, GNSS, crustal deformation, central Shikoku

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SCG64-P05 Room:Poster Time:April 30 18:15-19:30

Rate and state simulation of Yaeyama slow slip events in the southwestern part of the Ryukyu Arc, Japan

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Slow slip events (SSEs) are recurring on the plate interface beneath the source regions of the interplate large earthquakes. It has been proposed that the activity of SSE possibly changes before the occurrence of large interplate earthquakes. 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 through a data assimilation method which combines the observational data and the forecast ones derived from a simulation model, and then to give information on the occurrence of large interplate earthquakes. In this paper, as a first step of such a data assimilation, we construct a simulation model reproducing the observed spatio-temporal slip evolution of SSE.

In this paper, we consider the Yaeyama SSEs. Around the Yaeyama islands in the southwestern part of the Ryukyu Arc, Japan, GPS observations have caught the frequent recurrence of SSE activity. Around there have occurred almost no large earthquakes that affect the SSE activities during the observational period, which leads to a relatively simple simulation model of SSE. Those are the reasons that we select SSE on this area.

Heki and Kataoka(2008) reported the following features of Yaeyama SSEs; 1) SSEs recur on a plate interface at depths of 20-40km, 2) the average recurrence interval is 6.3 months, 3) its standard deviation is 1.2 months, 4) 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 mentioned features of SSE. 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). To simulate SSE, following Kato(2003), 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 rate 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 also consider the possible presence of a locked zone, namely an asperity, at the shallow portion of the plate boundary close to the Ryukyu Trench, which might cause the 1771 Meiwa tsunami (Nakamura, 2009). Dating of tsunami stones suggests a possible recurrence of 150-400 years of large tsunami (Araoka et al., 2013), and the large tsunami events close to the Ryukyu Trench might have recurred in several hundred years.

It is found that the interval of SSE can be adjustable by changing the friction parameters. For example, if a single asperity with the size of 80 km has frictional parameters of A=50 kPa, B=56kPa, and L=2.2 mm, the interval is about 6 months. Further, if we add another asperity with 40 % slip deficit rate of the convergent rate of 12.5 cm/yr just above the SSE asperity zone, the slip rate released by SSEs reduces to the observed rate of 11.0 cm/yr. The released slip rate depends on the location, size and assigned slip deficit rate of the shallow asperity. The locking state at the shallow portion is important to give information on the occurrence of possible tsunami earthquake, and we need the further investigation. For reproducing the observed fluctuation of recurrence intervals of SSE, we need to consider the interaction among multiple asperities or the hierarchical asperity model where a large asperity has small asperities with different properties inside itself.

Keywords: slow slip events, Yaeyama, a rate- and state-dependent friction law

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Array observation of short span strainmeter in the Kii peninsula

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Crustal deformations have been observed associated with deep low-frequency tremors occurring below the Kii peninsula and Shikoku. Strain measurements by an extensometer at Kishu operated by DPRI, for example, show that the sources with epicentral distance of 30 - 40 km causes strain changes of $10^{?9}$ to $10^{?8}$ occurring within several days. Although the traditional extensometer observations can detect these strain changes, it is difficult to make detailed analyses because of the limited number of stations. We designed a short-span extensometer with 1.5 m-long standard measure. Strong coupling of the instrument to the ground is important for stable observations, so three anchor bolts fixed to the base of the instrument are cemented into a 50-cm-deep hole. We observed crustal deformation associated with deep low-frequency tremors by the short-span extensometer installed at Nakaheji. We detected strain change associated with low frequency events occurred on March 2013. We are preparing another sites for installation of the strainmeter around the western Kii Peninsla to constract array of strainemters. The array observation contributes to improve the detection capability of crustal deformation by eliminating noise caused by weather disturbance and to have better understanding of slow slip events such as slip distribution.

Keywords: strainmeter, slow earthquakes, array observation