Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SCG62-01 Room:103 Time:May 20 09:00-09:15

Activity style of nonvolcanic tremor in southwest Japan

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In some subduction zones like as Nankai and Cascadia, slow earthquakes composed of slow slip event and non-volcanic tremor occur between the transition zone between the locked zone and downdip stable sliding zone. This slow earthquake source region ranges with a length of 600 km in southwest Japan or 1200 km in Cascadia; however, the region is divided into some segments based on their activity style. In each segment, the tremor episode recur at a certain interval with clear migration. Sometimes, the migration is observed across the different neighbor segments. Such activity style of tremor is very similar to that of megathrust earthquake because the tremor episode frequently occur. Therefore resolving the key factor that controls the activity style of tremor episode may contribute to understanding the occurrence mechanism of megathrust earthquake. Therefore, we investigate the detail activity style of tremor based on the clustering catalog (Maeda and Obara, 2009, Obara et al., 2010) because the tremor is well-detected and determined compared to other slow earthquakes.

The epicentral distribution of tremor is not uniform within the narrow belt-like zone. The tremor belt-like zone includes some aseismic portions. Some large aseismic portions in Ise Bay and Kii Channel is considered as the segment boundary because many tremor episodes stop at or start from the edge of the aseismic portion. However, the tremor activity in the central and eastern Shikoku clusters occurs continuously in space and time on both sides of a small aseismic portion. This indicates that the slow slip might propagate through the aseismic portion without tremor activity (Obara et al., 2011). The segment is defined as the rupture area of recurrent tremor episodes with a certain recurrence interval. However, sometimes the segment is divided into some small episodes with short time interval. These small episodes are not overlapped and finally cover the whole region of the segment. Therefore, the rupture area of the coming small episode is predicted in advance based on the occurrence style of previous small episodes. The rupture initiation point of the tremor episode is frequently away from the stop point of the previous tremor episode. This suggests that the effect of the stress concentration caused by the rupture propagation of the slow slip event is not so significant, but anyplace in the segment is ready to rupture and the rupture starts from the most weak point. These small episodes sometimes occur at the same portion within the segment. This might be defined as a sub-segment. The sub-segment boundary usually corresponds to the continuous tremor active spot. This spot also coincides to the rupture initiation discussed above. Therefore, the inhomogeneous spot on the plate interface may control rupture initiation and termination of slow slip event.

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

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SCG62-02 Room:103 Time:May 20 09:15-09:30

Spatial dependency of migration velocities of non-volcanic low frequency tremor active area at southwest Japan

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Non-volcanic low frequency tremors (NVTs) on a subduction zone in southwest Japan roughly migrate with about 10km/day along strike direction of Philippine Sea plate (e.g., Obara, 2010). Although the migration pattern can be categorized into several groups (Obara, 2010, Obara et. al., 2011), it is not always simple if we look at a small spatial scale.Previous studies suggest that these complexities are related to frictional properties on plate boundary (Ando et. al., 2012, Gosh et. al., 2012). In other words, there is a possibility that we can infer the frictional properties from the spatial distribution of NVT migration velocity.

Based on, In this study, we estimated along-strike migration velocities of NVT activities that occurred after July 2008 using LFT catalogue determined by the envelope correlation method and summarized their spatial dependency. The results suggest that the migration velocity is similar if we chose an arbitrary small segment and migration direction.

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Acknowledgements: We use seismic waveform data provided by National Research Institute for Earth Science and Disaster Prevention (Hi-net), JMA and University of Tokyo.

Keywords: Non-volcanic low frequency tremor, migration, subduction zone, fault heterogeneity

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SCG62-03 Room:103 Time:May 20 09:30-09:45

Spatial variation in size distribution of deep non-volcanic tremor in southwest Japan

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Magnitude-frequency distribution of ordinary earthquake satisfies the Gutenberg-Richter (GR) relation, indicating the size-frequency distribution satisfies the power law. The slope of semi-log graph of the GR law, b-value, is considered to reflect the stress state in earthquake source region. Size of deep non-volcanic tremor is estimated by the reduced displacement (RD) (Aki and Koyanagi, 1981) and their frequency distribution satisfies the exponential law (Hiramatsu et al. 2008). The slope of semi-log graph of this exponential law is very important when considering the friction property in the tremor source region on the subducting plate interface. In this study, we have investigated spatial variation in the RD-frequency distribution of tremor in southwest Japan. The result shows that the slope of RD-frequency distribution varies strongly from cluster to cluster. In each of the segment in western Shikoku, eastern Shikoku and Kii Peninsula, there exists a negative correlation between the observed slopes of RD-frequency distribution and the recurrence intervals of tremor activity: the larger the slope is, the longer the activity interval. In laboratory experiments, it has been shown that contact patches on friction surface grow and combine with time. The observed correlation might suggest time variation in the distribution of tremor patch size on the plate interface.

Keywords: non-volcanic tremor, size distribution

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SCG62-04 Room:103 Time:May 20 09:45-10:00

A New Method to estimate the tremor depth accurately

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To understand the mechanism of tectonic tremors, which have been discovered in many subduction zones and transform faults mainly around Pacific, it is important to determine the precise location of tremors, especially depth to know whether they occur on the plate boundary, in the oceanic crust, or in the upper plate. However, very weak and ambiguous signals of tremors prevent us to detect them and determine their hypocenters by popular location methods used for ordinary earthquakes, i.e., by reading P- and S- wave arrival times for each event. Therefore other methods are applied to detect and locate tremor, such as an envelope correlation method (e.g., Obara, 2002) and a matched filter analysis (e.g., Shelly et al., 2007). However, the accuracy of locations is not sufficient for detailed investigation.

In this study, we develop a new technique to determine tremor depth precisely by obtaining S-P times from tremor signals. S-P times are measured by comparing a vertical velocity seismogram with a synthetic moment rate function. The synthetic moment rate function is approximated by the energy rate function, which is proportional to the squared ground velocity. This technique will also provide us the information about the focal mechanism of tectonic tremors, because this method has a potential to reveal the green function of tectonic signals at each station.

Keywords: Subduction Zones, Tectonic Tremors, S-P times

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SCG62-05 Room:103 Time:May 20 10:00-10:15

Non-volcanic tremor characteristics in Taiwan and their stress interaction with local earthquakes

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Recent findings of tremor in Taiwan have shown it to be an ideal region in which we can study the relationship between tremor and earthquakes. Although several studies (Chao et al., GJI, 2012; Chao et al., SSA Meeting, 2011) have identified triggered and ambient tremor beneath the southern Central Range of Taiwan, a number of fundamental characteristics of tremor in Taiwan remain unclear. In this study, we auto-detected eight-year (2004~2011) continuous seismic waveforms and obtained tremor episodes under the southern Central Range using the Waveform Envelope Correlation and Clustering (WECC) method and a spatio-temporal clustering criterion. We also quantified tremor activity before and after the local 4 March 2010, Mw6.3 Jiashian earthquake, the hypocenter of which is located about 30 km away from active tremor sources, and the 2010 Mw8.8 Chilean earthquake, which occurred six days before the Jiashian mainshock. This special dataset provides a means of studying the relationships among ambient tremor, triggered tremor, and local and regional earthquakes.

Analysis of the data shows that ambient tremor in the southern Central Range of Taiwan is characterized by frequent recurrence of short duration (5~24 min. per day); however, unlike other subduction environments, the Nankai tremor zone exhibits a continuous occurrence of tremor episodes from a period of hours to days. The analysis also shows that ambient tremor in Taiwan surrounds an active triggered tremor source and that its spectrum is similar to that of triggered tremor, but with lower amplitude, which confirms the theory that triggered tremor is a sped-up result of ambient tremor. We found that background noise in this region during the local daytime period exhibits larger amplitude than that of ambient tremor, implying that if we employ borehole seismometers in the study region, we should be able to detect more tremor episodes. Our findings also show that maximum tremor activity occurred within ten days after the Jiashian mainshock, indicating a static stress interaction between the tremor rate and locally occurring earthquakes, and that tremor rate gradually returned to its previous status six months after the mainshock. Although the dynamic stress from the Chilean earthquake exceeded the tremor-triggering threshold of 8-9 kPa in Taiwan, it neither triggered tremor nor influenced local seismicity. The study found no evidence that significant change in tremor activity correlated with that of the Chilean earthquake or local seismicity. Finally, we examined potential slow slip events in nearby regions with geodetic observations from GPS data and found no direct evidence of a connection between the GPS observations and tremor episodes. Our investigation of ambient tremor in Taiwan can lead to more thorough understanding of tremor-generated zones and geological structures in this region.

Keywords: non-volcanic tremor, dynamics and static triggering, Taiwan, tectonic tremor

SCG62-06 Room:103 Time:May 20 10:15-10:30

Linear stability of plane Poiseuille flow in infinite elastic medium and volcanic tremors

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We investigate linear stability of a plane Poiseuille flow of a compressible fluid sandwiched between two semi-infinite elastic media, focusing on application to excitation mechanism of volcanic tremors. Previous studies have shown that, in the even mode, where the fluid-layer thickness becomes wider and narrower symmetrically, the flow speed needed to destabilize the system could be infinitesimally small when the wavelength of the wave-type fluid and solid motion is very long (Balmforth et al., 2005; Dunham and Ogden, 2012). We show that a similar instability occurs in the odd mode, where the width of the fluid layer does not change very much regardless of the fluid and solid motion. The odd-mode instability occurs with a slower flow speed than in the even mode, and the wave-type motion propagates oppositely to the basic flow. We calculate the critical Mach number for instability of the compressible Poiseuille flow for various dimensionless parameters and conclude that the odd mode is more possible to account for excitation of volcanic tremors than the even mode.

Keywords: fluid dynamics, dynamics of elasticity, flow-induced vibration, elastic surface wave

SCG62-07 Room:103 Time:May 20 10:30-10:45

Long-term seismic quiescence caused by partial decoupling of the plate boundary prior to the 2011 Tohoku earthquake

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Katsumata (2011) found that a long-term seismic quiescence started 22 years before the 2011 off the pacific coast of Tohoku earthquake (M=9.0) by analyzing an earthquake catalog compiled by Japan Meteorological Agency (JMA). A detailed analysis of the earthquake catalog between 1965 and 2010 using a gridding technique (ZMAP) shows that the 2011 Tohoku earthquake is preceded by a seismic quiescence anomaly that starts in the middle of 1989, and lasts about 22 years, until the occurrence of the main shock. The quiescence anomaly area is located around the deeper edge of the asperity ruptured by the main shock. The seismicity rate clearly decreases from 3.0 to 1.5 events/year (a drop of 50%). On the other hand Ozawa et al. (2012) found that a time-dependent analysis indicates aseismic slip offshore of Miyagi and Fukushima prefectures from 2004 based on global positioning system (GPS) data. They suggested that the aseismic slip is a precursor to the Tohoku earthquake. In this study I point out that the seismic quiescence area found by Katsumata (2011) overlaps almost exactly with the aseismic slip area found by Ozawa et al. (2012), suggesting that the seismic quiescence is caused by the aseismic slip.

Katsumata, K., A long-term seismic quiescence started 23 years before the 2011 off the Pacific coast of Tohoku Earthquake (M = 9.0), Earth Planets Space, Vol. 63 (No. 7), pp. 709-712, 2011.
Ozawa, S., T. Nishimura, H. Munekane, H. Suito, T. Kobayashi, M. Tobita, and T. Imakiire (2012), Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan, J. Geophys. Res., 117, B07404, doi:10.1029/2011JB009120.

Keywords: 2011 Tohoku earthquake, seismic quiescence, slow slip

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SCG62-08 Room:103 Time:May 20 11:00-11:15

Objective detection and catalog of short-term SSE

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Geological Survey of Japan (GSJ), National Institute of Advanced Industrial Science and Technology (AIST) constructed integrated observatories in and around Shikoku, Kii Peninsula and Tokai. In these observatories, we are observing groundwater, strain, tilt and earthquake. In addition to these data, using the tilt data of National Research Institute for Earth Science and Disaster Prevention (NIED) Hi-net and strain data of Japan Meteorological Agency (JMA), we are monitoring short-term slow slip events (SSE). At present, the occurrence of short-term SSE is determined by visual inspection with reference to the tremor. Therefore, it is considered that there is oversight of the short-term SSE.

Itaba *et al.* (2012) developed an objective detection method of tectonic crustal movement using redundant components of borehole strainmeter, and shown that it is effective for detection of short-term SSE in the Kii Peninsula. So, in this study, after tuning this method, we estimated the dislocation model of short-term SSE that detected tectonic crustal movement in more than one observatory.

In this presentation, we will introduce the detection results in some areas, the dislocation model and features of short-term SSE, and initiatives toward short-term SSE catalog.

Keywords: short-term SSE, strain, borehole strainmeter, tilt, groundwater, tremor

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SCG62-09 Room:103 Time:May 20 11:15-11:30

Detection of short-term slow slip events along Hyuganada and the Sagami trough using GNSS data

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[1]Geospatial Information Authority of Japan

Nishimura et al. (2012) detected tectonic offsets in GNSS time-series using the AIC and fault model estimation of short-term slow slip events (SSEs) on the subducting Philippine Sea plate along the Nankai trough. Here, we report results of detection and estimation of SSEs along Hyuganada and the Sagami trough using their method.

Daily coordinates of 314 GEONET stations in southwestern Japan were used to detect the deformation of SSEs along Hyuganada. We fitted a step function to the filtered daily coordinates to detect displacements in a direction of N135^{o}E which is opposite to the relative plate motion between the Philippine Sea plate and southwestern Japan. The candidate dates of the SSEs are determined if the significant displacements were detected. And three components (i.e., EW, NS, and UD) of the displacement were inverted to estimate a rectangular fault model. We finally recognized SSEs if the observed displacement were well reproduced by the fault model. The same procedure is applied for the analysis of SSEs along the Sagami trough. But we used 327 stations to detect displacements in a direction of N160^{o}E.

In the Hyuganada region, we estimated four M$_w$ 6.0-6.1 SSEs near the border between Oita Prefecture and Miyazaki Prefecture. Number of SSEs in the southern region decreases around Miyazaki Prefecture but increases around the Osumi Peninsula and Tanegashima again. The SSEs near the Oita-Miyazaki border occur at a depth of ~30 km and those near the Osumi Peninsula occur at a various depth between 10 and 50 km. It is interesting that SSEs with a depth of 30 km and shallower occur there, which have never been detected in the Shikoku region. Some SSEs accompanied with seismic activities along the Hyuganada. We also detected several episodes of SSE-related deformation along the Sagami trough. One of the largest SSEs occurs far east off the Boso Peninsula around April 14, 2007. The estimated moment magnitude ranges between 6.3 and 6.7.

In summary, many SSEs were found along Hyuganada and the Sagami trough, where significant activities of non-volcanic tremors are not observed. We found that some SSEs accompanied with seismic activities but that the others did not. Comparison among analyses for several neighboring regions revealed a problem that some false SSEs were detected by the present method because of a low signal to noise ratio. It is necessary to combine GNSS and strain/tilt data so as to improve the fault model estimation and estimate duration of SSEs.

Keywords: Slow slip event, GNSS, Crustal deformation, Subduction zone, Hyuganada, Sagami Trough

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SCG62-10 Room:103 Time:May 20 11:30-11:45

Development of a short-span strainmeter for observation of deformation of slow slip events

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Crustal deformations, such as strain and tilt changes, 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, Kyoto University, for example, show that the closer sources with epicentral distance of 30 - 40 km, have large deformations with strain changes of 10^{-9} to 10^{-8} occurring within several days. Although the traditional extensometer observations can these detect strain changes, it is difficult to make interpretations because of the limited number of stations

An instrument that is inexpensive and is easy to install will make possible strain array observations. We designed a short-span extensometer that is 1.5 - 2 m-long measure. The measure is made from a metal with a small temperature expansion constant and hanging by a thin string at one end. A linear variable differential transformer (LVDT) is used to detect displacement. 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 30-cm-deep hole.

As a test example, we constructed a one component short-span extensometer and installed it in a tunnel of Donzurubou observatory, Nara prefecture. Earth tides and strain oscillation caused by a teleseismic event are clearly observed by the short-span extensometer. We expect that the crustal deformation associated with deep low-frequency tremors can be observed by an array of these short-span extensometer, that have a length of 1.5-m.

Keywords: strain meter, slow earthquakes, array observation

SCG62-11 Room:103 Time:May 20 11:45-12:00

Anisotropic structures of oceanic slab and mantle wedge in a deep low-frequency tremor zone beneath the Kii peninsula

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Anisotropy is an important feature of elastic wave propagation in the Earth and can arise from a variety of ordered architectures such as fractures with preferential alignments or preferred crystal orientations. We studied regional variations in shear wave anisotropy around a deep low-frequency earthquake (LFE) zone beneath the Kii Peninsula, SW Japan, using waveforms of local earthquakes observed by a dense linear array along the LFE zone. The fast directions of polarization are subparallel to the strike of the margin for both crustal and intraslab earthquakes. The delay time of the split shear waves in intraslab earthquakes is larger than that in crustal earthquakes and shows a down-dip variation across the LFE zone. This indicates that anisotropy exists in the mantle wedge and in the lower crust and/or oceanic slab. We explain the observed delay time of 0.015~0.045 s by suggesting that the mantle wedge consists of a deformed, 1~15 km thick serpentine layer if the mantle wedge is completely serpentinized. In addition to high fluid pressures within the oceanic crust, the sheared serpentine layer may be a key factor driving LFEs in subduction zones.

Keywords: shear wave splitting, LFE, mantle wedge, serpentine, subduction zone, SW Japan

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SCG62-12 Room:103 Time:May 20 12:00-12:15

Slow earthquake associated with frictional healing of serpentinites

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Slow earthquakes occurred at subduction zone are distinct from regular earthquake in terms of their slip behaviors (e.g., Ide et al. 2007). We consider this difference to relate to localized hydration reactions at the plate interface that influence the frictional properties. The results of laboratory friction experiments indicate that simulated serpentine faults are characterized by a low healing rate and large slip-weakening distance compared with unaltered dry fault patches. These properties are consistent with the characteristics of subduction-related slow earthquakes, which exhibit a small stress drop and a relatively long duration. The results of numerical modeling suggest that slow slip events favor a large slip-weakening distance (e.g., Shibazaki and Iio 2003). These results may explain the slip mechanism of slow earthquake, suggesting that a locally serpentinized plate interface could trigger slow earthquakes assisted by pore pressure build-up, whereas unaltered dry patches that remain strongly coupled are potential sites of regular earthquakes.

Keywords: serpentinite, frictional experiment, frictional healing, slow earthquake

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SCG62-13 Room:103 Time:May 20 12:15-12:30

Geological and frictional aspects of very-low-frequency earthquakes in an accretionary prism

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Recent observations by on-land seismic networks and broadband ocean-bottom seismometers have identified the occurrence of very-low-frequency earthquakes (VLFE) along thrusts in accretionary prisms and near subduction plate boundaries at slip rates of 0.05-2 mm/s. However, the geological and frictional aspects of VLFE remain poorly understood. Here we show the characteristics of the thrusts in the Eocene Kayo Formation of the Shimanto accretionary complex exhumed from source depths of VLFE and the frictional velocity dependence of the thrusts materials. The host rock of the thrusts is quartz arenite that constitutes sandy turbidites. The thrusts are composed of quartz-rich fault rocks with or without clay foliations. The frictional slip in the thrusts is accommodated by the localized shear along quartz-coated slip surfaces or the distributed shear along clay foliations. Frictional velocity dependence of thrust materials was examined under wet conditions. At slip rates of 0.0028-0.28 mm/s, the powder sample from non-foliated rock show velocity-weakening behavior, while that from foliated fault rock exhibits velocity-strengthening behavior. All samples show velocity-strengthening behavior at slip rates of 0.28-2.8 mm/s. Microstructural analysis reveals that the velocity-weakening samples show a shear localization, while velocity-strengthening sample is marked by clay foliations oblique and parallel to shear zone boundaries. A frictional velocity dependence of the samples from quartz-rich thrust material, showing velocity weakening at 0.0028-0.28 mm/s but velocity-strengthening at 0.28-2.8 mm/s, is favorable for the occurrence of VLFE. The localized shear along quartz-coated slip surfaces in thrust may be the geological evidence of VLFE. However, when clay foliations develop in such thrust, thrust becomes frictionally stable as the samples with clay foliations shows velocity-strengthening behavior at 0.0028-2.8 mm/s. These results suggest that the quartz content and development of clay foliations along thrusts may be factors in controlling the occurrence and spatial distribution of VLFE in accretionary prisms.

Keywords: very-low-frequency earthquakes, accretionary prism, frictional velocity depenedence, fault zone structure

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SCG62-P01 Room:Convention Hall Time:May 20 18:15-19:30

Spatial variations of the temporal clustering properties of tectonic tremor activities inferred from a fractal analysis

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The spatial variation of tremor activities is characterized by means of a fractal analysis. The temporal distribution of tremor activity exhibits fractal behavior, and its fractal dimension (D) and the characteristic time (t_c) reflect the degree of temporal clustering and the recurrence interval of episodic tremors. By applying one-dimensional box-counting method for the tremor catalogs from the following tectonic regions: Nankai, Cascadia, Mexico, and New Zealand, we identify transitions of the temporal clustering properties in both the dip and the strike directions. A transition in the dip direction is possibly associated with the change in the thermal condition depending on the tremor depths, while significant variations in the strike direction is likely to be affected by other factors such as pore-fluid pressure and geometrical irregularities, as well as local temperature variations. The characteristic time has modest positive correlation with the tremor duration, probably representing the inherent correlation between the seismic moment release rate and the recurrence interval of tremors controlled by the frictional properties along the plate interface.

Keywords: tremor activity, fractal, subduction zone, recurrence interval, episodicity, temporal clustering

SCG62-P02 Room:Convention Hall Time:May 20 18:15-19:30

P- and S-wave detection of the low frequency earthquakes (LFE) using 3D array. Application to hypocenter determination

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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 relationship between the great interplate earthquakes and activity of LFEs, Tono Research Institute of Earthquake Science (TRIES) installed a seismic array with 10 stations in and around Shimoyama in 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 at Shimoyama. 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. Because of unclear P (especially) and S phases in LFE signals, we analyzed seismic data of the 3D array by using the semblance method (Neidel and Tarner, 1971). P phases were picked in vertical component of records with Vp=4.5 km/s in analysis. And S phases were picked in horizontal components of records with Vs=2.2 km/s. Semblance value (Sc) is calculated with the parameters of back-azimuth, incident angle and time. Developing and testing the semblance analysis method, we analyzed seismic wave data of five regular earthquakes observed by 3D array. And we obtained station corrections for the semblance analysis. The result shows that the semblance analysis method using the 3D array data is excellent for picking P and S phases. After analyzing 13 LFE data using the same method, we obtained five LFEs with higher semblance values in P and S phases (P-Sc $>$ 0.5, S-Sc $>$ 0.6) and smaller difference (less than 20 degrees) in incident angles between P and S waves. We read exact arrival times of P and S waves in seismic waves of the five LFEs, referring the time ranges of the higher semblance values. Using those arrival times and JMA's arrival time data, we calculated hypocenters of the five LFEs. The relocated hypocenters in this study are shallower than those of JMA. And we should suggest that our hypocenters locate near the subduction interface (e.g., Hirose et al., 2008) of the Philippine Sea Plate.

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

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Keywords: deep low-frequency earthquakes, 3D array, P and S waves, semblance, hypocenter determination, plate boundary

Japan Geoscience Union Meeting 2013
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SCG62-P03 Room:Convention Hall Time:May 20 18:15-19:30

Seismic array observations for study of nonvolcanic tremor activity and underground structure in western Shikoku

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Nonvolcanic tremor is a seismic phenomena associated with the short-term slow slip event on the transition zone between the downdip stable sliding zone and updip seismogenic zone along the subducting plate interface. In southwest Japan, the tremor is distributed within a belt-like zone with a length of about 600 km and a width of 20 to 50 km. The tremor activity style is gradually changed according to the depth even in the narrow width. In the shallow updip side, major tremor episodes associated with the crustal deformation caused by the slow slip event occur episodically at an interval of several months; however, in the deep downdip side, minor tremor episodes frequently occur. This depth dependence of tremor recurrence is also observed in Cascadia. Therefore, this might reflect the gradual change in the frictional property along the plate interface according to the depth and temperature. One of the possible reason for the depth dependent activity is reduction of normal stress due to increase of pore pressure. If the volume of fluid changes within the tremor zone, we expect to detect any change in the seismic structure along the plate interface. According to the purpose to detect spatial change of seismic structure and spatiotemporal detail distribution of tremor activity, we deployed dense array composed of high-sensitivity seismometers in western part of Shikoku Island because the width of the tremor belt-like zone is widest in this region.

The seismic array is mainly divided into two types: linear array and separated dense array. The linear array is composed of 70 three-component velocity seismometer with a natural frequency of 1 Hz. This array is placed along the Sadamisaki peninsula and coast line of the Bungo channel with a length of about 100 km at the space of 1~2 km. In order to detect the spatial variation in the seismic structure associated with the tremor activity change, the linear array was planned to include the updip and downdip edges of tremor zone. The separated dense array includes one large array composed of 30 seismometers at the spacing of 200 m and five small arrays composed of 9 seismometers. This array system is used to detect the tremor migration by beam forming method (Takeda et al., 2012). The observation period is 1.5 years from September 2011 to March 2013. During this observation period, we detected three major tremor episodes from December 2011 to January 2012, from May to June 2012, and from November to December 2012. Moreover we detected temporal tremor activity triggered by passing of the surface wave from Mw8.6 Sumatra earthquake on 11 April, 2012 (Enescu et al., 2012). This triggered tremor occurred at an interval of about 30 seconds at first, then the recurrence interval became to be about 20 seconds according to the dispersion of the surface wave. The relative arrival time of tremor envelope and amplitude pattern observed between these stations also changed in time. This suggests that the source and/or mechanism of the tremor might slightly change.

Keywords: non-volcanic tremor, slow earthquake, subduction zone, plate interface

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Improvement of tectonic tremor detecting and locating methods: Case study in western Shikoku and central Kyushu

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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. Obtaining accurate tremor sources in time and space is important because it provides essential information that reveals the mechanism of tremor activity. 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 the during testing period, the WECC was able to successfully auto-detect the same ambient tremor episodes listed in the NIED tremor catalogs. 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 central Kyushu 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. We plan to apply the WECC to search for potential ambient tremor in central Kyushu and present the updated results at an upcoming meeting. The improved tremor detecting and locating techniques, which combine the strengths of various algorithms, will be instrumental in the construction of an accurate tremor catalog in Japan.

Keywords: non-volcanic tremor, tremor locating/detecting methods, central Kyushu, Shikoku tremor zone

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Statistical hypothesis test for the detection of very low-frequency earthquakes in southwest Japan

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Very low-frequency earthquakes (VLF) have been observed with deep non-volcanic tremors (NVT) in southwest Japan. In previous studies, it has been shown that the fault strike and dip angles of VLF events reflect the upper boundary geometry of the subducting Philippine Sea plate and the slip angles are consistent with the motion of the subducting plate (Ito et al., 2007, 2009; Takeo et al., 2010). These studies, however, simply applied methods of grid moment-tensor analysis for ordinary earthquakes to the VLF detection, so that a considerable number of small VLF events might be missed. We thus developed a new method specialized to the detection of VLF events.

In our method, VLF events are assumed to occur on the Philippine Sea Plate interface with source mechanisms predetermined from the subducting plate surface geometry and the plate motion. We obtained possible VLF source mechanisms from the plate interface model (Hirose et al., 2008) and the relative plate motion (Miyazaki and Heki, 2001) to calculate VLF synthetic seismograms. Then we detected VLF events by comparing observed seismograms with synthetics using cross correlation and variance reduction (VR). We indicated the availability of this method in the last SSJ fall meeting. However, we did not discuss on validity of the results, which may be artifacts by random noise fitting.

In this study we apply a numerical statistical hypothesis test based on the bootstrap method to check validity of the results. The null hypothesis is "the obtained VR value is a result from random noise fitting" and the test statistic is VR. In the bootstrap hypothesis test, p value is obtained by

$p = \#\{ t* > t_{obs} \}/N$

where t* is a VR value from an analysis of bootstrap-replication waveforms based on the null hypothesis, t_{obs} is an observed VR value, N is the number of simulations, and '#' means the number of simulated values that stratify the condition in the braces. If the p value is less than a given significance level, we reject the null hypothesis. The bootstrap-replication waveforms are calculated from the observed seismograms using a method of frequency domain resampling. In the presentation we will show the result of real data analysis.

Keywords: very low-frequency earthquake, slow earthquake, statistical hypothesis test, bootstrap method

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Broadband features of the shallow low frequency events in Nankai trough, excited after the 2011 Tohoku-Oki earthquake

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Low frequency events are seismic events, which have longer duration and less energy radiation compared to regular earthquakes. The low frequency events detected in the shallow part of the Nankai trough (depth<10km), reported by previous studies, can roughly be divided into two groups depending on the observable frequency ranges of the signal, where the frequency ranges actually depend on the observed instrument.

The events of the first group are very low frequency earthquakes (VLFE), which were originally detected by broadband seismographs on-land (Ishihara et al., 2003; Ito & Obara, 2005), dominant in the frequency around 0.1-0.05 Hz. More recently a close-in observation was successfully made by temporally deployed broadband ocean-bottom seismometers (BBOBS), which revealed many intriguing features of the VLFEs (Sugioka et al., 2012). The events of the second group are low frequency tremors (LFT), which are recorded by OBSs equipped with 4.5?Hz short-period seismometer sited close to the source regions. They are dominant in the frequency range of 2?8 Hz with a lack of energy above 10 Hz (Obana & Kodaira, 2009). The classification between LFTs and VLFEs must be an important step toward estimating the physical process of the shallow low frequency events.

After the 2011 Mw9.0 Tohoku-oki earthquake, many shallow low frequency events were recorded at a cabled network of ocean bottom broadband stations (DONET) deployed in the northern part of Nanakai trough. The characteristics of the events are similar to previously observed LFTs at the frequency range around 2-8Hz. In addition, some of the events are accompanied by a lower frequency signal, clearly visible around 0.02-0.05 Hz, whose features are similar to those previously observed as VLFEs by Sugioka et al.(2012). One of such features of VLFEs is the ramp-type motion of the instrument-corrected seafloor displacement, which corresponds to a subsidence of up to 0.04 mm with a rise time of 10-20 s.

In order to examine whether the events accompanied by the 0.02-0.05Hz signal are intrinsically different from those without the 0.02-0.05Hz signal, the amplitudes of each event measured at 2-8Hz and 0.02-0.05Hz are compared. The comparison shows that the events without the 0.02-0.05 Hz signal tend to have lower amplitude in 2-8Hz than those accompanied by the 0.02-0.05 Hz signal. The result indicates that there is no such event, which is intrinsically missing the 0.02-0.05Hz components but has large amplitude in 2-8Hz. In other words, the events without the 0.02-0.05Hz signal are likely to be either smaller in size or to have occurred further away from the stations, compared to the events accompanied by the 0.02-0.05 Hz signal. Our dataset shows that the two types of low frequency events are likely the same phenomenon.

Keywords: very long frequency earthquake, low frequency tremor

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Long-term slow slip events around eastern Shikoku and Kii Channel (2)

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Long-term slow slip events around eastern Shikoku and Kii Channel are 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 2006 to December 2009. 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 homepage of the Geospatial Information Authority of Japan. We can see south-eastern displacements of a little less than 1 cm at GNSS stations in eastern Shikoku from 2001 to 2004. These unsteady displacements are also seen in the time series of coordinate and the baseline length. Moreover, the change of the baseline length is also seen in 1996.

We estimated slip distribution on the plate boundary, assuming the unsteady displacements were caused by the slip on the plate boundary. The estimated slip is distributed in the Kii channel. Non-volcanic deep low-frequency tremors are distributed belt-like along the Nankai trough. However, the active tremor is not observed in the Kii channel. In addition, considering the pattern of unsteady displacement, it appears that the source area of 1996 and 2001-2004 long-term slow slip events are almost the same. From this, long-term slow slip events with different size and time evolution may occur in the same area. These may provide important information about the condition of the plate interface.

Keywords: long-term slow slip, GNSS, crustal deformation, eastern Shikoku, Kii Channel

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Afterslip revisited: Scaling relation of slip rate versus mainshock magnitude and possible expansion of the definition

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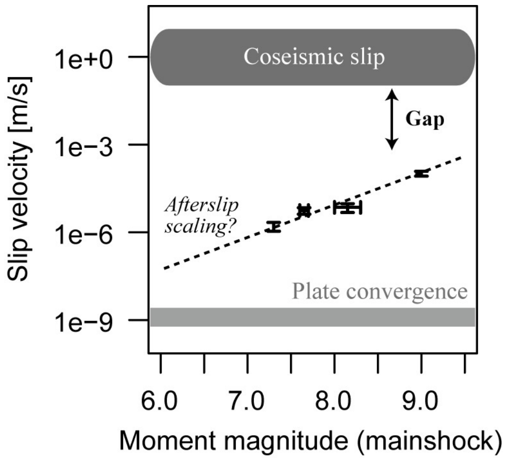
We discuss two topics about afterslip events at a subduction plate boundary, based on GPS data before and after the 2011 Tohoku-oki Earthquake.

Mitsui and Heki (in revision) estimated the amount of afterslip off-Sanriku during almost 30 minutes just after the 2011 Tohoku-oki Earthquake, separately from the subsidence amount by tsunami propagation. We found that the mean slip velocity of the early afterslip reached on the order of 0.1 mm/s. This value greatly exceeds those of previous afterslip in the neighborhood: after the 1994 Sanriku-haruka-oki Earthquake, the 2003 Tokachi-oki Earthquake, and the 2011 Miyagi-haruka-oki Earthquake (2 days prior to the Tohoku-oki Earthquake). Also we can read an increasing trend of the afterslip velocity for the mainshock magnitude (Mw), e.g., a scaling relation of the after slip velocity proportional to 10^{Mw} (see the figure below). The value of 0.1 mm/s may imply the maximal slip rate of afterslip phenomena. That fact corresponds to a change in velocity dependence of steady-state frictional coefficient based on rock experiments (Weeks (1993)).

Heki and Mitsui (2013, EPSL) found that landward velocity of GPS stations increased near segments adjacent to the ruptured segments after the 2003 Tokachi-Oki and 2011 Tohoku-Oki Earthquake, respectively. These enhancements of the plate coupling seemed synchronizing increases in trenchward velocity of GPS stations (so-called afterslip) near the ruptured segments. A similar phenomenon of the landward velocity increases was also observed after the 2012 Karafuto-Oki deep earthquake at GPS stations around eastern Hokkaido (Heki and Mitsui, this meeting). Based on the observations, we proposed a hypothesis of temporary subduction acceleration of the pacific plate associated with resistance loss for plate motion. This subduction acceleration can be interpreted as "afterslip" in a broader sense. In a previous narrowly-defined sense, afterslip is a relaxation process of stress concentration at edges of coseismic fault slip (e.g., Heki et al., (1997)). By contrast, in the new broader sense, afterslip is an adjusting process to balance forces of plate subduction. Monitoring this newly-defined afterslip may allow us to obtain original information about plate subduction processes.

Keywords: GPS, afterslip, frictional property, 2011 Tohoku-oki earthquake, plate subduction acceleration, deep earthquake



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Modeling of slow slip events along the subduction zone off the Pacific coast of Mexico

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Recent high-resolution geodetic observations have revealed the occurrence of slow slip events (SSEs), along the Mexican subduction zone. In the Guerrero gap, large slow slip events of around Mw 7.5 have been observed (Lowry et al., 2001; Radiguet et al., 2012), and the 2006 Guerrero slow slip propagated at an average velocity of 0.8 km/day. Recurrence intervals of SSEs are around every 3-4 years. On the other hand, in the Oaxaca region, SSEs of Mw 7.0-7.3 repeat every 1-2 years and last for 3 months(Correa-Mora et al., 2009). The present study models SSEs along the subduction zone off Mexico, based on a model by Shibazaki and Shimamoto (2007).

We use a rate- and state-dependent friction law with a small cut-off velocity for the evolution effect. We also consider the 3D plate interface, which dips at a very shallow angle at 100-150 km from the trench. We set the unstable zone from a depth of 10 to 20 km, and the zone of SSEs from 20 to 30 km. By setting the effective normal stress at around 1 MPa and the cut-off velocity for the evolution effect at 10E-7.5 m/s at the SSE zones, we reproduce SSEs occurring at intervals of around 5 years with propagation velocities of 1.0 km/day. In the present model, velocity strengthening occurs at a velocity greater than 10E-7.5 m/s, and therefore only small slips occur at the SSE zone when earthquakes occur in the seismogenic zones. A Mw 7.4 subduction earthquake occurred beneath the Oaxaca-Guerrero border on March 20, 2012, and the 2012 SSE coincided with this thrust earthquake (Graham et al., 2012). We verify our model by comparing numerical results with the observations.

Keywords: slow slip event, Mexico, Subduction zone, a rate- and state-dependent friction law