Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG63-01 Room:303 Time:May 20 09:00-09:15

Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake

ITO, Yoshihiro[1*], HINO, Ryota[1], KIDO, Motoyuki[1], FUJIMOTO, Hiromi[1], OSADA, Yukihito[1], INAZU, Daisuke[1], MIURA, Satoshi[2], OHTA, Yusaku[1], UCHIDA, Naoki[1], TSUJI, Takeshi[3], ASHI, Juichiro[4], MISHINA, Masaaki[1]

[1]Graduate School of Science, Tohoku University, [2]Earthquake Research Institute, The University of Tokyo, [3]Department of Civil and Earth Resources Engineering, Kyoto University, [4]Atmosphere and Ocean Research Institute, The University of Tokyo

We describe two transient slow-slip events that occurred before the 2011 Tohoku-Oki earthquake that occurred near the high coseismic slip region near the Japan Trench. A transient crustal deformation, which occurred over 7 days in November 2008, was measured using ocean-bottom pressure gauges and an on-shore volumetric strainmeter simultaneously; this deformation has been interpreted as an Mw 6.8 slow-slip event with a slip magnitude of 0.4 m at most. The other transient crustal deformation was observed in mid-February 2011, just before the 2011 Tohoku-Oki earthquake: the source model of this deformation is probably almost the same as that of the 2008 transient slow slip. The two transient slow deformations preceded interplate earthquakes of magnitudes M 6.1 and M 5.8 in December 2008 and February 2011, respectively. The hypocenters are located at the down-dip ends of the slow-slip area. Our findings indicate that the slow-slip events induced an increase in shear stress, which in turn triggered the interplate earthquakes. The slow-slip area is also located within the large coseismic slip area of the 2011 earthquake; in particular, the slow-slip area is mainly located in the down-dip end of the high coseismic slip region near the Japan Trench. The result suggests that a fault segment where velocity strengthening occurs at low slip velocity and velocity weakening occurs at high slip velocity probably exists in the down-dip portion of the high coseismic slip area of the 2011 Tohoku-Oki earthquake.

Keywords: Slow slip event, The 2011 Tohoku-Oki earthquake, Ocean-bottom pressure observation

SCG63-02 Room:303 Time:May 20 09:15-09:30

Depth-dependency on direction and velocity of tremor migration in Kii peninsula

OBARA, Kazushige[1]*, MATSUZAWA, Takanori[2], TANAKA, Sachiko[2], MAEDA, Takuto[1]

[1]Earthquake Research Institute, The University of Tokyo, [2]National Research Institute for Earth Science and Disaster Prevention

Coupling phenomenon of non-volcanic tremor and slow slip event in southwest Japan [Obara, 2002; Obara et al., 2004] and Cascadia [Dragert et al., 2001; Rogers and Dragert, 2003] called Episodic tremor and slip (ETS) is an evidence for weak coupling of the plate interface at the downdip side of the seismogenic zone. One of the most significant features of tremor is migration. So far there exist three types of tremor migration; along-strike long-term migration at a speed of about 10 km/day [Obara, 2010], rapid tremor reversal (RTR) which is along-strike migration at a speed of order of 100 km/day propagating in the opposite direction from the long-term migration [Houston et al., 2011], and much faster slip-parallel migration at a speed of order of 1000 km/day detected in southwest Japan [Shelly et al., 2007] and Cascadia [Ghosh et al., 2010]. These three migration modes might reflect the main and sub rupture processes during the slow slip episode. Whether the tremor migration is composed of only above three modes or more is very important to construct the appropriate physical model for slow slip phenomena. In this paper, we investigate tremor migration by detecting automatically linear distribution of tremor sequence in Kii peninsula, southwest Japan.

We mainly analyzed a tremor catalog derived from the modified envelope correlation method [Maeda and Obara, 2009] considering with amplitude information applied to borehole data of the High Sensitivity Seismograph Network (Hi-net) administrated by the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan [Obara et al., 2005] from 2001 to 2010. In order to extract various migrating tremor sequences, we set four different time scales; 0.5, 1, 2 and 4 hours. For the given time window, at first, we choose a linear trend from the space-time plot. In this process, outliers with their distances from the regression line greater than two times of the standard deviation are removed. Then, the linearity of the tremor distribution in the map view and the space-time plot is checked by the principal component analysis. Total numbers of extracted migrating tremor sequences are 167, 213, 169 and 203 for time scales of 0.5, 1, 2 and 4 hours, respectively. The direction of migration is clearly different depending on the time scale. As a result, the tremor migration is characterized by prefixed direction at widely ranging speeds from a few to several 10 km/hr depending on the location. Decrease in the migration speed with increasing measurement time scale suggests that a diffusion process controls migration. The along-strike migration at the slower speed is concentrated in the updip edge of the tremor zone, on the other hand, the slip-parallel faster migration is detected in the downdip side. The long-term migration seems to be composed of and excited by the updipmost along-strike creep propagation. The updip along-strike migration might reflect existence of abundant fluid accumulated at the corner of the mantle wedge. Both of the faster slip-parallel migration and RTR might represent a projection of the along-strike fluctuation of slip pulse propagation at the slip-parallel striation.

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

Japan Geoscience Union Meeting 2012
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Triggered non-volcanic tremor in SW Japan by the Love waves from the 2011 M9.0 Tohoku earthquake and its aftershocks

ENESCU, Bogdan[1*], Kevin Chao[2], Zhigang Peng[2], OBARA, Kazushige[3], MATSUZAWA, Takanori[1], TANAKA, Sachiko[1], TAKEDA, Tetsuya[1]

[1]National Research Institute for Earth Science and Disaster Prevention, [2]Georgia Institute of Technology, [3]Earthquake Research Institute, The University of Tokyo

The March 11, 2011 M9.0 Tohoku earthquake was followed by large aftershocks and broad seismic activation both inland and offshore Japan (e.g., Hirose et al., 2011; Ogata, 2011; Toda et al., 2011). Previous studies (Enescu et al., 2011; Miyazawa, 2011; Obara and Matsuzawa, 2011) reported remotely triggered seismicity at distances up to about 1350 km from the mainshock. Deep non-volcanic tremor in south-west Japan (Obara, 2002) was also clearly activated following the Tohoku earthquake. We focus here on the detailed analysis of the triggered tremor.

We detect tremor that correlates with the passage of the mainshock surface waves at several Hi-net seismic stations in Shikoku region, at distances of about 1000 km from the Tohoku earthquake epicenter. We use an envelope cross-correlation technique to locate the tremor sources. The best tremor location is determined using a 3D grid-search that minimizes the residuals between observed and calculated travel time differences at pairs of recording stations. While the depth of the tremor source is not well constrained by our grid search, the signal originates from a deep source in the lower crust. Our location results show that the mainshock triggered tremor in two distinct areas, in western and central Shikoku, in regions where ambient (i.e., not triggered) tremor occurs (e.g., Obara et al., 2010). The triggered tremor in western Shikoku also occurs close to the tremor triggered by previous large, remote earthquakes (e.g., Miyazawa and Mori, 2006).

We have also detected triggered tremor during the passage of the incoming surface waves from the earliest aftershock (M7.4) of magnitude above 7.0, which occurred about 23 min. after the mainshock, as well as from the largest aftershock (M7.7) that occurred about 30 min from the mainshock. However, we did not find any evidence of triggered tremor by the M7.3 foreshock, occurred on March 9th, 2011.

We have estimated the peak dynamic stresses during the passage of surface waves from the mainshock and the two aftershocks, using the observed peak ground velocity at nearby F-net and KiK-net stations. The obtained values are roughly between 10 KPa and 180 KPa (the upper value corresponds to the mainshock), higher than the apparent triggering threshold found in this and other regions (Chao et al., 2011).

We have checked whether the detected tremor was triggered by the passage of the Love or Rayleigh waves from the Tohoku mainshock and its aftershocks. Our results indicate that the Love waves were the main triggering factor. The tremor triggered by the mainshock and the M7.4 aftershock, in particular, correlate well with the Love waves cycle. Our results are consistent with theoretical modeling that shows that Love wave displacement to the south-east (sea-ward) would promote up-dip shear on the plate interface in the Shikoku region (Hill, 2010). In a related study, Chao et al. (2011) report Love wave triggering in Shikoku by other remote earthquakes. While the triggering by Rayleigh waves in south-west Japan has been well documented (e.g., Miyazawa and Mori, 2008), our recent work shows for the first time clear evidence of Love wave triggering in the region.

Keywords: Non-volcanic tremor, SW Japan, triggering, Love waves, 2011 M9.0 Tohoku earthquake

Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SCG63-04 Room:303 Time:May 20 09:45-10:00

Semi-Volcanic Deep Low-Frequency Earthquakes

ASO, Naofumi[1*], OHTA, Kazuaki[1], KURIHARA, Yoshiharu[1], IDE, Satoshi[1]

[1]The University of Tokyo

<**Backgrounds**>

Deep low-frequency earthquakes (LFEs) are categorized into three types based on their locations: volcanic LFEs near the Mohorovicic discontinuities beneath active volcanoes, tectonic LFEs on the plate boundaries, and isolated intraplate LFEs near the island arc Mohorovicic discontinuities far from active volcanoes. The geographical distribution of LFEs suggests that these three types of LFEs are related to great natural phenomena such as volcanic eruptions, interplate megathrust earthquakes, and large inland earthquakes, respectively. While tectonic LFEs have been revealed in many respects since their discovery in the beginning of this century, volcanic LFEs and isolated intraplate LFEs are less understood and the previous works on them tended to focus on individual activities of regional LFEs [e.g., *Hasegawa et al.*, 1991; *Ohmi and Obara*, 2002]. As a comparative study, *Aso et al.* [2011] pointed out that the isolated intraplate LFEs in Osaka Bay show similar activities to volcanic LFEs, but the universal characteristics of LFEs and the basic differences between three types of LFEs have never been revealed. In the present study, we extracted the common characteristics of isolated intraplate LFEs by analyzing the activities of isolated intraplate LFEs in multiple regions, and compared three types of LFEs based on a common method by analyzing volcanic LFEs and tectonic LFEs in the same way.

<**Data and methods**>

Based on the method developed by *Aso et al.* [2011], we analyzed and compared the seismicity of isolated intraplate LFEs in Osaka Bay and eastern Shimane, volcanic LFEs in Sakurajima, and tectonic LFEs in northern Kochi and central Ehime. Because the detected LFEs by Japan Meteorological Agency (JMA) are not sufficient for statistical analysis, in the present study, we automatically detected LFEs using waveform correlation on the Hi-net continuous records and estimated the magnitude of the detected LFEs based on the amplitude ratios. To study temporal and spatial characteristics, we quantified the sensitivity to tidal stress by taking activity spectrum and examined the detailed structure of hypocenter distribution by applying the NCC relocation method [*Ohta et al.*, 2008].

<**Result and discussions**>

The isolated intraplate LFEs and volcanic LFEs obey the Gutenberg-Richter law with a b-value of 2, while distinct upper limits were found in the frequency magnitude statistics of tectonic LFEs. The activity spectra of the isolated intraplate LFEs and volcanic LFEs show no evidence of tidal modulation, while those of tectonic LFEs have a clear peak at the M_2 period, suggesting tidal modulation. The relocated hypocenters of isolated intraplate LFEs and volcanic LFEs are distributed vertically as well as horizontally, while the distributions of tectonic LFEs are linear or planar on the nearly-horizontal plate boundary. These characteristics of three types of LFEs in five regions manifest that isolated intraplate LFEs are quite similar to volcanic LFEs, and that tectonic LFEs are different phenomena. Moreover, the discretized triggering model developed by *Kurihara et al.* [2012 (this meeting)] shows similar triggering probabilities for isolated intraplate LFEs and volcanic LFEs. In addition to the fact that most isolated intraplate LFEs occur beneath Quaternary volcanoes, these new findings about activities of LFEs suggest that isolated intraplate LFEs are generated by movements of fluids, as suggested for volcanic LFEs previously. Hence we propose that isolated intraplate LFEs should be named as "semi-volcanic" LFEs. In the future works on LFEs, semi-volcanic LFEs should be regarded as almost the same phenomena to volcanic LFEs, and their analyses may contribute to the understanding of volcanic LFEs and volcanism. Another kind of important information to identify the actual physical process is provided by focal mechanisms, which have been also estimated reliably by *Aso et al.* [2012 (this meeting)].

Keywords: Low-Frequency Earthquake, Semi-Volcanic LFE

Japan Geoscience Union Meeting 2012
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Detection of short-term slow slip events using GPS data in southwestern Japan (Part 2)

NISHIMURA, Takuya[1*], MATSUZAWA, Takanori[2], OBARA, Kazushige[3]

[1]GSI of Japan, [2]NIED, [3]ERI, Univ. of Tokyo

Nishimura and Suito (2011) reported that GPS was able to detect short-term slow slip events (SSEs) which had been observed only by tiltmeters and strainmeters on the plate interface of the Philippine Sea plate. Here, we present a method to detect the deformation associated with the SSEs in southwestern Japan and fault models of the SSEs inverted from GPS data. We also compare them with a tremor activity (Maeda and Obara, 2009; Obara et al., 2010) and the fault models of the SSEs estimated from tilt data (Sekine et al., 2010).

Daily coordinates of 565 GEONET stations in southwestern Japan were used to detect the deformation of the SSEs. We fitted a step function to the filtered daily coordinates to detect displacements in a direction of N130^{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.

201 candidides of SSEs were found in a period from June 19, 1996 to August 14, 2011. They were categorized into 88 certain SSEs, 51 probable SSEs and 62 non-SSEs. Moment magnitude (M_w) of the 137 certain and probable SSEs ranges between 5.4 and 6.4. SSEs with M_w => 6.2 have occurred only in western and central Shikoku 7 times. No certain SSEs occurred in the Kii Channel and east of 137.5^{o}E (Lake Hamana). A couple of certain SSEs have occurred in Ise Bay where the tremor activity is weak.

Comparing the fault models from GPS with those from tilt data (Sekine et al., 2010), we found 27 SSEs included in both catalogues. There is no systematic difference of their M_w estimated from GPS and tilt. SSEs with M_w => 6.1 were included in both catalogues. However, 25 and 17 SSEs were detected solely from GPS and tilt data, respectively. Those SSEs must be real slip events because they accompany tremor activities. It, therefore, suggests that the detectability of neither GPS nor tiltmeter is perfect for small SSEs. We calculated moment released by SSEs in each segment along the Nankai Trough. The moment rate is roughly constant in western Shikoku for 15 years but it increases around 2006 in eastern Shikoku. The increase may reflect a long-term change of conditions on the plate interface because similar increase is also observed in tremor activities (Obara et al., 2010). However, we cannot rule out that the increase is artificial due to replacement of GPS antennas and additional GPS stations.

Keywords: short-term SSE, GPS, southwestern Japan

Japan Geoscience Union Meeting 2012
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Activation of short-term slow slip events and deep non-volcanic tremors due to the Bungo-Channel slow slip event

KISHIMOTO, Tsuyoshi[1*], SUDA, Naoki[1], OZAWA, Shinzaburo[2], YARAI, Hiroshi[2]

[1]Hiroshima Univ., [2]GSI

In the Nankai subduction zone, slow earthquakes with various time constants occur in the transition region of the subducting plate interface. In particular in the Bungo Channel region, the westernmost part of the slow earthquake belt in southwest Japan, not only short-term slow slip events along with very low-frequency earthquakes and non-volcanic tremors with a recurrence interval of 2 to 3 months, but also long-term slow slip events occurred in 1997, 2003, and 2009-2010 at the shallower part of the subdudting plate interface. It has been observed that very low-frequency earthquakes are associated with these aseismic slips at the further shallower portion near the Nankai trough. These aseismic events also activate tremor occurrences at deeper part in the Bungo Channel region. These suggest that the long-term slow slip events affect the source regions of other slow earthquakes. In our previous study, we focused on activated tremor occurrences during the 2009-2010 long-term slow slip event. We calculated the coulomb stress rate in the tremor source region from the slip history of 2009-2010 long-term slow slip event, and compared it with tremor durations in the three subregions, southwest and northeast of Hiburi Island, and westernmost Shikoku. We found that observed tremor activity changes were consistent with the calculated Coulomb stress rate due to the long-term slow slip event in each subregion.

According to the steady-state seismicity rate theory based on the rate- and state-dependent (R/S) friction law, the calculated Coulomb stress rate should be proportional to the observed tremor duration, but we found that the observation did not satisfy this relation. This is because we assumed that the observed tremor activity change was a direct consequence of the long-term slow slip event. In the model of concurrent occurrence of slow earthquakes, tremors are triggered by the transient stress change due to the short-term slow slip events. In this study, on the basis of this model, we consider a two-step model for the observed activation of tremor occurrence: the long-term slow slip event first activates occurrence of short-term slow slip events, and then they activate the tremor occurrence. Using this model, we have found that the steady-state seismicity rate theory gives a better quantitative explanation to the apparent consistency between the calculated Coulomb stress rate due to the long-term slow slip event and the observed tremor activity.

Keywords: slow slip event, deep non-volcanic tremor, coulomb stress rate, Bungo Channel

Japan Geoscience Union Meeting 2012
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Slip history for the 2011 Boso peninsula slow slip event and the accompanying earthquake swarm

HIROSE, Hitoshi[1*], KIMURA, Hisanori[2], KIMURA, Takeshi[2], MATSUZAWA, Takanori[2]

[1]Department of Earth and Planetary Sciences, Kobe University, [2]National Research Institute for Earth Science and Disaster Prevention

Around the Boso peninsula, central Japan, slow slip events (SSEs) lasting for one to two weeks that are accompanied by earthquake swarm activity recur every 5-7 years in association with the subduction of the Philippine Sea plate (Sagiya, 2004; NIED, 2003; Ozawa et al., 2003, 2007). In October 2011, the latest episode occurred after the shortest interval of four years and two months in 30 years. The crustal deformations for this episode and the previous episode in 2007 are detected with the GEONET GPS array operated by the Geospatial Information Authority of Japan and the NIED Hi-net high-sensitivity accelerometers (tiltmeters). In order to clarify the relation between these SSEs and the accompanying earthquake swarms, it is important to estimate detailed source processes of the SSEs, and to compare them with the temporal and spatial distribution of the earthquakes. In this study, we investigate the slip source processes for the 2007 and 2011 SSEs based on the Hi-net tiltmeter data and the GEONET data.

The slip histories for both episodes show the following common features in an overall view: (1) slip initiates at the eastern offshore area of Katsuura and the center of the slip migrates to the west direction gradually as the slip accelerates, and (2) the earthquake activity also migrates from the eastern area to the west, corresponding to the slip migration. These evidence strongly suggests that the earthquake swarms are triggered by the slow slip. However, the two episodes have slightly different slip histories. For the 2007 episode, slip initiates at the eastern offshore area and migrates to the northern, deeper part in the initial stage. For the 2011 episode, the northward slip migration seen in the 2007 episode is not resolved significantly, but the slip propagates slightly to the southwestern, shallower area after the slip acceleration and the active phase of the earthquake swarm. Although these differences in the slip histories might be artifacts caused by different station coverages, there is a possibility that the differences show the variation in the slip processes through the cycle of the Boso SSEs. Since the source region of the SSEs is located by the rupture area of the interplate great earthquakes along the Sagami trough, the SSEs are important indicators to study the interseismic preparation process for the megathrust earthquakes.

Acknowledgments: The GPS data were provided by Geospatial Information Authority of Japan.

Keywords: Sagami trough, subduction zone, GPS, tilt change, earthquake swarm

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(May 20-25 2012 at Makuhari, Chiba, Japan)

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Atomistic origin of velocity-strengthening friction

HATANO, Takahiro[1*]

[1]ERI, Univ. Tokyo

Since the discovery of non-volcanic deep low-frequency tremor (Obara 2002), various kinds of slow earthquakes (or slow slips) have been discovered. However, the underlying physical mechanisms that yield such diversity of slow slips are still not known. Because the slow slips play an essential role in the stress accumulation processes in subduction zones through the cycle of slow slips and the moment release dynamics, various models have been proposed that address to reproduce slow slips and their cycle. In most of the models, friction laws are employed that possess positive velocity dependence. It is natural because the slow slips involve some kinds of stability, which may be represented as positive velocity dependence. However, from materials science point of view, it is not generally understood that under what conditions friction can have positive velocity dependence.

Here we report the atomistic nature of the rate- and state-dependent friction law, which is often adopted in modeling slow earthquakes. We begin with the creep constitutive law that describes the deformation process of a true contact junction and derive the rate- and state-dependent friction law. As a result, the empirical parameters (generally denoted by a, b, and L) are expressed in terms of atomistic parameters (activation energy, temperature, etc). By virtue of these expressions, one can determine the velocity dependence of friction from materials constants, and the length constant from the surface topography. We further discuss these results that are relevant to slow earthquakes: in particular, 1) crossover from negative to positive velocity-dependence. 2) role of water in velocity dependence.

Keywords: friction, rate- and state-dependent friction, creep

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Geological process of the slow earthquakes

KITAMURA, Yujin[1*], KIMURA, Gaku[2], KAWABATA, Kuniyo[3]

[1]IFREE, JAMSTEC, [2]Dept. Earth Planet. Sci, Univ. Tokyo, [3]Inst. Geophys., National Central Univ.

We present an attempt to unveil the geological aspects of slow earthquakes and the related plate boundary processes and to establish a model for slow earthquake formation. As we have investigated material along subduction channel from on-land outcrops and ocean drilling cores, a series of progressive deformation down to the down-dip limit of the seismogenic zone was revealed. Studied tectonic melanges in the Shimanto Belt, Japan are regarded as fossils of plate boundary fault zone in subduction zone. Detailed geological survey and structural analyses enabled us to separate superimposed deformation events during subduction. Material involved in the plate boundary deformation is mainly an alternation of sand and mud. As they have different competency and are suffered by simple shear stress field, sandstones break apart in flowing mudstones. We distinguished several stages of these deformations in sandstones and recognized progress in the intensity of deformation with increment of underthrusting. It is also known that the studied Mugi melange bears pseudotachylyte in its upper bounding fault. Our conclusion illustrates that the subduction channel around the depth of the seismogenic zone forms a thick plate boundary fault zone, where there is a clear segregation in deformation style: a fast and episodic slip at the upper boundary fault and a slow and continuous deformation within the zone. The former fast deformation corresponds to the plate boundary earthquakes and the latter to the slow earthquakes. We further examined numerically whether this plate boundary fault rock is capable of releasing seismic moment enough to fit the observed slow earthquakes. The shallow very low frequent earthquakes (VLFs) are chosen to be modeled and our estimation satisfies the natural data. These results make a strong impact on the study of seismic energy balance because we show a possibility to give an absolute value of them from geological approach, which could not have been achieved with seismology.

Keywords: Slow earthquake, Shimanto Belt, Nankai Trough, plate boundary earthquake, tectonic melange