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

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

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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

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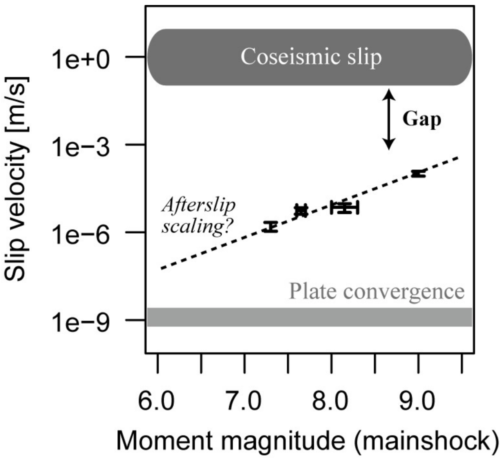
We discuss two topics about afterslip events at a subduction plate boundary, based on GPS data before and after the 2011 Tohoku-oki Earthquake.

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