Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SCG058-01 Room:302 Time:May 22 10:45-11:00

Migration properties of non-volcanic tremor

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Active burst of non-volcanic tremor detected in the Nankai and Cascadia subduction zone is usually associated with the short-term slow slip event, which is the stick slip in the deeper extension of the megathrust zone on the plate interface. The hypocenter of tremor and slip distribution of SSE are spatiotemporally synchronized each other. The duration time of the tremor episode is proportional to the moment of the SSE. Therefore, the tremor activity is considered as a sensitive sensor to monitor the interplate slip in the transition zone. The tremor activity is characterized by migration along the strike of the subducting plate at about 10 km/day. Moreover, the rapid migration at several 10 to 100 km/hour along the dip direction have been detected. The existence of the variation migration modes is important to resolve the fault slip process. Here we investigate some migration properties based on the new tremor catalog in southwest Japan.

In this study, we used the tremor catalog calculated every one minute by modified envelope cross correlation method (Maeda and Obara, 2009) and centroid tremor catalog calculated every one hour by the clustering process (Obara et al., 2010). The depth of the tremor is pinned on the plate interface given by the receiver function analysis. Based on the centroid tremor catalog, a depth dependent behavior of the tremor activity was clarified within the narrow tremor zone. At the shallower part, the major tremor episode with longer duration occurs at recurrence interval of a several months; however the short-duration minor tremor episode frequently occurs at the deeper part. The migration pattern also shows a systematic pattern in the dip direction. The major tremor activity usually starts from the deeper side and migrates updip at about 10 km/day. The updip migration is clearly observed on the tremor striation parallel to the slip direction. Based on the detail analysis of the space-time distribution by removing aftershock-like tremor activity, the tremor propagates radially from the initiation point and the migration front seems to be a circle. Therefore, the pre-known along-strike migration pattern may be interpreted as the radial migration within the narrow tremor belt. During the major tremor episode in northeastern Kii peninsula, we detected small-scale migration rapidly back along strike at velocity of 10 times faster than the slow-speed main migration. In this area, the tremor episode recurs every six months and migrates at 10-15 km/day. The tremor activity remains after passing through the migration front. During the aftershock-like period, the rapidly back migration at 5-20 km/hour occurred spanning 10-30 km in length. During the January 2006 episode propagating to the northeast direction, the rapid tremor reversal with a speed of 5 km/hour migrated southwestward; on the other hand, the rapid tremor reversal migrated northeastward on the same place during the June 2004 episode propagating to the southwest direction. Therefore, there exists at least three modes of tremor migration; along-strike migration at about 10 km/day over , along-strike reverse migration at about 100 km/day, and along-dip migration at about 1000 km/day.

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

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SCG058-02 Room:302 Time:May 22 11:00-11:15

Data quality characterization of deep low-frequency tremor catalogs and frequency-magnitude relation of tremor events

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A nationwide high-frequency seismograph network (Hi-net) deployed by the National Research Institute of Earth Science and Disaster Prevention (NIED) is a key contribution to discovering deep low-frequency tremor associated with subduction in south west Japan (Obara, 2002). The tremor was also found in the Cascadia margin of the North American continent, Taiwan, and the San Andreas Fault. The finding demonstrates that this phenomenon is not regional but universal. Previous studies have focused on developing the methodology to detect and locate tremor events as well as characterizing tremor episodes by migration, segmentation, and periodicity, while the collective (statistical) properties of tremor events are not yet fully understood. Before devoting to in-depth statistical research on tremor events, it is necessary to create tremor catalogs and use them to get better understanding of data quality for each catalog. In this study, we use the NIED tremor catalog as a primary data source and then investigate if the statistical properties of tremor events are similar to those of regular earthquakes. We also create a catalog consisting of events identified as tremors stored in the JMA catalog. This supplement is used for comparison with the NIED catalog. Our approach is based on the Gutenberg-Richter (GR) frequency-magnitude law of tremor events. This law is valid for all earthquakes both regionally and globally. We show that the GR law is also valid for tremor events, suggesting that earthquakes and tremor events are similar physical processes. Reported characteristics will allow us to move toward conducting in-depth statistical studies of tremor events.

Keywords: Seismic instruments and networks, Dynamics: seismotectonics, Statistical analysis, Data management, Earthquake dynamics

Japan Geoscience Union Meeting 2011
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SCG058-03 Room:302 Time:May 22 11:15-11:30

Deep non-volcanic tremors synchronized with surface waves from teleseismic large earthquakes (2)

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Deep non-volcanic tremors are sometime triggered by surface waves from large teleseismic earthquakes. Occurrences of triggered tremors are usually modulated with a period of about 20 seconds, the same as a period of dominant surface waves. Such phenomena are very important when considering the physical state of tremor source region. Tremor occurrences are also modulated by Earth tides with periods of about 12/24 hours. Using the seismicity rate theory based on the rate- and state-dependent (R/S) friction law, one of fault parameters in the friction law has been determined by inverting observations of tide-modulated tremor occurrences. In this study we tried to explain observations of surface-wave-modulated tremor occurrences using the same method as the tide modulation case. However, it was not possible to explain the observations consistently. This indicates that simple application of the seismicity rate theory based on the R/S friction law cannot explain surface-wave triggering of tremor.

Keywords: non-volcanic tremor, surface wave, dynamic triggering, southwest Japan, slow earthquake

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SCG058-04 Room:302 Time:May 22 11:30-11:45

Detection of non-volcanic deep low-frequency tremors recorded by the Horai seismic array, central Japan

Yoshiko Yamanaka[1*], Sayumi Yoshida[1], Haruhisa Nakamichi[1], Toshiki Watanabe[1], Toshiko Terakawa[1], Shinichiro Horikawa[1]

[1]Nagoya university

Non-volcanic deep low-frequency tremors (LFT) occur at regular intervals of about 4-6 months beneath the Tokai region, central Japan. We deployed a seismic array of short-period 3-component sensors at Horai near the Tokai tremor zone from September, 2008. We applied the zero-lag cross correlation method (ZLC) to LFT records in the period from February 5 to 15, 2009 to estimate the apparent velocities and back-azimuths of LFT. The LFT records were band-pass filtered and windowed with 2 sec windows to apply the ZLC. We obtained stable apparent velocities and back-azimuths for LFT, corresponding to the locations of deep low-frequency earthquakes detected by JMA.

Keywords: non-volcanic deep low-frequency tremor, non-volcanic deep low-frequency earthquake, seismic array, detection ability, cross-correlation, Philippine Sea plate

SCG058-05 Room:302 Time:May 22 11:45-12:00

Detection of P-waves and migrations of non-volcanic deep low-frequency tremors recorded by the Horai seismic array

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Non-volcanic deep low frequency tremors (LFTs) occur at regular intervals of about 4~6 months beneath the Tokai region. LFT signals are weak and lack of clear onsets of P and S waves. Therefore, it is difficult to estimate source locations of LFTs by ordinary methods. Array observations have been conducted to detect LFTs and estimate locations of LFTs (e.g., La Rocca et al., 2008).

We deployed a seismic array of short-period 3-component sensors at Horai near the Tokai tremors zone from September, 2008. We applied the zero-lag cross-correlation method (ZLC) to LFT records in the period from February 5 to 15, 2009 to estimate the apparent velocities and back-azimuths of LFTs. The LFT records were band-pass filtered and windowed with 2 sec windows to apply the ZLC.

We successfully detected several P wave phases for each LFT episode with apparent velocities of 8 km/s by the ZLC analysis of vertical waveforms. We estimated source locations of LFTs S-P times, apparent velocities and back-azimuth, and obtained the locations near the reported hypocenters by JMA. We also estimated source locations of LFTs without clear P arrivals using only apparent velocities and back-azimuths for S waves and assuming that the sources are located on the subducting plate boundary (Hashimoto et al., 2004). The migration of tremor location is detected by this location procedure for the LFTs episode in February, 2009.

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SCG058-06 Room:302 Time:May 22 12:00-12:15

Fault-zone models revisited

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Recent friction to flow constitutive equation (Shimamoto, 2004, JpGU; Shimamoto and Noda, 2010, AGU)allows to predict the behavior connecting frictional properties in the brittle regime and high-temperature plastic flow for faults and shear zones. The presentation will summariize current data on flow and friction properities to discuss (1) transitional behavior between friction and flow, (2) properties in slow slip regime and (3) how to reproduce the friction to flow transition using realistic rocks.

Keywords: fault-zone model

Japan Geoscience Union Meeting 2011
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SCG058-07 Room:302 Time:May 22 12:15-12:30

Generation mechanism of slow earthquakes: Numerical analysis based on a dynamic model

Ryoko Nakata[1]*, Ryosuke Ando[2], Takane Hori[1], Satoshi Ide[3]

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Various characteristics have been discovered for small, slow earthquakes occurring along subduction zones, which are deep nonvolcanic tremor, low-frequency earthquakes (LFEs), and very low-frequency earthquakes (VLFs). For example, the velocity spectra of seismic waves from tremor, LFEs, and VLFs are almost flat in a broad frequency range of 0.01 to 10 Hz [Ide et al., 2008]. The tremor sources migrate with a velocity of roughly 10 km/day in the strike direction of the subducting plate [Obara, 2002], and 100 km/h in the dip direction [Shelly et al., 2007]. The slow along-strike migrations of tremor episode are sometimes accompanied by the rupture propagation of slow slip events (SSEs) [Rogers and Dragert, 2003; Obara et al., 2004]. So far, there is no physical model available that encompasses all of the above characteristics. Ando et al. [2010] proposed a model that explains the anisotropy of the tremor source migration speed and the spectral property of small slow earthquakes in which dynamic ruptures occur on frictionally unstable patches triggered by a passing stress pulse of an SSE. In this study, we model these slow earthquakes using a dynamic model consisting of a cluster of frictionally unstable patches on a stable background by using slightly modified version of the model by Ando et al. [2010]. The key parameters in our model are related to the patch distribution and the viscosity of both the patches and the background.

By decreasing patch density or increasing viscosity, we observed the transition in rupture propagation mechanism, that is, from fast elastodynamic interactions characterized by an elastic wave propagation to slow diffusion-limited by viscous relaxation times of traction on fault patches and/or background. In addition, some parameter sets correctly explain observed characteristics such as moment rate functions, spectral properties, parabolic migration, and the scaled energy. Therefore, the characteristics derived from observations may provide information about the source structure and frictional properties of our dynamic model of tremor, LFEs, and VLFs, and potentially, SSEs. This model will be a powerful tool to understand the generation mechanism and various aspects of slow earthquakes in a simple framework engaging source structures and frictional properties of brittle-ductile transition zones along plate boundaries.

Acknowledgments
This work was partly supported by the project "Evaluation and disaster prevention research for the coming Tokai, Tonankai and Nankai earthquakes" of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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SCG058-08 Room:302 Time:May 22 12:30-12:45

Rupture propagation limited by on-fault diffusion

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We propose that the possible mechanism of slow earthquakes is a diffusion limited process realized by certain fault rheology with velocity hardening characteristics. However, the contribution of the diffusion will not be simple and we must understand how the diffusional processes appear in the observable features. In this talk, I will show a basic theory and discuss some observational facts based on this idea. In our model, developed in Ando et al [2010] and systematically analyzed in Nakata et al. [2010], source areas consist of unstable patches sparsely and heterogeneously distributed. The rupture speed is controlled by the density and sizes of the unstable patches and by the viscosity of the stable background area on the fault.

References

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Nakata, R., Ando, R., Hori, T. and Ide, S, Generation mechanism of slow earthquakes: Numerical analysis based on a dynamic model with brittle-ductile mixed fault heterogeneities, Journal of Geophysical Research, (submitted), 2010.

Keywords: Slow earthquake, model, theory, simulation, dynamics, dynamics

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SCG058-09 Room:302 Time:May 22 14:15-14:30

Volcanic-like Deep Low-Frequency Earthquakes beneath Osaka Bay

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Among the many deep low-frequency earthquakes (LFEs) recently discovered worldwide, LFEs beneath Osaka Bay, western Japan, are especially unusual. Their waveforms are monochromatic, resembling those of some volcanic LFEs, but there are no volcanoes around. The area is close to but clearly distinct from a belt of tectonic LFEs, and is near the site of a large inland earthquake (the 1995 Kobe earthquake).

To characterize the activity of these LFEs, we present an extensive catalog constructed using a matched filter analysis on continuous seismic records with template LFEs determined by the Japan Meteorological Agency.

The relocated catalog of 1221 events over a period of 5 years shows spatially concentrated activity in two volumetric zones, with several active periods including successive tremor-like events. The magnitude-frequency statistics satisfy the Gutenberg-Richter law with a b-value of 2. Unlike tectonic LFEs, which are highly sensitive to tidal stress, the LFEs beneath Osaka Bay show no spectral peak in activity at tidal periods, and the overall pattern of the spectrum is similar to that of volcanic LFEs beneath Sakurajima, Japan.

These findings suggest that the Osaka Bay LFEs are almost same as volcanic LFEs in origin, or at least related to fluid upwelling from the mantle.

Keywords: Low-frequency earthquake, Osaka Bay, Japan, Volcanic earthquake, Matched filter, Tidal modulation, G-R law

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SCG058-10 Room:302 Time:May 22 14:30-14:45

Phase portrait of non-linear low frequency volcanic tremors and structure estimation of differential equation system

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On September 1, 2004, a middle-scale eruption occurred at Mt. Asama, Japan. Before the eruption, we had observed several kinds of low frequency volcanic tremors and low frequency long-lasting volcanic events since October 2003. Takeo (2010) revealed the non-linear dynamics of these low frequency tremors and long-lasting events using an embedding method of time delays and a surrogate data analysis, and made clear that there existed a deterministic non-linear dynamics in the tremor and event excitations, which could be modeled with the system dimension between 3 to 7 (prospective dimension 3 or 4).

In this paper, we formulate a new topological approach for structure estimation of differential equation system exciting the non-linear low frequency volcanic tremors and long-lasting events based on a phase portrait analysis and a potential estimation. The basic concept of this approach is that the time series data exemplify a variable of differential equation exciting these tremors and events. The typical period of them are several to ten seconds, meaning that the wavelengths are longer than one or two kilometer. These signals were recorded by the seismometers installed at the crater rim, so the waveforms were not affected by wave propagation effect, and exemplified the excitation dynamics correctly. Therefore, it will be expected that we directly infer the structure of differential equation system.

At first, we divided the time series data (x) into several terms and made phase portraits of x vss. dx/dt and/or x vss. dˆ2x/dtˆ2 to examine differential structure in the particular term. As a typical example, we picked up a long-lasting low frequency event occurred at 12:34 on June 12, 2004. We employed a FIR low-pass filter with a cut-off frequency of 1 Hz to omit high frequency component. Before the event, the phase portrait of x vss. dˆ2/dtˆ2 (x, dˆ2x/dtˆ2) depicts two linear lines with different negative gradients and the portrait of x vss. dx/dt (x, dx/dt) does two circles with different radii. These phase portraits mean that the solution of differential equation consists of sinusoidal waves with two different frequencies and amplitudes. In the initial part of the event, the phase portraits dramatically change; (x, dˆ2x/dtˆ2) consists of several lines in which some of them have negative gradients and others do positive gradients. (x, dx/dt) consists of several circles but some of them are separated by cusps, and some turnaround orbits depict quick movements. The existence of positive gradient in (x, dˆ2x/dtˆ2) and of cusps in (x, dx/dt) indicates that a system potential with a number of local minimal surface is thought to exist and the solution jumps across a local maximal pass when some amount of energy is supplied. The quick movement of phase portrait suggests that the differential equation system includes a relaxation oscillator.

The results mentioned above reveal the source dynamics of these non-linear tremors and long-lasting events could be modeled by the differential equation system including a relaxation oscillator and with the system dimension between 3 to 7 (prospective dimension 3 or 4). Takeo (2010) proposed a hydraulic control valve model with the system dimension of 4 as a candidate of source model of these events. (x, dx/dt) and (x, dˆ2x/dtˆ2) phase portraits of this model have similar characteristics of the observed phase portraits, meaning this model is a leading candidate. During the first stage of eruption activity in Kirishima volcano in 2011, we also observed the analogous non-linear volcanic tremors. We will analyze these tremors using the same approach, and will examine other possible candidates of differential equation system.

Keywords: Volcanic tremor, Non-linear dynamics, Low frequency oscillation

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SCG058-11 Room:302 Time:May 22 14:45-15:00

Distribution and focal mechanisms of very low frequency earthquakes along the Ryukyu trench axis in 2007-2008

Yoko Tu[1*], Masataka Ando[1], Hiroyuki Kumagai[2], Yoshiko Yamanaka[3], Cheng-Horng Lin[1]

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Broadband seismograms from BATS (Broadband Network in Taiwan) and F-Net (NIED broadband network in Japan) were analyzed to find very low frequency earthquakes (VLFEs) along the Ryukyu trench. All seismograms in the years of 2007-2008 were band-path-filtered (0.02-0.05 Hz) to pick-up VLFEs. Several clusters of very low frequency events were found along the Ryukyu trench. First, high signal-to-noise-level events were selected out the broadband seismograms. Then, local and teleseismic earthquakes were removed from these events using the hypocenter catalogs of the PDE, the Central Weather Bureau (CWB) and the Japan Meteorological Agency (JMA). Through the procedure, about 1200 and 1000 events were identified as VLFEs in 2007 and 2008, respectively. Spectra of typical events in these earthquakes show peak frequencies between 0.06 to 0.1 Hz. These VLFEs were selected and grouped into three main clusters. The regionalization is possible based on arrival time, amplitude and similarity in waveform: 1) Yonaguni-Ishigaki, 2) Okinawa Island, 3) Amami Island. The CMT solutions were obtained for these VLFEs using the inversion technique by Nakano et al. (2008). The accurate locations and focal mechanisms were determined further by a grid-search method where a minimum residual is searched within each area of latitude range of 5 degrees and longitude range of 5 degrees and a depth range 0 to 100 km. About 100 events from the Ishigaki-Yonaguni group were well located with low residuals. For the analysis of this group, data from BATS were used. However, events in Okinawa Island and Amami Island groups were not as well located because they are small in terms of magnitude. Among the selected events, low angle thrust fault was found to be dominant. Although some strike-slip and normal faults are included, their reliability is low and they are not included in the list of reliable solutions. Based on the events herein studied, the distribution and depth of VLFEs suggest that these events occurred mostly in the accretionary prism along the Ryukyu trench similar to those found in Central Honshu. This similarity may suggest that the upper interface of Ryukyu trench is locked.

Keywords: Very low frequency earthquake, Subduction, Ryukyu trench, Source inversion

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SCG058-12 Room:302 Time:May 22 15:00-15:15

Very low frequency earthquakes near the western region of the Ryukyu subduction zone

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Very low frequency earthquakes (VLFEs) have been observed near the trench axis along the Ryukyu Trench in four distinct regions: south of Yonaguni-Ishigaki, south of Okinawa island, south of Amami Oshima and east of Kyushu (Tu et al., 2009). The previously identified events of VLEFs in the Yonaguni-Ishigaki region are generally characterized with a simple waveform and well-constrained mechanisms by the inversion scheme. In the present study, the focus is on the Yonaguni-Ishigaki region to examine a temporal change of activity and its relation to the slow slips based on GPS data. In this study we used the data from the Yonaguni station (YNG) together with Ishigaki station (IGK) that was set up as part of the F-net stations. This 2003 enhancement of the network significantly improved the accuracy of the hypocenter and mechanism determination of VLFEs in the western margin of the Ryukyu Trench. However, in 2003 the noise levels were high at some stations. Thus, only the data between 2004 and 2010 have been analyzed. VLFEs selected for analysis are chosen from the seismograms based on the following criteria: 1) recognizable VLFEs among 2004-2010 seismograms that were filtered through the bandpass of 0.02-0.05Hz; 2) events are not listed on PDE, JMA, and CWB (Taiwan Central Weather Bureau) catalogs; and 3) earthquakes that were recorded by at least 5 stations. The present study examined the number of VLFEs as an index of the seismic activity. Among the VLFEs in Yonaguni-Ishigaki region, the smallest VLFE is M2.0, occur as swarm type in a series of events, and sometimes as a single event. The swarm-type events are generally smaller than M3.0 comprised of a sequence of many VLFEs within 2- to 6-hour duration. Intervals between VLFEs are about 2-10 minutes. However, it was noted that no VLFE that is continuous for several days to 1-2 weeks was seen in this region. The peak of these activities will appear every 2-3 months with the longest lasting about six months. Furthermore, during a sequence of large waves from either large teleseismic event or a medium- to large-size local earthquake, VLFEs signals are masked and unidentifiable for 30 minutes or even up to 1 day, which totaled to about 10% of the whole observation period. In an earlier study, slow-slips in this region have been detected beneath the lands at depths 40-50km by analyzing GPS data (Heki and Kataoka, 2008; Nakamura, 2009). Moreover, Heki and Kataoka (2008) ascertained episodic slips that occurred every six months. In the present study, however, VLFE activity was not correlated with such slow slip activity from 2004 to 2010 observation period. Furthermore, unlike events off coast of Tokachi, the Kii peninsula and Kyushu, the occurrence of VLFEs in the present study area shows no correlation with teleseismic or local earthquakes. In the present region, if the shear stress increases on the VLFE patches due to continuous subduction plate loading, these patches would eventually rupture when cumulative stress reaches a yield stress without external disturbances. In the future study, we will include correlation between the VLFEs activity and the seismic moment.

Keywords: Very low frequency earthquake, Ryukyu trench, seismicity, slow slip, subduction, accretionary prism

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SCG058-13 Room:302 Time:May 22 15:15-15:30

Very-low-frequency earthquakes along the decollement of the Nankai trough

Hiroko Sugioka[1], Taro Okamoto[2], Takeshi Nakamura[1], Yasushi Ishihara[1], Aki Ito[1], Koichiro Obana[1], Masataka Kinoshita[1], Yoshio Fukao[1*]

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There is a long history of studies of submarine very low frequency (VLF) earthquakes since the celebrated discovery by Wadati (1928). After over 80 years, we for the first time detected a swarm of VLF earthquakes by broadband ocean bottom seismometers (BBOBS) placed just above the source region in the Nankai trough accretionary prism, where the seismic crustal structure is well known. The nearby BBOBS records show permanent seafloor displacements of 0.1-0.5 mm with rise times ranging 20-60 s. These rise times are anomalously long as compared to those of ~1 s for ordinary earthquakes with comparative magnitudes (Mw ~4). We made a waveform inversion for the source location and source mechanism for the selected 11 events, taking the heterogeneity of crustal structure into account. All the events but one are located roughly along the plate boundary as plate boundary-parallel thrust faults. Their source time functions show anomalously long durations, quantitatively consistent with the observed seafloor displacements at each site. Despite such long source durations, VLF events are extremely rich in high frequency components (~5 Hz). Anomalously long source duration and anomalously rich high frequency wave radiation are two unique features of VLF events, suggesting simultaneous, interrelated occurrence of shear failure across and hydrofracturing within the decollement at the base of the accretionary prism.

Keywords: Very-low-frequency earthquake, Nankai trough

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SCG058-14 Room:302 Time:May 22 15:30-15:45

Migrated activity of shallow very low-frequency earthquakes in and around Hyuga-nada, southwestern Japan

Youichi Asano[1*], Takanori Matsuzawa[1], Hitoshi Hirose[1], Sachiko Tanaka[1], Katsuhiko Shiomi[1], Yoshihiro Ito[2], Kazushige Obara[3]

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We have investigated detailed spatiotemporal distribution of shallow very low-frequency earthquakes (SVLFEs) in Hyuga-nada and Ashizuri-misaki-oki regions, southwestern Japan. Three component seismograms observed in a period from 2002 to 2010 at the NIED F-net stations in Kyushu and Shikoku regions were analyzed by using a cross-correlation technique. In this method, we detected SVLFEs having similar waveforms to those of reference events (known SVLFEs) and estimated their epicenters from phase delays of the present detected SVLFEs to the reference events at each station. Centroid moment tensors (CMTs) of those SVLFEs were also estimated from the NIED F-net and Hi-net high sensitivity accelerometer data. Initial centroid locations and times of this analysis were selected to be those estimated by the cross-correlation analysis. Obtained CMTs show that seismograms of SVLFEs are explained by thrust faulting with larger dip angles than the plate boundary between the subducting Philippine Sea Plate and the overriding plate. Those SVLFEs occur at a depth range of 1-15 km close to this plate boundary. On the other hand, spatiotemporal distribution shows migration in each episodic burst activities of SVLFEs. In an episode in 2010, SVLFE activity started on January 24 in east off Tanegashima Island and migrated toward north along the strike of the subducting plate for a week. Travel distance of migration is at least 100 km; its front reached Hyuga-nada on January 31. After temporal reduction of seismicity, the SVLFE activity restarted on February 12, migrated toward east, and continued strong activity in Ahishizuri-misaki-oki until the end of February. After another temporal reduction of seismicity, restart of the SVLFE activity and backward migration from Ahishizuri-misaki-oki toward Hyuga-nada were observed in the middle of March. Such a large scale migration is quite similar to that of non-volcanic tremor and deep very low-frequency earthquakes coincident with slow slip events in the deeper extension of the seismogenic zone along Nankai trough. This suggests that possible slow slip events associated with SVLFEs can exist even in the shallower extension of the seismogenic zone.

Keywords: subduction zone, very low-frequency earthquakes, slow slip events, Hyuga-nada

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SCG058-15 Room:302 Time:May 22 15:45-16:00

Tidal triggering of shallow very low frequency earthquakes in southwest Japan

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We widely observed tidal triggering of shallow very low frequency (VLF) earthquakes in southwest Japan. We investigated the statistical correlation between the Earth tide and VLF earthquakes occurring in ten active swarms in Hyuga-nada, off Cape Muroto, and southeast off Kii Peninsula. We detected and located VLF earthquakes by applying the array signal processing method (Asano et al., 2008) to the seismograms recorded by the high-sensitive borehole tiltmeter network (Hi-net TILT) throughout Japan for the period from 2003 to 2010. For each event, we assigned the tidal phase angle at the origin time by theoretically calculating the tidal normal and shear stresses on the fault plane. For the fault plane, we assumed a landward-dipping reverse fault from a well-determined focal mechanism solution by using the centroid moment tensor method (Ito and Obara, 2006). Based on the distribution of the tidal phase angles, we statistically tested whether they concentrate near some particular angle or not by using the Schuster's test. In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the VLF earthquakes occur randomly irrespective of the tidal phase angle. Of the ten VLF swarms, significantly small p-values less than 0.01% were found for nine, and seven of them (two, three, and two swarms in the Hyuga-nada, off Cape Muroto, and southeast off Kii Peninsula regions, respectively) showed extremely strong phase selectivity. In the regions we examined, the normal and shear stresses are nearly in phase, although their amplitudes differ (about 10 kPa for the normal stress and 1 kPa for the shear stress). For all the seven cases of strikingly high correlation, the frequency distributions of tidal phase angles exhibited a peak near the angle 0, which corresponds to the maximum extension for the normal stress and maximum in the slip direction for the shear stress. This indicates that the observed high correlation is not a stochastic chance but is a physical consequence of tidal influence.

Keywords: shallow very low frequency earthquakes, Earth tide, triggering, subduction zone

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SCG058-16 Room:302 Time:May 22 16:00-16:15

Modeling the activity of shallow very-low-frequency earthquakes in the region off Tokachi

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Recent observations reveal that very-low-frequency (VLF) earthquakes occur in the shallow subduction zones in the Nankai trough, Hyuganada, and off the coast of Tokachi, Japan (Obara and Ito, 2005; Ito and Obara, 2006; Asano et al., 2008; Obana and Kodaira, 2009; Sugioka et al., 2010; Okamoto et al., 2010). Asano et al. (2010) investigated the details of the shallow VLF earthquake activity in the region off Tokachi and found that the sequences of VLF earthquakes repeat with intervals of a few years before the 2003 off Tokachi earthquake and that the activity became very high just after the 2003 off Tokachi earthquake and then intervals between sequences of VLF earthquakes become longer gradually. They also found that the migration speed of VLF earthquakes is from 10 to 50km/day.

We perform 2D quasi-dynamic modeling of the sequential occurrence of VLF earthquakes in the region off Tokachi in an elastic half-space using a rate- and state-dependent friction law. Tsutsumi and Ujiie (2011) examined frictional properties of clay-rich fault materials collected from a major splay fault within the Nankai accretionary complex under water saturated condition. Their experimental results reveal that there are both velocity-weakening and velocity-strengthening fault materials for slip velocities from 0.026 to 26 mm/s. Their results suggest that both velocity weakening and strengthening regions are comingled in the shallow subduction zones. Since no experiments have been conducted using the fault materials in the subduction zone, NE Japan, we refer to the experimental results by Tsutsumi and Ujiie (2011). We consider several unstable patches of a few km in the stable zone to simulate VLF earthquakes. We set the effective normal stress to be on the order of 1.0 MPa. When we set the intervals between patches to be in a certain range, VLF earthquakes occur sequentially. We can also reproduce the migration speed (10-50km/day) of VLF earthquakes in a certain range of constitutive law parameters. After large earthquakes occur activity of VLF earthquakes is very high due to afterslips but the recurrence intervals between sequences of VLF earthquakes become longer gradually with time. We report the range of constitutive law parameters which explain the activity of VLF earthquakes in the region off Tokachi.

Keywords: modeling, rate- and state-dependent friction law, shallow very-low-frequency earthquake, subduction zone, the region off Tokachi

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Seismic structures in source areas of slow slips

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We show fine-scale variations of seismic velocities and converted teleseismic waves that reveal the presence of zones of high-pressure fluids released by progressive metamorphic dehydration reactions in the subducting Philippine Sea plate in Tokai district, Japan. These zones have a strong correlation with the distribution of slow earthquakes, including long-term slow slip (LTSS) and low-frequency earthquakes (LFEs). Overpressured fluids in the LTSS region appear to be trapped within the oceanic crust by an impermeable cap rock in the fore-arc, and impede intraslab earthquakes therein. In contrast, fluid pressures are reduced in the LFE zone, which is deeper than the centroid of the LTSS, because there fluids are able to infiltrate into the narrow corner of the mantle wedge, leading to mantle serpentinization. The combination of fluids released from the subducting oceanic crust with heterogeneous fluid transport properties in the hanging wall generates variations of fluid pressures along the downgoing plate boundary, which in turn control the occurrence of slow earthquakes.

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SCG058-18 Room:302 Time:May 22 16:45-17:00

Anomalous fluid pressure developed by permeability contrast in subduction zones

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Low-frequency tremor and slow-slip events mostly located at depths of 35-40 km, where the subducting plate meets the island arc Moho (Shelley et al. 2006). Such regions are characterized by low velocity anomaly and high Poisson ration, suggesting the presence of serpentine with excess aqueous fluids (Matsubara et al. 2009). This can be resulted of back stopped fluid migration at the island arc Moho due to the permeability contrast between serpentinite and gabbro. The excess fluid pressure could cause a stick-slip type unstable sliding of serpentinite, and may trigger the slow earthquake at the tip of mantle wedge.

Keywords: slow earthquake, fluid pressure, permeability, gabbro, Moho, subduction zone

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Slow earthquakes linked along dip in the Nankai subduction zone

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In the southwest Japan subduction zone, a wide variety of 'slow earthquakes' has been detected with fundamental observation networks, such as Hi-net operated by National Research Institute for Earth Science and Disaster Prevention and GEONET by Geospatial Information Authority of Japan. Those are deep low-frequency tremor (Obara, 2002), short-term slow slip events (SSEs; Obara et al., 2004), and deep very low-frequency earthquakes (VLFEs; Ito et al., 2007) in the deeper extension of the locked zone of the subduction plate interface, long-term SSEs updip of these three kinds in Bungo Channel and Tokai (SSE; Hirose et al., 1999; Ozawa et al., 2002), and shallow VLFEs (Obara and Ito, 2005) near the Nankai trough. Each phenomenon has a characteristic dominant wave frequency or duration, depth and activity. Not all of them occur independently, but some of them occur simultaneously. For example, tremor, short-term SSEs and deep VLFEs occur at the same time in a same place (Episodic Tremor and Slip (ETS): Rogers and Dragert, 2003; Obara et al., 2004; Ito et al., 2007). Also, long-term SSEs that recur every six years in the Bungo channel region affect the frequency of occurrence of ETS episodes in western Shikoku (Hirose and Obara, 2005) and the tremor activity in the Bungo channel (Obara et al., 2010). However, the relation between shallow VLFEs and the other slow earthquakes has not been clear. Here we present the coincidence of the Bungo channel SSEs in 2003 and 2010 and deep tremor and shallow VLFEs that are distant from the source region of the SSEs and the tremor (Hirose et al., 2010).

The controlling process of this along-dip correlation is possibly the SSE because the SSE is several orders of magnitude larger in the corresponding seismic moment than the tremor and the shallow VLFEs. In addition, the locations of the correlated tremor is covered by the SSE source area, while those of the VLFEs occurred near the Nankai trough, distant from the SSE area. A plausible explanation is that a similar relation to the one between the SSE and the tremor is held between the SSE and the shallow VLFEs; that is, the SSE slip area may extend through the region of no measurable slip to the shallow VLFE source area and activate the VLFEs.

If this is the case, the source area of these slow earthquakes might act as a barrier to nearby megathrust rupturing because the slow slip area repeatedly releases the accumulated strain in an interseismic period of the megathrust events. Moreover, the slip area adjoins the megathrust rupture zone, suggesting that the repeating aseismic slip can modulate the stress buildup on the rupture zone. This indicates the importance of monitoring slow earthquakes as proxies for the stress modulation process.

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

Keywords: subduction zone, nonvolcanic tremor, very low-frequency earthquakes, slow slip events, earthquake generation cycle

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SCG058-20 Room:302 Time:May 22 17:15-17:30

Seismic quiescence and activation induced by a long-term slow slip event in the Bungo channel area during 2002-2004

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Katsumata(2010) presented a slow-slip-event (SSE) model to explain the precursory seismic quiescence lasting five years before the 2003 Tokachi-oki earthquake (Mw=8.3). The purpose of this study is to show an example of the seismic quiescence and/or activation caused by a long-term SSE. A long-term SSE in the Bungo channel area in the southwestern Honshu, Japan, occurred during 2002-2004 (e.g., Hirose and Obara, 2005; Ozawa et al., 2007). I investigate the seismicity in the Bungo channel area by using an earthquake catalog compiled by the Japan Meteorological Agency: time period is from 1 January 1998 to 31 December 2007, latitudes are from 31N to 35N, longitudes are from 130E to 135E, depths are from 30 to 100 km, and M>=2.0. The number of earthquakes are 3216 and I apply ZMAP (Wiemer and Wyss, 1994) to these earthquakes. The grid spacing is 0.05 degree, the N=100 earthquakes are selected around each grid point, and the length of time window is two years. As a result, I find a seismic quiescence within a circle centered at (33.55N, 132.85E) with a radius of 35 km, which is characterized by Z=+5.2, and starting in April 2002. I also find a seismic activation within a circle centered at (33.30N, 132.15E) with a radius of 13 km, which is characterized by Z=-3.2, starting in November 2002. The seismic quiescence and activation start at the same time as the Bungo channel SSE. The seismic quiescence and activation areas are very close to the area of the Bungo channel SSE. Therefore I suggest that the seismic quiescence and activation found in this study are induced by the Bungo channel SSE lasting from 2002 to 2004.

Katsumata, K (2010), Precursory seismic quiescence before the Mw=8.3 Tokachi-oki, Japan earthquake on 26 September 2003 revealed by a re-examined earthquake catalog, J. Geophys. Res., in print.

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Keywords: seismicity, seismic quiescence, seismic activation, slow slip event, Bungo channel

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SCG058-21 Room:302 Time:May 22 17:30-17:45

Direct evidence and generation conditions of triggered slow slip event

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In recent years, quite regular recurrences of episodic slow slip events (SSE) were revealed in the deep portion of many subduction plate interfaces in the association with long lasting tremor burst. As breaking such regularity, there exists many evidence of triggered tremor with only transient excitation by incoming seismic waves for various tectonic setting, however SSEs, which are much larger in seizes and continue longer after the transient excitation, have been yet to be identified. Here we found robust and direct geodetic evidence of a SSE with tremor activity in southwest Japan triggered by an earthquake in strain records from a highly sensitive strainmeter network. Based also on spatio-temporal recurrence patterns of the tremor/SSEs, we examine the physical conditions induced this event, including the stress changes by a transient seismic wave, by the tectonic load and by a nearby SSE. As the result, we found that the previous SSE in this fault segment occurred three months earlier almost equal to the regular recurrence period there. On the contrary, the other segments, where the elapse time was up to about 90% of the regular periods, did not show a significant activity at that time. Therefore, it is suggested that the overall segment of the triggered SSE had been necessarily very close to the critical stress level due to tectonic loading, and the seismic wave gave only the last push. Our results provide physical constraints to elucidate how earthquakes start and growth not only for the slow earthquakes but also for regular earthquakes.

Keywords: slow slip event, tremor, slow earthquake, triggering, strain

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Detection of short-term slow slip events in southwestern Japan using GPS data

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Slow earthquakes with a wide range of time constants occur in a deep part of the Philippine Sea plate subducting from the Nankai Trough (cf. Obara, 2010). It is important to investigate characteristics of the slow earthquakes for understanding the earthquake cycle and the process of stress accumulation. Although long-term SSEs (slow slip events) with a time constant of months to years have accompanied surface deformation detected by GPS in the Bungo Channel and the Tokai region, deformation associated with short-term SSEs was detected by not GPS but tiltmeters and strainmeters because its signal is presumably below a noise level of GPS. Recently, the noise level of the GPS data has been improved by revising the strategy of the GEONET baseline analysis. We expect that GPS becomes to detect the deformation of the short-term SSEs because the fault models for the short-term SSEs estimated from tilt data predict up to 3 mm of surface displacement. Hama et al. (2009) reported that GPS could detect the deformation of the short-term SSEs in the Tokai region. In this paper, we present results for detecting signals of the short-term SSEs in GPS data and estimating their fault models.

Because repeatabilities of daily coordinates in GEONET timeseries are 2-3 mm, it is difficult to judge an existence of 2-3 mm signals related with short-term SSEs by visual inspections. We reduce short-wavelength noises by spatial filtering which remove a common component in timeseries for clusters of GPS stations (Tabei and Amin, 2002). We found several offsets which are coincident with deep low-frequency tremors in filtered timeseries. Spatial pattern of horizontal displacement calculated from the offsets is concordant with that predicted by the fault model of short-term SSEs.

Although the National Research Institute for Earth Science and Disaster Prevention (Sekine et al., 2010) has investigated the short-term SSEs from the tilt data, we tried to detect signals of the short-term SSEs solely using GPS data. First, we calculated AIC (Akaike's Information Criterion) by fitting two functions for the filtered timeseries with shifting a 180-days-long time window. The GPS data spanned from 2005 to 2010. One function is a linear trend and the other is a linear trend with a step at the middle of the time window. Second, we calculated the AIC difference between two functions for two specific regions, that is, the Tokai and the northern Kii Peninsula regions. A candidate date for the short-term SSEs has a local minimum of the AIC difference. Finally, we visually inspected horizontal displacement for the candidate dates and recognized specific SSEs patterns for 9 events in 21 candidates. These events accompanied deep low-frequency tremors. In several cases, it is possible to estimate fault models of SSEs from the GPS displacement. Moment magnitudes for the events occurred around February 13, 2007 and March 4, 2008 are estimated to be 5.82 and 6.05 from GPS data, respectively. We, therefore, conclude that GPS can detect large short-term SSEs. However, we need to improve the method to detect them because some large events reported by Sekine et al. (2010) cannot be recognized by the present method.

Keywords: Short-term slow slip, GPS, Southwest Japan, Fault model, Philippine Sea plate

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SCG058-23 Room:302 Time:May 22 18:00-18:15

Numerical model of slow slip events in the Nankai trough -Reproduction of observations and expectations from the model-

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Slow slip events (SSEs), low-frequency tremors, and very low frequency earthquakes have been found in several subduction zones. These events are interpreted as a slip on the plate interface based on geodetic observations of SSEs and the focal mechanisms (e.g. Hirose and Obara, 2005; Ide et al., 2007; Ito et al., 2007, 2009). As recent studies have reported the detailed characteristics of these slow earthquakes (e.g., Obara, 2010; Ide, 2010; Hirose et al., 2010), a numerical model is necessary to interpret those observations and understand the stress state at the deeper extent of the major slip region of megathrust earthquakes. We have developed a numerical model of SSEs and reproduced the behavior of SSEs observed in the Nankai subduction zones.

SSEs occur at the transitional area of frictional property from stick-slip behavior to ductile deformation. To model such frictional behavior, we adopted a rate- and state-dependent friction law with cut-off velocities, which approximates the experimental result (Shimamoto, 1987). In addition, as high Vp/Vs around SSE region suggests the existence of water (e.g., Shelly et al., 2006; Matsubara et al., 2009), we assumed high pore pressure in the SSE region. We modeled a plate interface within a semi-infinite elastic medium, and calculated the temporal evolution of slip, assuming the above frictional properties and loading velocity on the interface.

At first, we simulated a simple case of a flat plate interface (Matsuzawa et al., 2010). In this model, long- and short-term SSEs were successfully reproduced in each model with different pore pressure distribution. Changing pore pressure distribution along the strike direction, both of long- and short-term SSEs were also simulated in the same model. In our result, the recurrence interval of SSEs shortened during an inter-seismic period. The shortening of the recurrence interval of SSEs was also found with the increase of the slip velocity between the SSE region and the locked region of megathrust earthquakes. These suggest that the recurrence behavior of SSEs may be affected by the stress accumulation process of megathrust earthquakes.

To reproduce the observed segments of tremor and SSEs, we constructed more realistic model introducing the shape of the subducting plate and the actual distribution of tremor in the Nankai trough. We assumed transitional friction around the tremor region, and stable sliding behavior outside of the region. This numerical model successfully reproduced the characteristics of the segments and recurrence intervals of SSEs. For example, in the model of the Kii and Tokai region, the reproduced interval in the southern Kii region was shorter than those in the northern Kii and Tokai region, as in observations (e.g., Obara, 2010).

In our result, the segmentation of the SSE regions is reproduced with the actual shape of the plate interface and tremor distributions. As suggested in Shibazaki et al. (2010), this segmentation is characterized by the width of SSE region in the dip direction. Shortening of the recurrence intervals during an inter-seismic period may reflect the stress accumulation process of megathrust earthquakes, as discussed in Matsuzawa et al. (2010). In the early stage of a seismic cycle, recurrence intervals of SSEs are relatively long as the locked region is close to the SSEs. In the later stage, recurrence intervals of SSEs shorten reflecting accelerated slip velocity at the bottom of the locked region. In the model considering the actual shape of plate interface and tremor distribution, however, this shortening behavior is less clear, although the tendency still remains.

Numerical studies to reveal the relationship between SSEs and megathrust earthquakes may be in the developing stage, as new findings are reported constantly. Reproduction of such observations and examining the expectations from the numerical model may lead to the further understanding of the subduction process and megathrust earthquakes.

Keywords: slow slip event, numerical simulation, seismic cycle, Shikoku

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A slow rifting episode at the Izu back-arc since 2004 September

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Lots of slow slip events (SSE) have been observed at plate convergence margins so far. In the present study, I report that similar events occur at divergent plate margins as slow rifting episodes. East-west tensile stress prevails in the northern part of the Philippine Sea Plate. Behind the volcanic arc of the Izu-Bonin arc, numbers of rift zones composed of north-south trending normal faults develop constituting the Izu back-arc rift zone. Recently, Nishimura (2010) found that the block defined with the three GPS stations in Aogashima, Hachijojima and Mikurajima are moving toward N81E by 6.8 mm/year with respect to the stable part of the Philippine Sea Plate defined by the Daito Islands, Okinotorishima and the Bonin Islands.

While I confirm this result, I found that this eastward movement used to be much slower and has accelerated suddenly in early September 2004. This transient eastward movement is decaying with a time constant of about 4 years, leaving excess eastward cumulative movement up to 3-4 cm in Hachijojima and Aogashima. This acceleration signature becomes faint northward, but is still recognizable in the Miyake and Izu-Oshima Islands.

In 2004 September 5-6, earthquakes occurred in the off southwest Kii Peninsula (M7.2 foreshock, M7.4 Main shock and M6.6 aftershock). Their coseismic deformation is characterized north-south shortening and minor amount of east-west extension (Suito and Ozawa, 2009). The eastward transient movement of the Izu Islands started almost simultaneously with these earthquakes, and appears, at a first glance, postseismic crustal deformation of these earthquakes. However, the afterslip inferred from the movements of GPS stations near to the epicenter. and calculated postseismic crustal movements due to viscoelastic relaxation, are far smaller than the observed transient movements. In fact, the Izu Islands are ~200 km east of the epicenter. The Muroto GPS station, ~200 km west of the epicenter, does not show any postseismic movement.

In this study, I hypothesize that the observed eastward transient movements of the Izu Islands are due to the occurrence of a slow rifting episode (SRE) at the Izu back-arc, triggered by the 2004 earthquakes. Because the static stress change by these earthquakes will discourage rifting, it must have been a remote triggering by the passage of seismic waves. After the last rifting episode many years ago, the rift zone has been glued tightly allowing E-W tensile stress to build up. Then the earthquake destroyed the glue for a length exceeding 200 km from Aogashima to Izu-Oshima, making the boundary mechanically free. Then the accumulated stress will be released slowly being balanced with the viscous coupling with underlying asthenosphere, i.e. stress diffusion goes on as suggested by Bott and Dean (1973). By using a realistic value of stress diffusion (Heki et al., 1993), I was able to simulate the SRE in a computer.

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Keywords: GPS, back-arc rifting, Izu-Bonin arc, stress diffusion, rifting episode, slow slip event