Porarization解析による日本海溝浅部微動の検出

Polarization evidence for the occurrence of shallow tremors in the Japan Trench subduction zone

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In the Japan Trench subduction zone, northeast Japan, the coincidental occurrences of the tremors with the slow slip events (SSEs) have been identified by using the ocean bottom seismometer (OBS) records (Ito et al., 2013; Ito et al., 2015). However, since the previous detection was based on the amplitude changes of ambient noise levels at few stations near the trench axis, the locations and source mechanisms of tremors are still uncertain. Here we investigate the polarization of OBS data to validate and deduce further source information of shallow tremors beneath the Japan Trench subduction zone.
Following the method proposed by Jurkevicks (1988), we calculate the average particle motion polarization for every 10-minute time window on the basis of the three-component covariance matrix of ground motion. Three principal axes of the best-fit ellipsoid to the particle motion correspond to the eigenvectors of the matrix in the least squares sense. The polarization azimuth is given by the direction of first eigenvector and the degree of linearity is given by the ratio among three eigenvalues. We analyze the continuous velocity seismograms for 5 months from November 2010 to March 2011 recorded at 17 short-period OBS network stations deployed in the Japan Trench axis area off Miyagi, northeast Japan.
We obtain several long sequences of high linearity and nearly constant polarization azimuths associated with tremors from the records of at least three stations near the trench. Three major sequences correspond to the tremor sequences reported in Ito et al. (2015). The stable and nearly constant azimuths in these sequences indicate the similarities of focal mechanisms and epicenters of tremors. The dominant polarization azimuth shows the angle of about 130 degrees, which may suggest shear slips in the subduction direction of the Pacific plate. Furthermore, the azimuths slightly change toward the timing of the largest foreshock of the 2011 Tohoku-Oki earthquake, which possibly indicates the migration of tremor sources.
We further apply the method to three different frequency bands (0.5-2 Hz, 2-8 Hz, 10-20 Hz) of OBS data to examine frequency characteristics. While the results from three bands show quite different background polarization azimuths, the specific polarization patterns associated with the SSE are only shown at the frequency of 2-8 Hz, which also supports the occurrences of tremors.

キーワード：日本海溝、微動、振動方向解析、海底地震計
Keywords: Japan Trench, tremor, polarization analysis, OBS

日奈久断層帯下部で定常的に発生する非火山性微動の活動特性(2)
Tremor activities beneath the Hinagu fault zone (2)

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日奈久断層帯において，遠地地震の表面波がもたらした動的応力により非火山性微動が誘発されていることが明らかになっている(Chao and Obara, 2015). 微動は断層帯の深部延長部で発生し，地震波トモグラフィー(Matsubara and Obara, 2011)との比較では，震源域の深部にＰ波速度の低速度域，地震発生層に対応する浅部に高速度域という速度構造の変化があることが明らかになっている(Miyazaki et al., 2015).

外部からの応力擾乱がない場合でも断層の深部において非火山性微動が発生しているかを知ることは，発生過程を理解するうえで重要である．著者らはこれまでに，誘発微動波形をテンプレートとして，Matched Filter法(Gibbons and Ringdal, 2006)により定常的な活動の検出を行ってきた(宮崎他, 2014, SSJ). 本発表では，検出されたイベント波形を新たにテンプレートに加えた結果について報告する.

本発表で使用したテンプレート波形は，誘発微動の波形と比較して見かけの継続時間が短い．この性質を利用し，渡辺の式(渡辺, 1971)を用いてマグニチュードの決定を試みた．検出されたイベントのほとんどはノイズに埋もれていたが， SN比が比較的良いイベントについては，マグニチュードが-0.4～-1.0程度であることが分かった．また，グーテンベルグ・リヒター則を適用すると，ｂ値が1.4程度となった．浅部の地震発生層で起きている地震活動のb値はおよそ1であり，浅部と比較して相対的にやや大きな値をとることが分かった.

また，数十分の時間規模で微動活動が活発化する場合があることを新たに発見した．活発化している間の波形の振幅は，個々の観測点におけるノイズレベルの変動を大きく超えるほどではなく，ノイズレベルの大きい観測点ではシグナルがノイズに埋もれている．また，プレート境界で見られる非火山性微動のような継続時間の長い振幅の高まり(Obara, 2002)も，あまり顕著では無い．Miyazaki et al. (2015) では，地震波トモグラフィーの結果を比較し（Shelly et al, 2006; Matsubara and Obara, 2011），日奈久断層周辺では，間隙流体圧の高い領域が沈み込み帯（四国西部）と比較して局所的である可能性を指摘している．同様に考えると，日奈久断層帯における微動活動の規模が小さいのは，すべり領域が小さいことが一因にあると示唆される.

謝辞
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キーワード：日奈久断層、内陸地震、非火山性微動
Keywords: the Hinagu fault zone, inland active fault, non-volcanic tremor

深部微動震源決定のための改良エンベロープ相関法の開発と性能評価
Develop and evaluate modified envelope correlation method for deep tremor

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西南日本での深部低周波微動の発見[Obara, 2002]以降、微動についての多くの研究が行われている。これらの研究の基礎として微動の震源決定が必要であり、これにはエンベロープ相関法[Obara, 2002]が広く持ちいられてきた。これを改良した手法として、Wech and Creager(2008)では相互相関係数の和を最大化する手法が提案されている。本研究ではWech and Creager(2008)を改良し、震源決定精度と検出能力が向上する手法を開発した。

エンベロープ相関法では、エンベロープ波形の観測点間の相関係数を最大化する走時差を説明するように震源位置を決める。本研究では、Wech and Creager(2008)と同様に震源位置から計算される観測点間の走時差に対応する相関係数を求め、各観測点ペアでのこれらの和が最大となるような位置に震源を決定するが、Wech and Creager(2008)と異なり相互相関関数の重み付けは行わない。これは全ての観測点ペアの正規化されたエンベロープ波形の差の二乗和を最小化することに相当する。目的関数の最適化は、グリッドサーチで得られた局所解から勾配法を用いて行った。

本研究では、提案手法を西南日本のHi-Netデータに適用し、微動の検出を行った。ブートストラップ法を用いた誤差推定によって、震源決定精度は水平方向・垂直方向共に約1kmと推定された。これは報告されているエンベロープ相関法の震源決定精度[Ide, 2010 など]より向上している。従来の手法では１つのタイムウィンドウに対して１つの微動か地震しか検出できないが、提案手法では複数の微動や地震が１つのタイムウィンドウで発生するとそれぞれが局所解として現れることが確認された。

キーワード：深部微動、震源決定、エンベロープ相関法
Keywords: Deep tremor, Hypocenter determination, Envelope correlation method

３Ｄアレー観測による東海地域・深部低周波地震のＰ波・Ｓ波の検出方法 －震源決定への応用－

A detection method for P and S waves of deep low-frequency earthquakes using a 3D array in the Tokai area and its application to hypocenter determination

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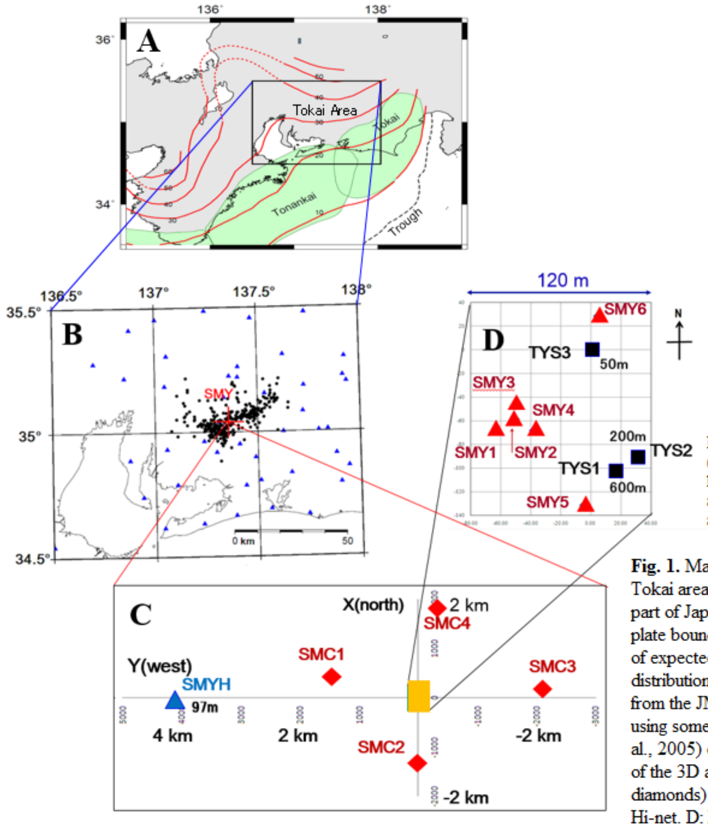
We have developed a novel method that uses a 3D array to detect the P and S waves of deep low-frequency earthquakes (LFEs) that occur along the subduction zone of the Philippine Sea plate in southwest Japan. Obtaining accurate hypocenters of LFEs is very difficult because their seismic waves are characterized by low amplitude and the absence of sharp pulses. In particular, identifying P phase arrivals is not readily possible using conventional methods and seismic networks. To determine their hypocenters accurately-not only their epicenters but also their depths-we tried to find their P and S wave pairs and obtain S-P times. We constructed a 3D array (6 km x 4 km area, see Fig.1) using 14 seismic stations in the Tokai area with three component seismographs, including ones with deep (600 m at the deepest) borehole seismographs. We observed remarkable LFE activity occurring in the Tokai area over November 10-30, 2010. We successfully detected not only S waves but also very weak P waves of LFEs using the 3D array data and the semblance method. Assuming a homogeneous half-space model with P wave velocity=4.5 km/s and S wave velocity=2.2 km/s in the 3D array, we calculated the semblance distributions for more than 20 LFEs to obtain their propagation parameters (back azimuth and the incident angle of seismic waves) and to identify P and S-waves. Using the time of the maximum value of the semblance in each component, we detected the direct P wave in the vertical component and the S wave in the horizontal component, providing S-P time. Fig.2 shows an example of hypocenter determination (red star) using estimated S-P time and propagation parameters, where we found 8.2 km difference in depth between the hypocenter in this study and that (green star) listed in Japan Meteorological Agency (JMA) catalogue. This example suggests that the inclusion of the S-P time strongly reduces the uncertainty on source depth, because the LFEs in the JMA catalogue were generally located using only S-arrival times. Choosing 4 LFEs with reliable results obtained from the semblance analysis, we located their hypocenters and found they distribute in the depth range from 28 km to 35 km approximately along the plate interface inclining in depth from 30 km to 32 km.Because a single array inherently has a limitation in the precise location estimate, especially for epicenter, we also tried to locate hypocenters (for example, a blue star in Fig.2) of LFEs using 3D array data together with arrival times (in many cases, S-arrivals) of surrounding stations that listed in JMA catalogue. For the LFE in Fig.2, we found 4.5 km difference (between a blue star and a red star) in the epicenter by combining the arrival times of surrounding stations, which is not always negligible for better understanding the spatial and temporal distribution of LFEs.

キーワード：深部低周波地震、立体アレー、Ｐ波とＳ波、センブランス解析、プレート境界
Keywords: deep low-frequency earthquake, 3D array, P- and S-waves, semblance analysis, plate boundary



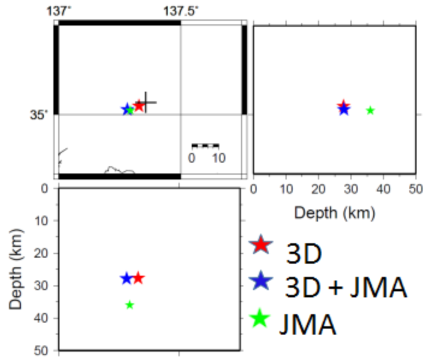


Fig. 2. An example of the difference in depth of hypocenter of LFE (LFE13) between 3D, 3D+JMA, and JMA. The 3D and 3D+JMA hypocenters were located using not only S-arrival times but also P-arrival times, while the JMA hypocenter was located using only S-arrival times.

Fig. 1. Map of seismic stations comprising the 3D array of SMY in the Tokai area, located in the central part of Japan. A: Index map of the central part of Japan. Red lines represent the depth contours of the Philippine Sea plate boundary (Hirose et al., 2008). Green areas show the source regions of expected Tokai and Tonanki interplate earthquakes. B: Epicenter distribution (black points) of LFEs occurring in November 2010 derived from the JMA earthquake catalog. The epicenters were located mainly by using some of the seismic stations (blue small triangles) of Hi-net (Obara et al., 2005) operated by NIED. A thin red cross shows the central location of the 3D array of SMY. C: Distribution of four SMC stations (red diamonds) of a medium-sized array and SMYH station (blue triangle) of Hi-net. D: Distribution of six stations (red triangles) of a small-sized array and three borehole stations (black squares). Numbers followed by m show the depths of the boreholes.

豊後水道周辺域におけるスロー地震の相互作用

Interaction between slow earthquakes in and around Bungo channel, Nankai subduction zone

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Slow earthquakes occur at transition zones from locked to stable sliding zones along megathrust faults at both shallow and deep parts. So far, various types of slow earthquakes with different characteristic time scales have been detected in many subduction zones along the Pacific Rim. In each subduction zone, the activity style, combination and interaction of slow earthquakes are different. Therefore, the slow earthquake is considered as an index to characterize each subduction process. Interaction between long-term slow slip event (SSE) and downdip tremor has been observed in southwestern Japan, Mexico, and Alaska even though detailed relationship is slightly different. In Bungo channel near the western edge of deep tremor belt-like source region along the Nankai subduction zone in southwest Japan, the long-term SSE occurs at a recurrence interval of about six years. During the 2003 and 2010 long-term SSEs, tremor activity increased at the shallower part of the tremor zone, which is the adjacent region of the SSE source fault. On the other hand, the deeper tremor activity is stable irrespective of the SSE. Takagi et al. (2016) detected tiny crustal deformation and estimated a sequence of long-term SSEs with eastward migration through the gap between locked and tremor zones. Associated with the migrating long-term SSE, the long-term variation of tremor activity seems to migrate eastward at speed of a few 10 km per year in western Shikoku. These observation suggest that the long-term SSE may trigger the downward neighboring tremor activity.
On the other hand, shallow tremor has been recently detected associated with shallow very-low-frequency earthquake near the Nankai trough (Yamashita et al., 2015). This shallow slow earthquake activity shows along-strike variation. At the updip side of the 1946 Nankai earthquake rupture fault, shallow slow earthquake seismicity is quite low. On the other hand, slow earthquake frequently occurs at Hyuga-nada where the quasi-stable sliding zone with many repeaters exists at the downdip side of the shallow slow earthquake region. The slow earthquake seismicity is usually limited at the southern part from the Kyushu-Palau ridge. However, slow earthquake region extended eastward with a length of 100 km from the Kyushu-Palau ridge at the beginning stage of the Bungo channel long-term SSEs in 2003 and 2010. This might suggest that the shallow slow earthquake seismicity is an indicator for the coupling status at the downdip portion of the plate interface.

キーワード：スロー地震、沈み込み帯
Keywords: slow earthquake, Subduction zone

Constraints on source parameters of low-frequency earthquakes in Parkfield, CA

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Low-frequency earthquakes (LFEs) are small repeating earthquakes that occur in conjunction with deep slow slip. Like typical earthquakes, LFEs are thought to represent shear slip on crustal faults but when compared to earthquakes of the same magnitude, LFEs are depleted in high frequency content and have lower corner frequencies, implying longer duration. Here we exploit this difference to estimate the duration of LFEs on the deep San Andreas Fault (SAF). We find that the M<1 LFEs have typical durations of ~0.2 s. Using the annual slip rate of the deep SAF and the average number of LFEs per year we estimate average LFE slip rates of ~0.24 mm/s. When combined with the LFE magnitude this number implies a stress drop of ~10^4 Pa, two to three orders of magnitude lower than ordinary earthquakes, and a rupture velocity of order 0.7 km/s, 20% of the shear wave speed. Typical earthquakes are thought to have rupture velocities of ~80-90% of the shear wave speed. Together the slow rupture velocity, low stress drops, and slow slip velocity explain why LFEs are depleted in high frequency content relative to ordinary earthquakes and suggest that LFE sources represent areas capable of relatively higher slip speed in deep fault zones.

深部低周波微動の高速移動現象
High-speed migration of tremor along the Nankai subduction zone, Japan

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As an underlying source physics of episodic tremors and slip (ETS), a diffusion process of stress or fluid along plate boundary fault has been proposed as one of plausible mechanism [e.g., Houston et al., 2011]. Most rapid migration phenomenon is categorized as high-speed tremor migration features, where the propagation speed of tremor-front rises up to ~ 100 km/h. However, there is little constraint on spatio-temporal evolution of high-speed tremor migration features. To reveal spatio-temporal evolution of high-speed tremors migrations, we applied a matched-filter technique to continuous seismograms during 6 years, using relocated template low-frequency earthquakes (LFEs) at the western part of Shikoku Island. We newly detected about 60 times the number of template LFE events, which is fairly larger than ones obtained by conventional envelope cross correlation method. We identified hundreds of repetitive sequences of high-speed tremor migrations, which evolve in a diffusional manner with diffusion constant to be 10^5 m2/s. The length scale of the fast diffusion is relatively short, up to ~20 km. Most of the rapid migrations seems to be triggered by ocean and solid Earth tides. As a fundamental elements for diffusive propagation of ETS, stress diffusion on the background ductile shear zone [Ando et al., 2012] or slip and fluid diffusion [Shelly, 2015] is considered to be a likely explanation of the high-speed tremor migrations.

Universality of very low frequency signals from slow earthquakes

Universality of very low frequency signals from slow earthquakes

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The scaling law for slow earthquake [Ide et al., 2007] provides a unified view of deep tectonic tremors, low frequency earthquakes, and slow slip events (SSE). This view has been strengthened by several kinds of evidence and explanations using theoretical models. One of the strongest evidence is the detectability of intermediate phenomena between seismically observed tremor above 1 Hz and geodetically observed SSE longer than several hours. The signals are especially clear in the very low frequency (VLF) range from 0.02 to 005 Hz, where Ito et al. [2007] first discovered signals accompanied with tremors. Since their discovery, similar phenomena have been found in many places, with simultaneous tremor observation. This fact suggests the universality of VLF signals behind tremors, and we can enhance the signal amplitude in the VLF range to overcome environmental noises, by stacking broadband seismograms relative to tremor timing.

We arrange many reference points in a tremor zone, extract VLF signals by stacking broadband seismograms, and determine moment tensor corresponding to the underground deformation. This method was first applied to a wide tremor zone in the Nankai subduction zone [Ide and Yabe, 2014], and then to a small tremor cluster in Taiwan [Ide et al., 2015], the Guerrero tremor region in Mexican subduction zone [Maury et al., 2016], around southern Vancouver Island in Cascadia subduction zone, and the Parkfield section of the San Andreas Fault. In every region, moment tensor solutions consistent with regional plate motion were determined. These solutions will constrain tectonic interpretation in each region. The reliability of solution is not homogeneous: we can constrain solutions with only 500 tremors in Nankai, while noises are too large after stacking 5000 tremors in Parkfield. This is partially due to the different quality of seismic networks, but the size of source is not the same everywhere. Average moment magnitudes corresponding to VLF processes are Mw 2.2-3.0 in Nankai, Guerrero, and Cascadia, but less than Mw 2 in Parkfield. The similarity and difference for these results will provide keys to understand physics that govern these slow deformation processes.

キーワード：slow earthquake、deep tectonic tremor、very low frequency
Keywords: slow earthquake, deep tectonic tremor, very low frequency

日向灘における浅部超低周波地震の自動検出
The detection of shallow very low frequency earthquake in Hyuga-nada

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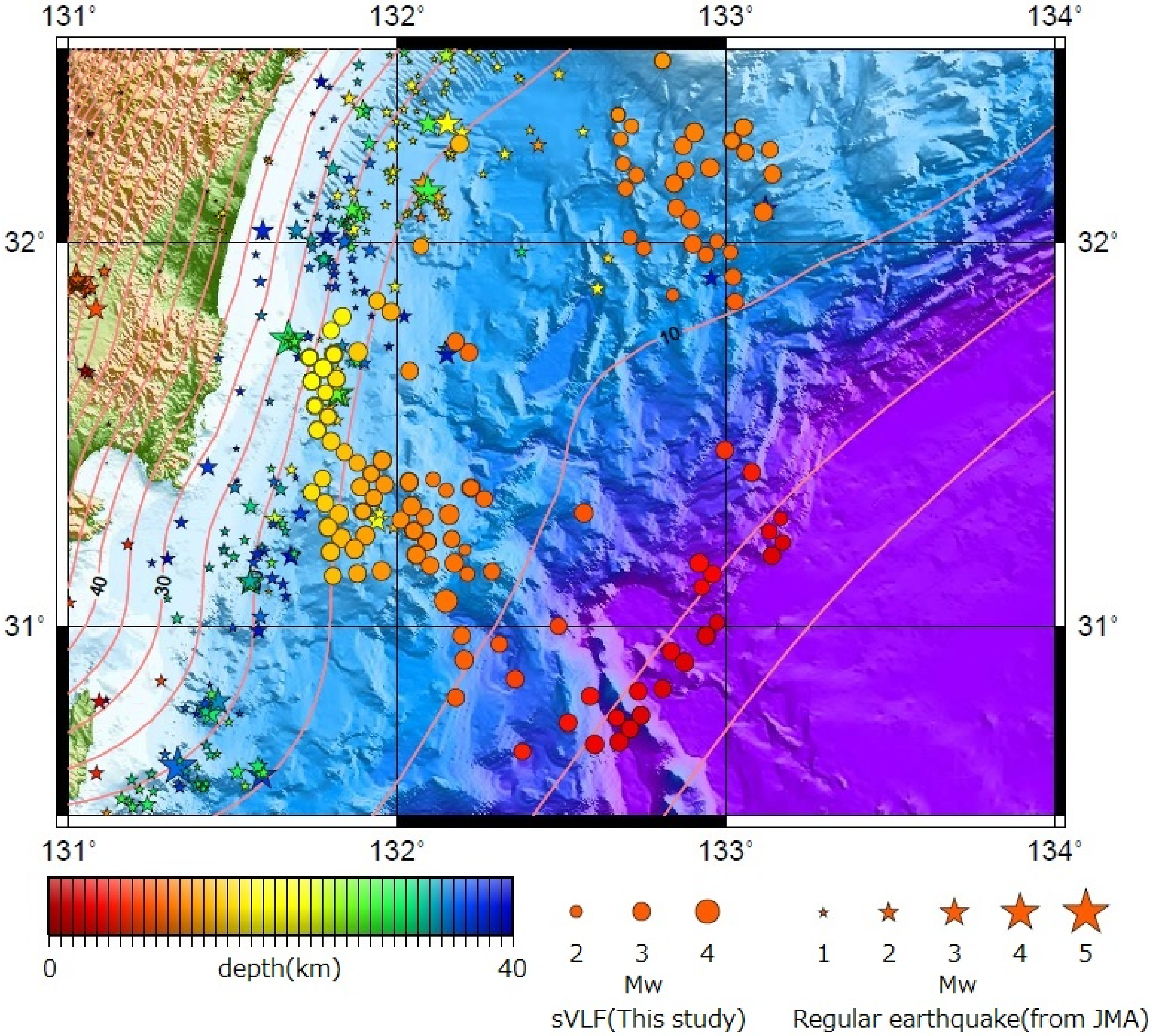
GPS continuous observation system of Geographical Survey Institute, Hi-net and F-net of National Research Institute for Earth Science and Disaster Prevention have been nationally developed. Thanks to these seismic network systems that “Slow earthquake” exceling normal earthquake on a long period is discovered in southwest Japan for these 10 years [e.g. Obara, 2002]. The slow earthquake is a generic name of the different multiple phenomena of the time scales. These phenomena are classified by frequency, e.g. Slow Slip Event (SSE), Non volcanic tremor (tremor), Very Low Frequency earthquake (VLF) [Ito et al, 2007]. Tremor and VLF are observed due to earthquake vibration and these signals are in 2-8Hz and 0.02-0.05Hz respectively [Ito et al, 2007]. It is shown that tremor and VLF are activated by SSE and the relationship with the giant earthquake is pointed out. In Hyuga-nada that is located in the west end of an area that is expected to have a major earthquake along Nankai trough, understanding the seismic activity including the slow earthquake and exactly sliding properties of plate are the purpose of this study.
The analysis in this study is carried out on data between September 1, 2006 and September 30, 2006 in the same area as that of Asano et al, [2014]. It is supposed that shallow VLFs are activated by SSE, so the analysis is carried out in a period when tremor are used occurred frequently, and also before and after the period. 21 points observation data of F-net in west japan are used. The data of each observation point are comprised of horizontal north and south direction east and west direction and up-and-down motion.
The result of analysis shows that shallow VLF occurred in the area where asperity of the regular earthquake did not exist. This result indicates that the frictional force at the plate boundary shows different behavior by depth. Similar to a prior study, this study shows that after the shallow VLF’s migration towards the east, the migration to the opposite direction started. Thus, the migration direction of the shallow VLF is almost same in the different period. This result suggests that destruction origin and destruction spread direction of SSE considered to activate the activity of VLF are approximately same irrespective of duration period. In addition, the result shows the possibility that in the shallower part (shallower than 15km) of study area where the regular earthquakes do not occur, the unknown slow slip event occurs and activates shallow VLFs.

キーワード：浅部超低周波地震、スロースリップイベント
Keywords: shallow Very Low Frequency earthquake, Slow Slip Event


131°
132°
133°
134°
32°
31°
40
30
10
0
depth(km)
40
2
3
4
Mw
sVLF(This study)
1
2
3
4
5
Mw
Regular earthquake(from JMA)

広帯域海底地震計データの階層的クラスタリングにより得られた、南海トラフ東部における浅部超低周波地震の時空間分布

Spatio-temporal distribution of very low frequency earthquakes in the eastern Nankai accretionary prism revealed by hierarchical clustering analysis of ocean bottom seismometer records

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Many low frequency tremors (LFTs) occurred in the eastern Nankai accretionary prism in October 2016 through a period of about one week and were recorded by the 20 broadband ocean bottom seismometers of the DONET1 ocean floor network. We detected more than 900 tremors at the frequency range of 2-8 Hz. Among these, 144 events were accompanied by signals at lower frequency range (> 0.1 Hz). In this study, the events with the low frequency signal are referred to as very low frequency earthquakes (VLFEs).

The observed waveforms of the entire network suggest that many of the events are spatially clustered. However, due to the large errors introduced during the travel time measurement processes, the estimated location of each event is spatially scattered, which makes it difficult to evaluate the distribution of the clustered events.

Here, we introduce a hierarchical clustering algorithm to group some of the closely located events. The degree of similarity between any two events is defined by comparing the arrival times of the peak amplitude obtained by a set of stations at which the signals of both events were observed. The peak amplitude at each station is measured from the root-mean-square envelope of two horizontal components filtered at 2-8 Hz, and then smoothed by a low-pass filter with a cutoff frequency of 0.059 Hz.

Thus far, the algorithm has been applied to only the VLFEs, although we intend to eventually cluster all of the events, including the LFTs. Among the 144 VLFEs, 121 events grouped with at least one other event, and a total of 27 groups appeared.

Finally, the horizontal location of each cluster was determined by using the median of the measured differential travel times between stations obtained for individual events within the cluster. The differential travel times were calculated from the previously described peak amplitude arrival times. This procedure also allowed us to detect and remove outliers of measured times, which are caused mostly by noise. The locations were estimated by assuming a constant shear velocity structure.

The results showed that the cluster locations are largely divided into two groups. The clusters in the first group (Group 1) are distributed around a major reverse fault in the northern part of DONET1. They occurred within the first 3 days of the total activity. The cluster locations of the second group (Group 2) are distributed form around the major reverse fault of the southern part of DONET1 and slightly toward the trench axis side. Many of the events in the trench axis side seems to have occurred in the latter part of the total period of activity.

The waveforms of events in Group 1 tended to show somewhat discernable S wave onsets compared to events in Group 2. Furthermore, we were able to identify systematic P arrivals for many events in Group 1 by aligning the waveforms within the individual clusters. By using manually picked P and S arrival times, we relocated some clusters by a grid search through a 3-D velocity model. The results showed that the depth of the clusters varies from ~8 km to ~2 km beneath the seafloor. Whereas many events are located near the major reverse fault, some are located ~5 km landward of the fault. Our result suggests that the stress state that promotes the occurrence of VLFEs is not limited to the narrow range along the major fault, but exists through a broader range in the shallow accretionary prism.

キーワード：浅部超低周波地震、広帯域海底地震計、階層的クラスタリング、付加体
Keywords: Very long frequency earthquake, BBOBS, hierarchical clustering analysis , accretionary prism

Tremor location in Guerrero, Mexico from catalog comparison: identification of new clusters

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Tectonic tremor are known to occur in two areas in the Guerrero subduction zone, one updip of the other. However these locations are obtained from only 29 months of recording and more precise location is needed. To do this we used two datasets, the previously used MASE dataset and the GGAP dataset. The MASE network is a linear network that allows good along dip resolution. The GGAP network is located around the downdip cluster and is better able to locate the events in this area. We generate a tremor catalog by envelope correlation method for the two time periods. In a second step we estimate their moment tensor from stacking broadband seismograms in the VLF band (0.02-0.05 Hz).
Results shows two different tremor distributions depending on the time period. From MASE data we detect the previously known two clusters, one southern transient cluster and one northern more active cluster. The second dataset reveals that the northern cluster is in fact formed of two clusters in the strike direction. Analysis of the error of the first dataset shows the lack of resolution in the strike direction due to the linearity of the network explaining the difference between the two catalog. To confirm these results our tremor locations are also compared to other catalogs obtained with the tremor energy and polarization (TREP) method [Cruz-Atienza et al, 2015] and the cross station cross correlation method [AGU abstract Peng and Rubin, 2015]. Results from these methods agree globally with our result. The comparison of these three different catalogs underlines the complexity of determining tremor location.
Moment tensor inversion reveals low angle thrust mechanism with slip direction in agreement with TREP results and close to the convergence direction. Additionally the depth of the VLF events is coherent with the depth of the subduction interface highly suggesting that these events represent shear slip on the plate interface.

Keywords: tremor location, moment tensor of slow earthquakes

The fluctuation of the slip accumulation rate of long-term SSE and its relation to VLFE beneath the Iriomote Island, southwest Ryukyu Arc

The fluctuation of the slip accumulation rate of long-term SSE and its relation to VLFE beneath the Iriomote Island, southwest Ryukyu Arc

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37 slow slip events (SSEs) beneath the Iriomote Island, the southwestern Ryukyu Arc, were detected in the GEONET F3 solution GNSS data 1997-2015. Their average moment magnitude (Mw) is 6.6, and the average recurrence interval is ~6 months, which are in accord with Heki and Kataoka (2008). However, the recurrence interval was found to vary in time during the 18 years time span. During 2005-2009, the interval remained as short as ~4 months, and then returned to ~7 months after that. Moreover, the SSE slip rate (cumulative slip/ lapse time) increased from 9 to 11 cm/y and from 6 to 11 cm/y during two time periods, 2003-2006 and 2013-2015, respectively. Heki and Kataoka (2008) and Nakamura (2009) suggested that the slip rate could increase due to occurrences of large thrust earthquakes near the Ryukyu trench. However, no noticeable events occurred in this region prior to the trend increase around 2013. Conversely, two earthquake swarms occurred in the Okinawa Trough during these periods. In addition, southward motion of the Yonaguni Island, to the west of the Iriomote, has accelerated together with the SSE slip accumulation rate. From these results, we hypothesize that both the spreading at the Okinawa trough and the subduction at the Ryukyu trench could modify the SSE slip accumulation rate beneath the Iriomote Island.
In additions to SSEs, very low frequency earthquake (VLFE) is another kind of slow earthquakes that occur along the Ryukyu subduction zone. To understand the relationship between SSE and VLFE activities, we analyzed the broadband seismic data of the F-net in Japan and the BATS in Taiwan in order to identify VLFEs in southwestern Ryukyu Arc. During 2005-2010, we detected 2575 VLFEs there, and most of them were found to be thrust events in the shallow part of the plate boundary. According to the distributions of SSEs and VLFEs, we found VLFEs are often activated by SSEs 10-30 days after the SSE onsets. We also found that the VLFE activity becomes higher during the periods of the enhanced SSE slip accumulation rate.

キーワード：slow slip events、very low frequency earthqaukes、The Ryukyu subduction zone
Keywords: slow slip events, very low frequency earthqaukes, The Ryukyu subduction zone

Repeating Slow Slip Events in the Bonin/Ogasawara Islands Observed by the Continuous Global Navigation Satellite System (GNSS)

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Slow slip events (SSEs) are the episodic movement across a fault, characterized as a slow fault deformation that releases energy on timescales of hours, to weeks or even years, which is much longer than seconds to minutes timescales of regular earthquakes. Numbers of SSEs has been recognized from various subduction zones around the world. The character of SSE was first recognized in Cascadia subduction zone in the Northwestern of United States and Canada. These studies were followed by some reports of similar event including Japan.
The dense geodetic observation by Continuous Global Navigation Satellite System (GNSS) station operated by Geospatial Information Authority of Japan (GSI), also widely known as GPS, contribute a big impact on observing such events in Japan. It has been used as a way to measure the motion of Earth's crustal plates. In Japan, from the starting of their installation in 1996, various SSEs have been recorded to have occured.
We have been conducting the same study of this event and reporting the possibility of this occurence in other part of Japan which is never reported before. The area of this newly found SSE is in the remote islands of Japan, Bonin (Ogasawara) islands, which lies along the convergent boundary where the Pacific Plate subducts beneath the Philippine Sea Plate. These islands are located at the southern part of Japan, very close to the edge of Mariana arcs.
The events are detected by using GNSS data from GSI together with additional supporting data from National Astronomical Observatory of Japan (NAO) to confirm the occurence of these events. GNSS stations on Bonin Islands recorded the plate deformation and reveals the possible existence of Slow Slip Events (SSEs) near the boundary between the Philippine Sea plate and Pacific plate. The Slow Slip Events (SSEs) together with other crustal deformation in this area has been observed since the beginning of GNSS installation in two islands, Chichijima and Hahajima from 1996 until now. This ~20 years of observation contribute the result of finding of repeating SSEs.
Using data from this dense geodetic network, we focus our study on the repeating SSEs in the latest decade, reporting that there are at least 5 SSEs have occured within 10 years with the recurrence interval of ~2 years, detected by stations in Hahajima and Chichijima islands. These 5 SSEs have uniform characters in the time constants as well as the recurrence interval, and we modeled the rupturing due to these SSEs by using rectangular fault plane model. This study is giving the result of slip approximately 8-10 cm for each event or 4-5 cm/yr. These events have magnitude from 6.8 to 6.98, varies especially from the size of the fault rupture, with the seismic moment of 2×10^{19} Nm - 3.75×10^{19} Nm.

Keywords: Bonin Islands Arc, Fault Rupture, GNSS, GPS, Ogasawara, Slow slip event (SSE)

2010-2014年に琉球弧南西部で発生したSSEの地殻変動解析
Analysis on Crustal Deformation of Slow Slip Events Occurred in the Southwestern Ryukyu Arc in 2010-2014

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In the last 20 years, various types of slow earthquakes have been reported mainly on the plate boundary. For example, Slow Slip Events (SSEs) are one of the slow earthquakes. They don’t radiate seismic wave and last for a few days to years. Discovery of slow earthquakes encourage us to examine about strain accumulation and release on plate boundaries.

In the southwestern ryukyu arc, SSEs were reported by Heki and Kataoka (2008). They estimated a simple rectangular fault model from displacement data at 8 GNSS stations. And they reported that SSEs are repeatedly occurred beneath Iriomotejima island. Though, we think faults which cause SSE are probably more complicated, and there is a difference on slip distribution between SSEs.

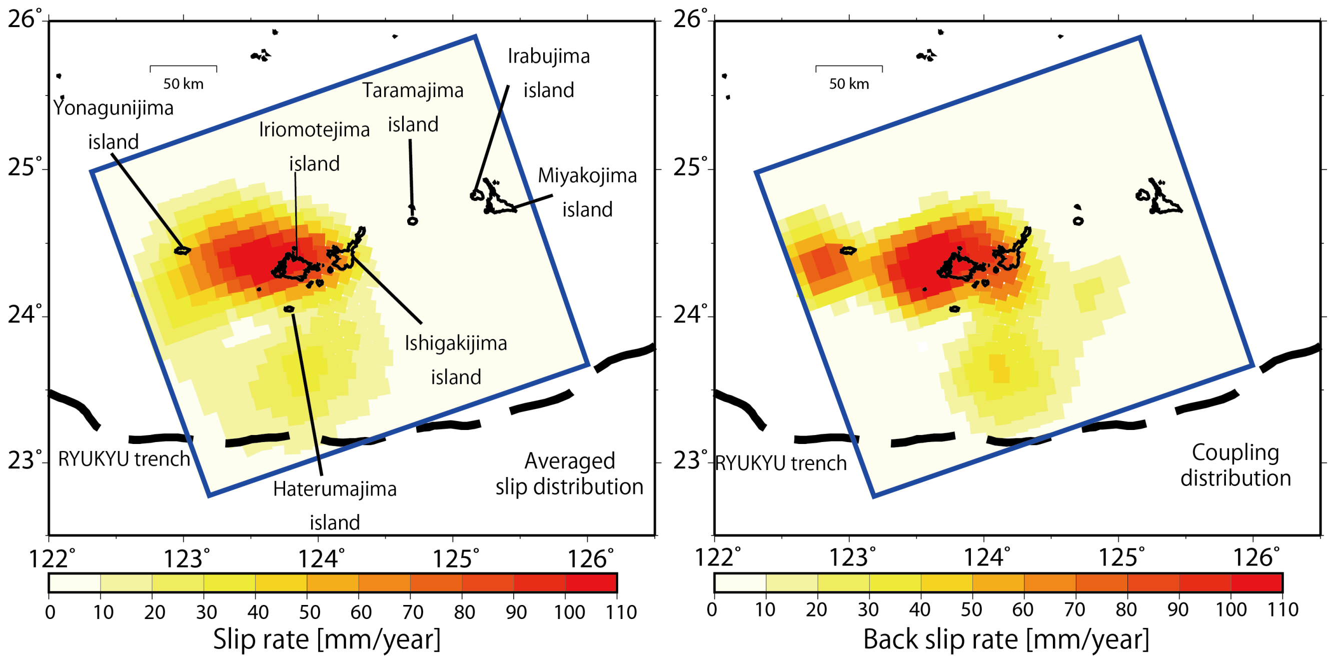
In this study, we estimate slip distribution of each SSE by using 13 GNSS stations including new stations (one station in Miyakojima island and four stations in and around Iriomotejima island). We adopt a station in Irabujima island as a reference. Then, we analyze GNSS daily coordinates from Apr. 1, 2010 to Jan. 31, 2015, and estimate crustal deformation by fitting a function to the time-series data. We estimate displacement of SSE and earthquake, linear velocity, and initial offset by least square method, and estimate SSE occurrence time and time constant for duration of SSE by grid search method. We assume temporal evolution of SSE is expressed by an exponential decay function proposed by Heki and Kataoka (2008). Then, we obtain horizontal and vertical displacement for eight SSEs.

We estimate slip distribution of SSE by inversion analysis from displacement data. We estimate dislocation on each patch in an elastic half-space (Okada, 1985). We decide fault patches as follows. First, we divide a slip area to small patches, whose size is 10 km square. Then, we set rectangular fault lying on the plate interface on each patch. We adopt constraints on smoothness of slip distribution and non-negative slip. Slip azimuth and weight between data and smoothness are determined by minimizing ABIC. The geometry of the plate interface is based on the Slab 1.0 model (Hayes et al., 2012).

As a result, average moment magnitude, recurrence time, and slip azimuth are estimated to 6.90, 7 month, and 155 degree, which is clockwise angle from north, respectively. Heki and Kataoka (2008) successfully estimated characteristics of SSEs in the southwestern ryukyu arc. However, we found more complicated slip distribution which is varied among SSEs. We introduce obtained results. The slip region is biased to the west on the SSE occurred on Aug. 9, 2010. In case of the SSE occurred on Apr. 30, 2012, slip is also estimated in the region south off Yonagunijima island, besides the slip region on the SSE occurred on Aug. 9, 2010. And south off the Yaeyama islands at a depth of 15~20 km is commonly suggested as a slip area from some SSEs. The depth of the slip area around Iriomotejima island and Yonagunijima island are estimated to be 35~50 km, which is deeper than that in the previous study, mainly because of the adopted geometry.

We also estimate coupling distribution from average velocity data during inter-SSE period. The result suggests strong coupling region. This region is almost the same as slip region of SSE. In this region, coupling rate is calculated to be 75 %. Because back slip rate is almost equal to the average slip rate of SSEs in this region, most strain is released by the SSEs. Furthermore, we estimate weak coupling south off Taramajima island, although this region has poor resolution. We propose the hypothesis that strain may be accumulated over a long time in this region, and that this region has a potential of a future megathrust earthquake. To examine this hypothesis, we must continue geodetic observation for a long time, and set new stations including ocean bottom pressure gauges.

キーワード：スロースリップ、固着、琉球弧南西部
Keywords: Slow Slip Event, Coupling, Southwestern Ryukyu Arc



四国におけるスローリップイベントの潮汐応力への応答
Slow slip events response to tidal stress in western Japan

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日本の南西部、紀伊半島から四国地方にかけての沈み込み帯ではスロースリップイベントが度々発生している。スロースリップイベントはプレート境界の摩擦特性が変わる遷移領域で発生しており、その振る舞いを知ることは、プレートの挙動を考える上で非常に重要である。
CascadiaではPBO(Plate Boundary Observatory)の歪計データを用いた統計解析により、スロースリップイベントが潮汐応答を示すことが知られている[Hawthorne & Rubin, 2010]。そこで本研究では、GNSSを用いて検出された南海トラフでの短期スロースリップイベント[Nishimura et al., 2013]に対して、AIST(Advanced Industrial Science and Technology)のboreholeで観測された歪計のデータを用いて、Hawthorne & Rubin, 2010と同様の統計解析を試みた。
それぞれのイベントについて、プレート境界上での応力の計算にはNishimura et al., 2013で推定された断層パラメタを用いた。海洋潮汐による応力テンソルはNAO.99b [Matsumoto et al.,2000]を用いて求めた理論海洋潮汐にグリーン関数[Okubo & Tsuji, 2001] を掛け併せることで求め、また、固体潮汐による応力テンソルはTamura [1987] のポテンシャルを用いて求めた。
SSE前後の期間のデータを用いることで生データからノイズとなる要素を取り除き、その加工した歪み計データと上記で計算した潮汐による剪断応力の位相を比較した。加工データから求めた歪みレートと、速度強化摩擦則に基づいて剪断応力から予測される歪みレートは整合的であり、このことはSSE発生域での摩擦パラメタを制約できる可能性を示唆している。また、本研究の結果は、数kPaの応力擾乱が沈み込み帯遷移領域での滑り速度に影響をあたえることも示唆するものである。

キーワード：歪計データ、ゆっくり滑り、潮汐応答
Keywords: strain data, slow slip, tidal modulation

Earthquake swarms along the Oaxaca segment of the Mexico subduction zone and relationships to slow slip phenomena

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Earthquake swarms are thought to differ from traditional mainshock-aftershock sequences due to a separate driving processes such as slow slip or fluid flow. Several recent studies have suggested that tracking earthquake swarms may provide an indication of broader fault movement, which could eventually result in triggering of larger earthquakes. We utilize waveform correlation techniques to enhance the detection and characterization of earthquake swarms. We focus on the Oaxaca region of the Mexico subduction zone where a locally deployed joint seismic-GPS network has been maintained for 10 years. This network has previously been used to identify and locate many episodes of slow slip and nonvolcanic tremor across the study region. The improved temporal and spatial characterization of the earthquake swarms will be compared with the patterns of slow slip and nonvolcanic tremor to investigate the potential physical relationships between these different aspects of fault slip.

伊豆弧を構成する岩石の摩擦特性とその房総スロースリップに対する意義
Frictional property of rocks in the Izu forearc: implications for the Boso slow slip events

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As different from the Nankai and Tohoku subduction zones, island-arc components composing the Izu arc subducts beneath the Kanto region. The collision and subduction of the Izu arc into the Kanto region could result in occurring the different type of earthquakes, including seismic slip (e.g., the 1923 great Kanto earthquake) and aseismic creep (i.e., the Boso slow slip events). Based on a source location map of the Kanto earthquake and the Boso SSEs (e.g., Hirose et al., 2014), the seismic and aseismic slip at the Kanto region seems to generate side by side at almost same depth, probably nearly same P-T conditions. We thus hypothsis that the different types of slips arise from different materials of the Izu arc.

To address this hypothesis, we have performed friction experiments on five types of rocks from the Izu forearc at temperature of 300oC (nearly seismogenic condition), confinig pressure of 156 MPa and fluid pressure of 60 MPa using a high P-T gas medium apparatus at AIST. Rock types used in this study were marl, boninite, andesite, antigorite and chirysotile serpentinites that were recoverd by Leg 125, Ocean Drilling Program from the Izu forearc. Considering the direction of plate motion, igneous rocks composing the arc is expected to be subducted into the hypocentral area of the Kanto earthquake, while serpentinite appeared as a diaper in the forearc is to be subducted into the area where the Boss SSEs occur. In the experiments, we fixed the temperature and pressure conditions to investigate the difference in slip behavior between the rock types.

In the experiments we conducted velocity-stepping tests at slip rates of 0.1-1 μm/s. At the experimental condition, serpentinites exhibited velocity strengthening behavior. In contrast, marl, boninite and andesite characteristically showed a periodic stick-slip behavior. Slip duration of the stick-slip events was an order of seconds, three orders of magnitude longer than the ideal slip duration of stick-slip event as expected from the stiffness and mass of the apparatus. We thus called such slip behavior as “slow stick-slip”. Linear relationship between the slip duration and the stress drop of slow stick-slip hold for the observed slow stick-slip events, except for the event of marl sample of which the relationship shifted from linear to cubic with displacement. The linear relationship between the duration and the stress drop is consistent with that between the duration and the seismic moment of slow earthquakes in nature (Ide et al., 2007), as the stress drop is proportional to the seismic moment. The result implies that the Boso SSEs may be hosted by igneous rocks (e.g., boninite or andesite) composing the Izu arc, rather than serpentinite which is often considered as a source material for slow earthquakes. However the result should be taken carefully, because whether slow sticks-slip occurs or not depends on the balance between the stiffness of fault surrounding mdedium and the critical stiffness which is defined by effective normal stress and friction parameters of fault materials. To connect the slow stick-slip observed in laboratory with slow earthquake in nature, it is necessary to consider the coupling between the stiffness components.

キーワード：スロースティックスリップ、房総スロースリップ、摩擦
Keywords: slow stick slip, the Boso SSEs, friction

Constraints on friction, dilatancy, hydraulic diffusivity, and effective stress from low-frequency earthquake rates on the deep San Andreas Fault

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Similar to their behavior on the deep extent of some subduction zones, families of recurring low-frequency earthquakes (LFE) within zones of non-volcanic tremor on the San Andreas fault in central California show strong sensitivity to stresses induced by the tides. Taking all of the LFE families collectively, LFEs occur at all levels of the daily tidal stress, and are in phase with the very small, ≤~200 Pa, shear stress amplitudes while being uncorrelated with the ~2 kPa tidal normal stresses. Following previous work we assume LFE sources are small, persistent regions that repeatedly fail during shear within a much larger scale, otherwise aseismically slipping fault zone and consider the constraints on two different models of the fault slip: 1) that the correlation of LFE occurrence reflects modulation of the fault creep rate by the tidal stresses, and 2) that creep occurs episodically, triggered by the tides. With these models we examine the predictions of laboratory-observed rate-dependent dilatancy associated with frictional slip. The effect of dilatancy hardening is to damp the slip rate, so high dilatancy under undrained pore pressure reduces triggering of slip and modulation of slip rate by the tides. The undrained end-member models produce: 1) no sensitivity to the tidal normal stress, as first suggested in this context by *Hawthorne and Rubin* [2010], and 2) fault creep rate or earthquake rate in phase with the tidal shear stress. For these models, the observed tidal correlation constrains the hydraulic diffusivity to be less than about 1×10^{-6} /s and the product of the friction and dilatancy coefficients to be at most 5×10^{-7} in the LFE source region. The product is more than an order of magnitude smaller than observed at room temperature for talc, an extremely weak and weakly dilatant material. This may reflect a temperature dependence of the dilatancy and friction coefficients, both of which are expected to tend towards zero at elevated temperatures at the brittle-ductile transition. Alternatively, in the absence of dilatancy the ambient effective normal stress would be no more than about 50 kPa. In summary, for friction models that have both rate-dependent strength and dilatancy rate-dependence, the observations require intrinsic weakness, low dilatancy, and lithostatic pore fluid pressures.

Keywords: low frequency earthquake, friction, tremor

Two effects of slow earthquakes on large megathrust earthquakes: Triggering and facilitating of coseismic slip

Two effects of slow earthquakes on large megathrust earthquakes: Triggering and facilitating of coseismic slip

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We propose that slow earthquakes may have two effects on ordinary megathrust earthquakes, especially in the shallow subduction zone. The first effect is triggering of coseimic rupture by slow slip events; this is well modeled in previous work. The second is facilitation of coseismic slip on a fault which is experiencing slow slip. The fault hosting ongoing slow slip may be more easily induced to slip coseismically if a dynamic rupture from a large earthquake propagates onto the fault.

Before the 2011 Tohoku-Oki earthquake, two shallow episodic tremor and slip events (ETS) were observed in the same area of the 2011 mainshock near the Japan Trench, where the huge coseismic slip exceeding 30 m occurred. The first ETS event occurred over a week in November 2008 and included a slow slip event that exhibited an equivalent moment magnitude of 6.8. Shortly prior to termination of the slow slip, a M6 earthquake was induced by the slow slip event at the down-dip edge of the slow slip rupture area. The second ETS event was observed from the end of January 2011 until just before the 2011 Tohoku-Oki earthquake and exhibited an equivalent moment magnitude of 7.0. This slow slip event induced the largest foreshock (M7.3 on March 9) and probably triggered the March 11 mainshock of the 2011 Tohoku-Oki earthquake. Both of the ETSs clearly trigger interplate earthquakes on the plate interface.

The difference between 2008 and 2011 ETSs is whether they continued or ceased before they induced large interplate earthquakes. To investigate the effect of ETS on coseismic slip occurring on the same fault, we performed laboratory friction experiments on simulated fault gouges. We observed that increases in sliding velocity could induce slip-weakening behavior, which overwhelms the velocity dependence resulting in large overall weakening. Therefore, a fault which is experiencing a transient slip or slow earthquakes may be more easily induced to slip coseismically if a dynamic rupture from large earthquake propagates onto the fault.

キーワード：スロー地震、巨大地震、岩石実験
Keywords: slow earthquake, Megathrust event, rock experiment

The Hydrologic, Metamorphic, and Frictional Habitat of Shallow Slow Earthquakes

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Slow slip events (SSE) and very low frequency earthquakes (VLFE) in the outermost forearc of subduction zones demonstrate that unstable slip nucleates at shallower depths and nearer the trench than previously recognized. These events provide an opportunity to unravel the physical processes governing the nature of slip on subduction megathrusts; their source regions are accessible by drilling and well-imaged by geophysical surveys, enabling investigation of the properties and state of the plate interface. Here, we describe recent drilling, modeling, and laboratory results that, collectively, advance our understanding of the habitat of these events.

Estimates of in situ pore fluid pressure obtained by combining laboratory measurements on core samples with P-wave velocities from regional geophysical surveys show that the slow earthquake source regions are highly and locally overpressured, with pore pressures 75–90% of lithostatic. Kinetic models of smectite-illite transformation show that the reaction and peak fluid release occur mostly updip of the slow earthquake source areas; this may contribute to fluid overpressure, but is unlikely to be the primary driver. Laboratory frictional experiments on samples from subduction faults document primarily velocity-strengthening behavior, suggesting that nucleation of unstable slip is unlikely. However, a minimum in friction rate dependence (*a*-*b*) occurs at sliding velocities of ~1-10 μm s^{-1}, and we note increasing rate weakening with increased quartz content. Additionally, slip-weakening trends in these materials occur over larger distances (several mm) than commonly used to define frictional rate dependence, and are quantitatively consistent with several characteristics of slow earthquakes.

The emerging picture is that VLFE occur in a zone of highly overpressured fluids, low stress, and transitional frictional behavior. Although illitization is largely complete updip of the events, clay dehydration may augment fluid overpressures generated by disequilibrium compaction, and the accompanying release of SiO_2 may lead to greater tendency for unstable slip. Taken together, elevated pore fluid pressure and low effective normal stress, coupled with a minimum in frictional rate dependence at slow slip rates likely produces a fault zone with transitional frictional stability and reduced rigidity, favoring long rise times and slow rupture.

Keywords: Slow Earthquakes, Pore Pressure, Friction

流体の3次元的移動とそのスロー地震の空間変化への示唆
3D migration of fluid and its implications for the spatial variation of slow earthquakes

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In recent years, slow earthquakes have been studied extensively because of its importance for better understanding of interplate slip behavior in the subduction zone. At least in southwest Japan and Cascadia where relatively dense seismic and geodetic observations are available, we can clearly see the spatial variation of the activities of slow earthquakes. In southwest Japan, non-volcanic tremor may not be active around Kii Channel and Ise Bay, where the geometry of subducting Philippine Sea Plate changes significantly. In Cascadia, the amount of slip due to slow slip events is largest beneath Port Angeles where we can see the bend of the subducting Juan de Fuca Plate. These observations suggest a possible relationship between slab geometry and the activities of slow earthquakes. Considering that fluid may play an important role in generating slow earthquakes, one explanation for it is that fluid released from the subducting slab migrates in 3D due to complex slab geometry and it leads to the along-arc variation in porosity.

To investigate 3D fluid migration due to complex slab geometry, we construct 3D subduction zone models based on finite element approach. The model domain is divided into crust, subducting slab, and mantle wedge. Mantle wedge is subdivided into a thin serpentinite layer just above the slab and the remaining part. We assume that the serpentinite layer has permeability anisotropy so that the fluid can move nearly parallel to the slab surface and reach the region where slow earthquakes occur. We first compute matrix flow and temperature. Matrix flow is computed only in the mantle wedge and temperature is computed for the whole model domain. Next, we compute fluid migration in the mantle wedge. We assume that fluid migrates as porous flow. 3D fluid migration arises from the combined effects of permeability anisotropy and complex slab geometry.

For a simple oblique subduction case, we find that fluid moves nearly parallel to the maximum-dip direction of subducting plate, not subparallel to the direction of plate motion. For the case with slab geometry similar to that of Cascadia, the fluid concentrates around the bend of the slab, which results in the increase of porosity there. This may help explain the observed along-arc variation in the slow slip events in Cascadia. Our results show that 3D fluid migration may have a strong impact on the spatial variation of slow earthquakes.

キーワード：3次元流体移動、沈み込み帯、スロー地震
Keywords: 3D fluid migration, subduction zone, slow earthquakes

Toward unified source model of seismic phenomena
Toward unified source model of seismic phenomena

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Seismic phenomena on the plate interface are diverse, including ordinary earthquakes, shallow and deep slow earthquakes, and stable slip. Ordinary earthquake, which is characterized by power-law statistics, and slow earthquake have different scaling relation between seismic moment and duration of the event. The M9 Tohoku earthquake in 2011 provides us interesting observation about the hierarchical structure of ordinary earthquakes. Foreshocks and aftershocks on the plate interface occurred only at the area where seismicity has been observed so far. This observation suggests that hierarchical structure is stick to space. This view of seismic source is similar to the model by Ando et al. (2010, 2012) and Nakata et al. (2011), which reproduce the behavior of slow earthquakes. In their model, brittle patches are distributed on the ductile background.
Nakata et al. (2011) showed that their model could reproduce both ordinary earthquake and slow earthquake with different density of brittle patches. However, Nakata et al. (2011) did not show the detail condition how slip behavior of the fault transit from ordinary earthquake to slow earthquake. This study will investigate how this boundary is determined. For easy understanding, we use a 2D model space (line fault) with rate and state friction, which can explain the slip behavior of rock at slow slip speed, although Nakata et al. (2011) used slip-weakening law with Newtonian rheology as friction law. We calculate quasi-static elastic stress interactions between sub-faults with a cyclic boundary condition and radiation damping at a prescribed seismic speed. Frictional parameter (a and b) was set heterogeneously on the fault as either velocity weakening (VW, $a-b < 0$) or velocity strengthening (VS, $a-b > 0$), but characteristic length (Dc) was distributed uniformly. We tested bimodal distributions of frictional parameter. The distribution of frictional parameter is characterized by the length of cyclic unit L and the ratio h of VW region within the fault. The stress loading by the plate is characterized by stiffness k. We have tested many sets of h and k, and have investigated the slip behavior. As a result, three types of slip behavior are observed, (i) stable slip, (ii) seismic slip in VW regions and afterslip in VS regions, and (iii) entire seismic slip. When h is small, the size of a VW region is smaller than the nucleation size of constant-weakening regime ($a/b=5/6$ in our study, Rubin and Ampuero, 2005), and slip occurs stably. Stable slip also occurs with a sufficiently large k. When k is below a critical stiffness, slip in VW regions is accelerated to the seismic speed. The boundary between (ii) and (iii) is determined by whether slip in VS regions exceeds Dc, accelerated by seismic slip in the adjacent VW regions. When h is small, slip in VS regions does not reach Dc and the decrease of state variable is small, before the termination of the seismic slip in the VW regions. Later, relatively slow slip occurs in VS regions as an afterslip. When h is large, slip in VS regions exceeds Dc and state variable decreases rapidly, before the termination of seismic slip in the VW region. Therefore, the slip in VS regions is also accelerated to the seismic speed, and the entire fault slips seismically at the same time. The boundary between the regimes (ii) and (iii) shifts to smaller h when k is decreased. Given that small randomness exists in the bimodal distributions in the regime (ii), seismic slip in VW regions occurs independently separated by slowly slipping VS regions. These successive slip events occurring in a short period appear to be a single event with almost constant moment rate function, which looks like a slow earthquake. On the other hand, the entire seismic slip in the

regime (iii) is considered as an ordinary earthquake. Thus the boundary between regimes (ii) and (iii) separates two modes of seismic slip.

キーワード：Heterogeneity、Earthquake、Source model
Keywords: Heterogeneity, Earthquake, Source model

ヒクランギ沈み込み帯における長期・短期的スロースリップと大地震との相互作用モデル
Modeling long- and short-term slow-slip events and their interaction with large earthquakes along the Hikurangi subduction zone

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Recent geodetic observations revealed the occurrence of various slow slip events (SSEs) along the Hikurangi subduction plate interfaces (Wallace and Beavan, 2010). Long-term SSEs with a duration of 1.5 years (e.g., Manawatu SSEs) occur at the deeper portion of the Hikurangi subduction zone, and shallow short-term SSEs with a duration of 1-3 weeks occur along the northern and central parts of the subduction zone. One of the fundamental questions is how SSEs interact with large earthquakes. In the present study, we performed quasi-dynamic modeling on short-term and long-term SSEs and their interaction with large earthquakes along the Hikurangi subduction zone. We used a rate- and state-dependent friction law with a cut-off velocity to the evolution effect (Shibazaki and Shimamoto, 2007). We investigated a realistic configuration of the plate interface. On the basis of the study on interseismic coupling by Wallace and Beavan (2010), we set the seismogenic zone where a-b is negative. The long term average relative slip velocity of each element was fixed at 4.5 cm/year for simplicity.
We set both the Manawatu and Kapiti SSE regions at the deeper extension of the seismogenic zone. The activity of Kapiti SSEs changes significantly during a cycle of large earthquakes. When large earthquakes approach, slip velocities increase at the deeper extension of the seismogenic zone. Consequently, slip velocities of the Kapiti SSEs at the deeper extension of the seismogenic zone increase. During a large earthquake, coseismic slips occur at the Kapiti SSE zone, but the occurrence of SSEs is subsequently restrained for some time. We also developed a model which investigated subducting seamounts in the northern segment of the Hikurangi subduction zone. The effective stress is assumed to be very high in the region of seamounts. The seamounts act as barriers of slow slip but between seamounts slips propagate to the shallow fault zones. Comparison between our results and observations will be necessary to develop a more realistic model of SSEs in this region.

キーワード：長期的・短期的スロースリップ、ヒクランギ沈み込み帯、モデル化、大地震
Keywords: Long- and short-term slow slip events, The Hikurangi subduction zone, Modeling, Large earthquakes

スロースリップを起こす断層面上の摩擦パラメータ推定法 -アンサンブルカルマンフィルタを用いて-
Numerical experiments on estimation method of frictional parameters on the SSE fault -Through Ensemble Kalman Filter-

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海溝型地震震源域の深部プレート境界上で発生する、スロースリップイベント(SSE) の活動は、海溝型大地震発生の前に変動する可能性が指摘されており(Peng and Gomberg, 2010)、SSE を引き起こすプレート境界面の摩擦特性を知ることは、海溝型大地震の発生を知る上でも重要な鍵を握る。我々の最終目標は、GNSSによって得られたSSE発生時の地表での変位データに対して、データ同化の手法の一つであるアンサンブルカルマンフィルタ(EnKF)を用いることによりSSE断層面上のすべり発展と摩擦パラメータを推定し、海溝型地震の発生の予測に役立てることにある。本研究では、シミュレーション計算によって得られたSSE発生時の断層面上のすべり速度や地表観測データに誤差を加えた模擬データを作成し、EnKFを用いて数値実験を行い、推定可能性について議論した。
まず、均質半無限弾性体中の深さ20-40km のプレート境界上に傾斜断層を設定した。断層面上の摩擦力は速度状態依存構成則に従うものとし、また発展則にはスローネス則を用い、準動的計算ですべり速度の時空間発展を求めた。本研究では、摩擦パラメータＡ[kPa], Ｂ[kPa], Ｌ[mm]に対して、Ａ－Ｂ＜０（速度弱化）かつ摩擦パラメータによって決まる臨界半径に対する断層のアスペリティの半径の比が１より少し小さい領域（条件付安定すべり域）となるように摩擦パラメータを設定することにより、平均発生間隔約6ヶ月のSSEを再現する力学的モデルを作成した。
本研究では、このモデルと設定した真値、観測値(模擬データ)を用いてEnKFを用いた断層面上の摩擦パラメータおよびすべり速度・状態変数の推定についての数値実験を行う。EnKFは、力学的モデルの計算によって得られた値（予報値）を、各タイムステップで観測値とそれらの分散共分散行列を用いて統計的に修正することで、最適な値（解析値）を推定する手法である。この分散共分散行列は初期値に乱数を与えて作った大量のアンサンブルメンバーを計算することで得られる。
まず、断層面上でのすべり速度をデータとした場合の実験結果から、SSE発生前後での断層面上でのすべりの浸透や広がりをとらえる観測点配置が必要であることが分かった。また、実験を行う中で断層モデルの不確実性を表すシステムノイズは可変にする必要があり、第一推定値(初期値)はより安定すべりに対応する摩擦パラメータ値にした方が良いことが分かった。さらに、この結果を基に、実際の場合に対応する地表観測点の場合に必要な観測点密度や、偏った観測点分布に対する推定可能性についての実験を行い、実際に観測されているSSE域での観測データに対して、本手法の適用可能性を議論した。その結果、豊後水道や東海沖SSEの地域には適用できる可能性があり、今後これらの地域について数値実験による検証を行う必要がある。

キーワード：アンサンブルカルマンフィルタ、スロースリップイベント
Keywords: Ensemble Kalman Filter, slow slip event

南海トラフの深部低周波微動のエネルギー総量の推定
Total energy of deep low-frequency tremor in the Nankai subduction zone

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Deep low-frequency tremor was first discovered in the Nankai subduction zone of southwest Japan, and is now known to occur in other subduction zones along the Pacific Rim. Because tremor usually occurs simultaneously with short-term slow slip events spatially and temporally, clarifying tremor activity is considered to be an important role to understand the slip process on the megathrust plate interface.
In this study, we estimated the total seismic energy of deep low-frequency tremor in the Nankai subduction zone, southwest Japan, over an 11-year period from 2004 to 2015. For precise estimation of the energy, continuous time sequences of tremor activity were carefully detected using a new procedure designed to minimize false-negative detections. By the result of spatial distribution of accumulated total energy of tremor, we found high-energy area in the western Shikoku region. Tremor activity rate, defined as the yearly average of total tremor energy per unit square, was investigated in each area throughout the Nankai subduction zone. Tremor activity rate averaged in 11 years is very high in near Bungo channel region compared to other regions. In the Bungo channel, the long-term SSE is known to occur at every six or seven years and activate nearby tremor activity. During the analyzing period, the long-term SSE occurred in 2010 and 2014. The tremor activity rate in this region in these two years increases to at least two or three times higher than that of quiescent period without the occurrence of long-term SSEs. This may indicate that external stress perturbations from the source of long-term SSEs in the Bungo Channel increased tremor activity by a factor of two to three. Slip on the plate interface in the tremor source region may be accelerated by nearby long-term SSEs. The relationship between tremor activity and nearby long-term SSEs in the Bungo Channel is consistent with the characteristics of tremor energy. We also note that tremor activity rate in this region is higher than that of other region even in the quiescent period.
In general, the tremor activity rate is high and low in areas west and east of the Kii Channel, where the plate geometry is complicated, respectively. In this comparison, tremor activity rate during quiescent period is used for Bungo channel region. The plate convergence rate shows the same spatial pattern as that for tremor activity. We infer that tremor activity is influenced by accumulated strain due to plate convergence. Strain at the plate boundary may be well accumulated where the plate convergence rate is high; tremor activity begins as a result of accumulated strain. In some areas in eastern Shikoku, the tremor activity rate is extremely low, although the plate convergence rate is relatively high. This may occur because the dip and convergence directions differ. Another possibility is that heterogeneous structures reduce the coupling between subduction rate and strain accumulation. Further investigation of this region is needed to constrain the tremor source mechanism.

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Disaster Prevention.

キーワード：微動、エネルギー、南海トラフ
Keywords: tremor, energy, Nankai

マッチドフィルタ法を用いた遠地地震による誘発微動の検出
Detection of deep low frequency tremor triggered by teleseismic surface wave based on matched filter technique

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沈み込み帯深部のスロー地震発生帯では，遠地地震からの周期約30秒の表面波によって，その位相に同期した周波数1-10Hz程度の深部低周波微動が励起されることがある．このような誘発微動と呼ばれる現象は，南海トラフの沈み込み帯では，2003年9月26日の十勝沖地震（Mw8.3）や2004年12月26日のスマトラ地震（Mw9.0）などで観測された（Miyazawa and Mori, 2005; 2006）．これらは，プレート沈み込み帯で短期的スロースリップイベントに伴って発生する深部低周波微動（Obara, 2002; 以下では定常微動と呼ぶ）の発生領域内で観測されているが，誘発微動の発生場所は定常微動活動の全域に分布するのではなく，限られたいくつかのスポットに集中しているという特徴がある．また，北海道や関東地方，九州地方では，沈み込む海洋プレート境界から離れた上盤プレート内の内陸地域でも誘発微動が確認されている（Chao and Obara, 2016）．このように，誘発微動と定常微動にはその活動様式に異なる点がある．本研究では，地震波形記録を用いて，誘発微動と定常微動の関係をより詳細に調べた．
まず，防災科学技術研究所の高感度地震観測網Hi-netで記録された2012年4月11日のスマトラ地震（Mw8.6）での三重県中部で観測された誘発微動のデータを使って，ほぼ同じ場所で発生している定常微動と周波数スペクトルの比較を行った．その結果，誘発微動と定常微動はどちらも同じようなスペクトルの形を持っていた．
次に，マッチドフィルタ法を使って誘発微動と定常微動の関係を調べた．テンプレートとして使うイベントには誘発微動から震央距離30 km以内の気象庁一元化カタログに載っている2014年中に検出された全ての低周波地震（LFE）を選択した．波形記録には帯域2-8Hzのバンドパスフィルターを適用し，テンプレートにはS波到来時刻周辺の5秒の記録を用いた．10観測点，3成分での355個のテンプレート波形と表面波到来時間帯の波形での相互相関係数の和を計算して，LFEと類似した波形の検出を行った．
2012年のスマトラ地震発生から日本列島への表面波到達時間を含む約1時間の波形記録にマッチドフィルタ法での解析を行った．高周波地震波の観測記録からは,表面波の位相に合わせて周期的に発生する誘発微動が確認されていたが，その部分ではテンプレートとしたLFEと相関の高いイベントは検出されず，誘発微動の開始から約400秒後の波形から顕著に相関の高いイベントが検出された．また，波形記録からは誘発微動の発生が終息したように見える後続波部分においても高い相関係数を示し，振幅の極めて小さな微動波形が検出できている部分があった．解析結果から，誘発微動は一つの地震の表面波によって励起される一連のイベント中でも，その断層の機構解の変化や震源の移動などによって波形が変化している可能性がある．

キーワード：スロー地震、深部低周波微動、誘発微動、マッチドフィルタ法
Keywords: slow earthquake, deep low frequency tremor, triggered tremor, matched filter technique

日向灘で観測されたスロー地震によって放出されたエネルギーの検証
Estimated the apparent released energy of shallow low-frequency tremor occurred Southeastern Kyusyu through frequency scanning at a single station

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Slow earthquakes, such as tectonic tremors and very-low-frequency earthquake (VLFE), share a common mechanism as shear slip on the plate interface and occur at both ends of updip and downdip of coseismic slip areas. Shallow low-frequency tremors have been observed in the subduction zone off southern Kyusyu [Yamashita et al., 2015].

Yamashita et al. (2015) have detected the shallow low-frequency tremors off southern Kyusyu from ocean-bottom seismometer (OBS) data. Although the seismicity has been documented, the released energy of these tremors has not been calculated. Here we calculate the released energy of tremor sequences off southwestern Kyusyu with applying the frequency scanning analysis [Sit et al., 2012] to OBS data.

Sit et al. (2012) proposed “the frequency scanning analysis” to detect tectonic tremors by calculating ratios of the envelope waveforms through different bandpass filters of broadband data at a single station in the Cascadia margin. We apply this method to the seismic data recorded at 12 short-period OBS stations deployed off southeastern Kyusyu, Japan. Three types of bandpass filters with frequencies of 2–4 Hz, 10–20 Hz, and 0.5–1.0 Hz, corresponding to the predominant frequency band of tectonic tremors, local earthquakes, and ocean noises, respectively, are adopted. When ratio value is over the threshold, we define that the tremor signal is detected in the time window. We estimate the apparent released energy as an approximation that is calculated from the squared amplitude of the median of absolute amplitude within the time window.

We have successfully detected the some sequences with large radiated energy, which correspond to the tremor events reported in Yamashita et al. (2015). In addition, we have also identified other possible sequences of tremors, which have occurred at the further southward that has been reported in Yamashita et al. (2015). The most largest released energy of tremors observed around the southern part of the tremor swarm.

Long-term ocean bottom monitoring of slow earthquakes on the shallow plate interface in the Hyuga-nada region (3)

Long-term ocean bottom monitoring of slow earthquakes on the shallow plate interface in the Hyuga-nada region (3)

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The Hyuga-nada region, nearby the western end of the Nankai trough in Japan, is one of the most active areas of shallow slow earthquakes in the world. We have started long-term ocean-bottom monitoring of them in this area from May 2014 using three kinds of sensors: broadband seismometer with pressure gauge (BBOBSP) and short-period seismometer (LTOBS). During the first observation (March 2014 to January 2015), we already reported minor shallow tremor and very-low-frequency earthquakes (VLF) activity and very-low seismicity of ordinary earthquakes within the focal area of shallow earthquakes in the Hyuga-nada. The second observation started from January 2015 using 3 BBOBSPs and 10 LTOBSs, and all sensors were retrieved in January 2016. From the monitoring using land-based seismic observation, many shallow tremors and VLFs occurred just under the OBS network during second observation period, which started from early in May and continued approximately 2 months. We confirmed the existence of these signals in the data recorded by each OBSs. Though the detailed hypocenter determination is still being performed, the observed records strongly suggests that the shallow tremor migrated within the OBS network, which reached at off Cape Ashizuri area where shallow VLFs have been occurred every 6-7 years associated with long-term SSE at Bungo channel. This off Cape Ashizuri’s activity (tremor and VLF) started at the end of May, especially increased activity after the large deep-focused earthquake at Ogasawara region (Mw7.8, 30 May 2015). In the presentation, we will introduce the preliminary result of second observation, in particular focus on the migration of shallow tremor.
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キーワード：shallow slow earthquake、Hyuga-nada、Ocean bottom observation
Keywords: shallow slow earthquake, Hyuga-nada, Ocean bottom observation

防災科学技術研究所関東・東海地震観測網紙記録からの低周波微動活動検出の試み

A tentative investigation to detect past activities of deep low-frequency tremor from the paper recording of the Kanto-Tokai observation network for crustal observation

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南海トラフ沿いでは，深部低周波地震が数か月間隔で繰り返し活発化しており，現在防災科研Hi-netの地震計等の解析から，その活動状況が明らかにされている．しかしながら，Hi-netの運用開始は2000年10月からであるため，それ以前の活動を知るためには別の記録が必要となる．防災科研は1979年から関東・東海地殻活動観測網の定常処理を開始しており，その後も順次観測点が増加している（Okada et al., 2000）．この観測網の上下動成分の連続地震波形は，ペンレコーダーによる紙記録として，防災科研内に保管されている．まず，この記録を用いて，2000年以前の深部低周波微動の活動状況の把握が可能かを検討した．また，これらの紙記録については膨大な冊数となるために保管場所確保の問題があり，記録の電子ファイル化についても検討を行った．以下，これらの結果について報告する．
東海地方の短期的スロースリップイベント(SSE)の活動については，1984年以降の歪計記録を用いて検出が行なわれ，結果が報告されている（小林他，2006）．短期的SSEの発生時には，微動の活発化がみられることから，小林他により短期的SSEが報告されている期間の前後について紙記録を確認したところ，数ヘルツに卓越する振動が継続するような，深部低周波微動に特徴的な波形が，下山観測点をはじめとして，串原，東栄等の東海地方の観測点で認められた．例えば，小林他(2006)では，短期的SSEの期間は1984年8月13～14日，1986年12月3～4日，1987年5月8～12日と報告されているが，比較的明瞭に微動の波形がみられる下山観測点の記録からは，1984年8月13～16日，1986年12月4～5日，1987年5月8～10日に活動が認められた．微動の活動領域は移動し，地震計と歪計の位置は20 kmほど離れているため，歪計の記録の期間と地震計の活動期間の数日のずれは，こうした時空間的な活動状況に起因すると考えられる．また，振幅は数百nm/s程度であり，Hi-net整備以降に捉えられた微動の振幅と同程度である．
次に微動活動が確認された下山観測点の紙記録について，電子画像ファイル化を検討した．画像ファイル化にあたっては，適切な解像度等を選択する必要がある．下山観測点における紙送り速度は4 mm/sであり，紙上の1 mmの振幅が336 nm/sに相当する．解像度が300dpiの場合，1ピクセルは約0.085 mmであることから，時間方向の分解能は約47Hzサンプリング相当となる．また，振幅については１ピクセルが約28 nm/s相当となる．低周波微動の特徴的な周波数は数Hzであり，振幅は数百nm/sであるから，300dpi程度の解像度であれば，実用上問題ない．ただし，観測点により振幅の設定が異なるため，この数値はすべてについて共通のものではない．また，ペンと背景の境界は明瞭であるため，階調は白黒２値で十分と考えられる．
画像化の作業時間は，確認を含め，１観測点１日分で5分程度は必要であった．下山観測点は1980年5月から観測を開始しており，Hi-net運用開始までの約20年間のデータの画像化には，単純計算で600時間を超える作業時間となる．この紙記録はもはや得ることのできない貴重なものであるが，関東・東海観測網の高感度地震計設置点は1985年で66点となっており，もしすべての記録を画像化する場合には，多くの作業が必要となる．

キーワード：深部低周波微動、紙記録、スロースリップイベント
Keywords: deep low-frequency tremor, paper recording, slow slip event

グリッド固定震源メカニズム法を用いた浅部超低周波地震の検出
Detection of shallow very low-frequency earthquake using a grid-based, fixed focal-mechanism method

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Recent observations of shallow very low-frequency earthquake (sVLFE) show the large-scale migration of activity and the simultaneous occurrence with shallow tremor, indicating sVLFE and shallow tremor are induced by background shallow slip event as is the case with the deep slow earthquakes (Asano et al. 2015; Yamashita et al. 2015). Understanding the relationship between the shallow slow earthquakes along the Nankai trough is important in view of occurrence of the future Nankai great earthquake.

In September 2006 a major activity of deep very low-frequency earthquake (dVLFE) and deep tremor occurred in the Bungo Channel and western Shikoku region. This activity is considered to be induced by a small long-term Bungo Channel slow slip event (SSE) because small surface displacements were also observed in GPS records. It is known that large long-term Bungo Channel SSE induces high sVLFE activity in the Hyuganada region (Hirose et al. 2010). Therefore sVLFE activity is expected to be observed also in Sept. 2006.

In this study we applied the grid-based, fixed focal-mechanism method (Suda et al. 2014) to detection of sVLFE in the Hyuganada region. We analyzed the F-net data from 33 stations between August 20 and September 30, 2006. We used only the F-net data because one purpose of this study is to check the feasibility of real-time monitoring of sVLFE using JDXnet data, which include no Hi-net accelerometer data.

We detected over 90 events in the analysis period. The main activity occurred in August 28-31 and only a small number of events occurred in September 7-21 when the activity of dVLFE and deep tremor occurred. This observation is in contrast to that the 2010 sVLFE activity in the Hyuganada region occurred in the acceleration stage of dVLFE and deep tremor activity in the Bungo Channel and western Shikoku region. The present observation suggests that a possible SSE that induced dVLFE and deep tremor in September 2006, if any, was not large enough to induce the high sVLFE activity in the Hyuganada region. The sVLFE activity observed in August might be due to a local shallow SSE.

キーワード：スロー地震、浅部超低周波地震、日向灘
Keywords: slow earthquake, shallow very low-frequency earthquake, Hyuganada

南西諸島における超低周波地震に伴って発生する低周波地震の震源分布
Distribution of low frequency earthquakes accompanied with very low frequency earthquakes along the Ryukyu Trench

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南西諸島では広範囲で超低周波地震が長期的かつ継続的に発生している。その超低周波地震は低周波地震を伴っている場合が多い。高橋・他（2015）では南部琉球海溝で海底地震観測をおこなった際に検出された超低周波地震と低周波地震を解析し、低周波地震が超低周波地震に伴って発生しているとした。これは長期的・琉球海溝の他地域でも一般的に見られる傾向なのか、さらに低周波地震は超低周波地震の震源近傍で発生しているのか明らかにするため、低周波地震の検出および震源決定をおこなった。
低周波地震の長期的発生傾向（2004年から2013年）はF-net広帯域地震記録に1Hzのhigh-pass filterをかけた波形を用い、超低周波地震が発生した時刻にそれに対応する低周波地震が近傍の観測点で見られるか否か、目視で調べた。その結果、低周波地震は長期的に2%（奄美地域）～16%（八重山地域）の割合で一定して見られることがわかった。M4.0以上の超低周波地震ではほぼ確実に低周波地震が観測される一方、M3.7以下の超低周波地震では低周波地震が観測されなかった。これは小さな超低周波地震ではノイズに紛れてしまうため低周波地震が観測されなかった可能性が高い。
次に低周波地震の震源決定をおこなった。震源決定には気象庁が南西諸島に設置している短周期地震計記録を用いた。超低周波地震のカタログ（Nakamura and Sunagawa, 2015）を用いて超低周波地震の群発活動を探し、その期間の気象庁短周期地震計記録を解析した。期間は2004年から2013年である。震源決定は地震観測網がある程度面的に配置してある八重山諸島近傍と沖縄本島周辺で発生した超低周波地震について実施した。低周波地震の観測点への相対到達時間はEnvelope Cross-correlation Method (Obara, 2002)を用いて決定した。地震波形の水平動成分を合成してその10秒間の二乗平均を計算して波形の外形を求めた。観測網内の観測点間の波形の相互相関を計算し、相関係数が0.85以上の組み合わせが4箇所以上であった場合、震源決定をおこなった。振幅はS波が卓越すると仮定してS波速度構造で震源決定をおこなった。
主な超低周波地震活動を選び、それに伴う低周波地震活動の震源を決めた結果、八重山諸島の場合、与那国島から西表島の南方沖で、かつ琉球海溝と南西諸島の間に震源が集中した。この位置は高橋・他（2015）が海底地震計で決定した低周波地震の位置に近い。ただし観測点配置が島にしか配置されていないこと、およびS波のみによる決定のため、海溝に沿う方向と直交する方向の位置誤差はそれぞれ30kmおよび70kmにおよぶ。しかし経度方向で比較すると、低周波地震の分布はSemblance法を用いて解析した超低周波地震の分布と非常によく対応する。このことから、八重山諸島では超低周波地震と低周波地震はおおよそ同じ場所で発生している傾向があるといえる。低周波地震は超低周波地震の発生と供に見られ、低周波地震単独での発生は殆ど見られない。また、沖縄本島近傍では低周波地震は沖縄島南部の南東側および沖永良部島の南東側で集中して発生していることが明らかになった。八重山諸島と沖縄本島周辺ともに低周波地震は半径約40kmのクラスター状に発生している。一方、海溝軸に沿った活動の移動現象は検出できなかった。これはこの地域では陸上観測網で観測可能な規模の低周波地震の移動現象は40km以内の狭い範囲で発生している可能性があることを示している。

キーワード：超低周波地震、低周波地震、琉球海溝
Keywords: very low frequency earthquake, low frequency earthquake, Ryukyu Trench

四国における臨時広帯域地震計設置で観測された2015年豊後水道浅部超低周波地震活動

Swarm of shallow very low frequency earthquakes in the Bungo channel region in 2015 observed by temporal broadband seismic stations in the Shikoku island, southwest Japan

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The Bungo channel region in southwest Japan is one of regions where various types of slow earthquakes are observed at the top surface of subducting Philippine Sea plate. The slow earthquakes includes (i) long-term slow slip events (SSEs) at depths around 30 km and short-term SSEs at deeper depths recorded by geodetic instruments, (ii) shallow/deep low frequency tremor recorded by short-period seismometers at 1-10 Hz, (ii) and shallow/deep very low frequency earthquakes (VLFEs) recorded by broadband seismometers at 10-100 s. Although the coincidence of long-term SSEs and shallow VLFEs indicates relationship between them, there still exists a gap area between their estimated source areas without detection of any slow earthquake at this moment. For further understanding of slip distribution at the plate interface, we installed one Guralp CMG-3T (100 s) broadband seismometer and two Nanometrics Trillium (120 s) broadband seismometers in the southwestern part of the Shikoku island in February 2015 and June 2015, respectively. The observation plan at least continues to 2020.
The preliminary records showed seismic waves from shallow VLFEs activated in early June 2015. The data quality of vertical components was comparable to that of permanent stations of F-net broadband seismograph network operated by National Research Institute for Earth Science and Disaster Prevention at a period range of 20–50 s. We first applied the GRiD MT method (Tsuruoka et al. 2009) to records of 18 F-net stations as well as three new stations on June 8th filtered at a period range of 20–50 s for determining location and focal mechanism of each VLFE. We then applied the matched filter technique (Shelly et al. 2007) to detect similar events for eight months from May to December in 2015 by using a Mw4.1 event as a template event. The total number of detection is 1,476. We also determined the amplitude and location of each event with respective to the template event by grid search and waveform fitting.
The space-time plot of detected events showed two migrationg sequences of shallow VLFEs from southwest to northeast for two times, and several rapid reversal movements in June 2015. The cumulative number plot of time interval between adjacent events shows power-low distribution, which is different from exponential distribution for normal earthquakes and may characterize the swarm-like activity of VLFEs. The cumulative number of amplitude could be explained by both exponential and power-low functions due to limited range of amplitudes. Further discussion about the detection level for small amplitude is needed to conclude which function better explains the obtained distribution.
We also applied various band-pass filters to the waveforms at the time-windows aligned by the origin time of detected events. As a result, we could observe coherent signals between each time-windows at a period range of 10–100 s. Since the data quality was limited especially at periods longer than 50 s, we improved the signal-to-noise ratio by calculating station-averaged waveforms for each event. The averaged waveforms showed constant phase shifts between each time-windows at least at a period range of 20–100 s. This result indicates that the moment release function of each VLFE has a typical duration less than ~20 s.

キーワード：超低周波地震、西南日本、広帯域地震観測
Keywords: Very low frequency earthquake, Southwest Japan, Broadband seismic observation

DONETで観測された2015年南海トラフにおける超低周波（VLF）地震
Shallow very-low-frequency (VLF) earthquake activities along the Nankai trough in 2015

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In 2015, we observe shallow very-low-frequency (VLF) earthquakes along the Nankai trough by DONET, a permanent ocean-floor observation network. The activity started off the Shiono-misaki in August, which is followed by the activity off the Kii channel in September. In October the activity moved beneath the Kumano fore-arc basin. I investigated their source location and mechanism. Previous VLF activities along the Nankai trough are observed in 2004 (Obara and Ito, 2005), 2009 (Sugioka et al., 2012), and 2011 (To et al., 2015).
I determined the source location and mechanism of the VLF events by a waveform inversion using the SWIFT system (Nakano et al., 2008). Bband-pass filtered waveforms between 20 and 30 s, of which VLF signal is dominant, are used for the inversion.
Obtained CMT solutions show that the VLF sources are concentrated in several clusters located off the Kii channel, off Shiono-misaki, and Kumano fore-arc basin. These clusters well overlaps those reported by Obara and Ito (2005). The sources in the Kumano fore-arc basin can be divided into two clusters, which are located east and west of the previous major activity reported by Sugioka et al. (2012).
The source depth is between 7 and 10 km, corresponding to the base of the accretionary prism. The focal mechanism solutions represent low-angle thrust; one of the nodal planes is almost horizontal and the slip direction is almost perpendicular to the dip of slope of the sedimentary wedge. These results infer that the VLF events are caused by a slip along the plate boundary beneath the accretionary prism. We note that the dip of slope of the sedimentary wedge above the cluster off the Kii channel rotates about 60 degrees eastward due to the subduction of a seamount, but the rake angle of the obtained focal mechanism is very similar to those in the other clusters.
The obtained magnitude is at most about 4. The b-value obtained from the frequency-magnitude distribution is 2.4, inferring low stress level at the source.
I found that the occurrence of each event corresponded to minimal (not always the minimum) of ocean-bottom pressure caused by the ocean tide observed at DONET stations. This feature is evident in the activities off the Kii channel and off the Shiono-misaki. The correspondence to the low pressure was not evident in the activity beneath the Kumano fore-arc basin because of the swarm activity, although several events before the swarm activity corresponded to minimal of ocean-bottom pressure.
Assuming almost horizontal fault plane for the VLF sources, unclamping the fault by the decrease of hydrostatic pressure would promote VLF events. The tidal pressure change is about 10 kPa, comparable to the stress drop estimated for VLF earthquakes (Ito and Obara, 2006), which would be enough to perturb the state of stress at the source. But the truth would not be as simple as this because several of VLF events did not occur at minimum of the pressure. Combined effect of tidal force and external loading, a proposed model for deep non-volcanic tremor (e.g. Nakata et al., 2008; Ide and Tanaka, 2014), would be necessary to model the trigger of VLF earthquakes.

キーワード：DONET、紀伊水道沖、潮岬沖

Keywords: DONET, off Kii channel, off Shiono-misaki

四国地方における SSE と微動活動の関係

Investigating the relationship between slow-slip events and tremor in the Shikoku region, Southwest Japan

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In the subduction zone of Southwest Japan, Obara (2002) discovered nonvolcanic tremor, which is characterized by longer duration than regular earthquakes. After this discovery, other new slip phenomena at the plate boundary, characterized as well by longer durations, have been discovered in subduction zones around the world. These phenomena are collectively known as “slow earthquakes”. Understanding of slow earthquakes is an important issue for understanding the physics of subduction zones and may help the risk assessment of huge earthquakes. Fortunately, by the strengthening in recent years of the observation networks, the routine analysis of slow earthquakes is becoming possible and open observation data are being made available.
In this study we analyze and discuss the characteristics of slow earthquakes by using catalog data which have been newly developed in the recent years in the Shikoku region. This area has a new catalog of SSEs (Nishimura *et al.*, 2013; Nishimura 2014) and tremor (Idehara *et al.*, 2014).
Our results show that in the Shikoku region, almost all of the short-term SSEs (S-SSEs), which were detected by Nishimura (2013, 2014), synchronize with tremor activity. Assuming that tremor activities reflect the destruction of small patches on the SSE fault, we observe a consistent relationship of linear increase in the duration of the activation of tremors with the moment of SSEs. This result is in agreement with the scaling law of SSEs (Ide et al., 2007) and observation case of long-term SSEs (L-SSEs) (e.g., Miyazaki *et al.*, 2006). In addition, the calculation of the magnitude of L-SSE by using the tremor activation period during the periodic L-SSEs at Bungo Channel and the scaling law obtained in this paper is consistent with geodetic observations (Yoshioka *et al.*, 2015).
The obtained results suggest that the space-time pattern of tremor is well explained by SSEs characteristics and that the tremor can be used as a proxy for the detection of SSEs.

キーワード：ETS、tremor、scaling law of SSEs
Keywords: ETS, tremor, scaling law of SSEs

豊後水道SSE隣接領域の固着と微動発生レートの関係

Relationship between coupling and tremor rate in the region adjacent to the Bungo Channel SSE area

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豊後水道では長期的スロースリップイベント（SSE）が数年おきに繰り返し，また豊後水道を含む西南日本では深部低周波微動の活動が知られている。豊後水道の長期的SSEは1997-2010年の間には1997年，2003年および2010年頃にほぼ同じ領域で発生したことがわかっている。また，この領域の微動活動に目を向けると，これら長期的SSEの北端部の微動活動がSSEに同期して活発化していることが報告されている（Hirose et al., Science, 2010）。

Ochi（EPSL, 2015)は中国・四国地方のGEONET日座標値を利用して同時期のスロースリップと固着の同時推定を行ったが，この結果によると2010年のSSE領域の東側に隣接する場所では，SSEの発生と同期して固着の強化がみられる。一方，産総研ではエンベロープ相関法（例えばMaeda and Obara, JGR, 2009）を用いて2008年7月以降の微動カタログを作成しているが，この微動カタログによれば，長期的SSE発生時に固着が強化したとみられる領域では，長期的SSE収束後の2011年以降に微動の発生レートが増加していることがわかった。増加した発生レートは2014年中頃まで継続し，再び2011年以前の発生レートに戻っている。豊後水道では2014年中頃からふたたび長期的SSEが発生したことが明らかになっており（国土地理院，地震予知連絡会会報94, 2015），微動の発生レートの減少はこの長期的SSEと同期しているように見える。以上のように長期的SSEに隣接する東側の領域で長期的SSEと同期した固着・微動活動の変化がみられる。今後2011年以降の固着分布を推定し，定量的な評価をおこなう予定である。

キーワード：スロー地震、深部低周波微動、プレート間固着
Keywords: Slow earthquake, deep low-frequency tremor, interplate coupling

GNSSデータによって検出された関東地方における短期的スロースリップイベント
Short-term Slow Slip Events in the Kanto Region, Central Japan Detected Using GNSS Data

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The Kanto region, central Japan is situated under complex tectonics where the Philippine Sea and the Pacific plates subduct from the Sagami Trough and the Japan Trench, respectively. Several large earthquakes including the 1923 M7.9 Kanto earthquake historically damaged the Kanto region. Shallow short-term slow slip events (SSEs) were observed by continuous GNSS east off the Boso Peninsula in 1996, 2002, 2007, 2011, and 2014 [e.g., Ozawa *et al.*, 2014]. These Boso SSEs with M_w ~6.6 occurred on the Philippine Sea plate in a depth of 10-20 km. Some studies reported that SSEs occurred on the Pacific plate. However, spatiotemporal distribution of SSEs remains unclear in the Kanto region. In this study, we accomplish systematic searches for SSEs along both the Sagami Trough and the Japan Trench using GNSS data.
An operation of a continuous GNSS network was started in 1994 in the Kanto region. We estimate daily coordinates at all available stations operated by the Geospatial Information Authority of Japan and the Japan Coast Guard using GIPSY 6.2 software. We apply the method of Nishimura *et al.* (2013) and Nishimura (2014) to detect a jump associated with short-term SSEs in GNSS time-series and estimate their fault models from observed displacements. A rectangular fault on the Philippine Sea or the Pacific plates is assumed for each SSE. The stacking of GNSS time-series based on the displacement predicted by the fault model [Miyaoka and Yokota, 2012] enable us to estimate duration of SSEs. For SSEs on the Philippine Sea plate, five Boso SSEs are detected with duration of 9-13 days. Although the largest SSE with M_w6.7 is detected far east off the Boso Peninsula, no apparent seismicity is observed. The duration of the SSE is estimated to be 23 days, which is longer than the Boso SSEs. The longer duration may be a cause of no seismicity related with the SSE. For SSEs on the Pacific plate, we found 24 SSEs. Their moment magnitude ranges between 6.0 and 6.4. Many SSEs are clustered near the eastern rim of the overriding Philippine Sea plate. This may reflect on a difference of interplate coupling controlled by geology of the overriding plate [Uchida *et al.*, 2009]. It is also suggested that the SSE cluster corresponds to a subducted seamount induced from a bathymetry.

キーワード：スロースリップイベント、GNSS、関東地方
Keywords: Slow Slip Event, GNSS, Kanto region

九州で発生する複数の長期的スロースリップイベント
Long-term slow slip events beneath the Kyushu Island

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はじめに

四国西部から九州にかけてのフィリピン海プレートの沈み込み帯では，豊後水道や日向灘で長期的スロースリップイベント（SSE）が繰り返し発生していることが知られている．しかし，それらの間の領域では，これまで長期的SSEの発生は指摘されていなかった．今回，九州における非定常地殻変動を調査したところ，その間の領域でも長期的SSEが発生していることが分かった．

検出された非定常地殻変動

GEONETのF3解を用い，2012年1月から2013年1月の1年間の変動を定常状態と仮定して差し引くことで，九州における2013年以降の非定常地殻変動について調べた．その結果，2014年1月上旬から4月上旬の約3ヶ月間において，九州全域にわたる非定常的な地殻変動が検出された．変動量は最大で5mm程度，変動の向きは内陸では南東方向で，宮崎県の海岸線付近では南南東～南方向を示している．内陸での変動方向は，フィリピン海プレートの沈み込み方向と概ね並行である．変動の継続時間や変動方向等の特徴から，非定常変動はプレート境界面での長期的スロースリップによるものと考えられる．

滑り分布の推定

得られた非定常地殻変動を基に，プレート境界面上の滑り分布を推定した．プレート境界をalong-strike方向に細分化し，小矩形断層の帯で近似した．それぞれの帯中の滑りの分布形状を深さに対するGaussianと仮定し，深さ，幅，滑り量を推定した．滑り分布の滑らかさの制約としてラプラシアンを用いた．

2014年1月上旬からの非定常地殻変動に基づき滑り分布を推定した結果，宮崎県の海岸線付近に滑りが推定された．滑りが大きな領域は北側と南側の2つに分かれている．推定された滑り量は最大5cm程度となった．

九州の非定常地殻変動を過去に遡って調べたところ，九州全域にわたるものだけではなく，九州南部のみ，あるいは九州北部のみで非定常地殻変動が見られるケースがいくつか見つかった．九州南部の非定常地殻変動は，日向灘SSE (Yarai and Ozawa, 2014, JGR)に該当している．また，九州北部の非定常地殻変動の滑り域は，日向灘SSEと豊後水道SSEの両者の滑り域の間に推定され，2014年1月からの九州全域の非定常地殻変動の推定滑り域のうち，北側の滑り域とほぼ重なる．

考察

今回推定された北側の滑り域は，大分県南部から宮崎県北部の海岸線付近を中心とし，豊後水道の長期的SSEの滑り域に隣接している． 2009～2010年のイベントに引き続いて西側に隣接する領域で長期的SSEが発生した可能性が指摘されており（矢来・小沢，2011，測地学会），その滑り域は，今回の北側の滑り域に含まれている．この北側の滑り域のみが活動するケースがいくつか見出されたことから，北側の滑り域単独でも長期的SSEが発生していると考えられる．ここでは宮崎北部SSEと仮称する．

豊後水道SSE，日向灘SSEと宮崎北部SSEの活動時期を見ると，それぞれが独立で活動する場合と，日向灘SSEと宮崎北部SSEが同時に活動する場合が見られる．ただし，豊後水道SSEと九州側の2つのSSEは同時には活動していない．

今回，豊後水道SSEと日向灘SSEの間の領域を埋める長期的SSEの発生が見出されたことは，巨大地震の震源域のように，長期的SSEにも海溝軸に沿ったセグメンテーションが存在する可能性を示唆していると考えられる．

キーワード：長期的SSE、豊後水道、日向灘
Keywords: long-term SSE, Bungo-channel, Hyuga-nada

Comparison of the spatio-temporal evolution of slow slip events in the Yaeyama Islands, southwestern Japan

Comparison of the spatio-temporal evolution of slow slip events in the Yaeyama Islands, southwestern Japan

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Along the Ryukyu Trench, the most southwestern part of Japan, no historical records of large thrust type earthquakes (Mw > 8.0) exist for the last 300 years (Ando et al. 2009) and therefore it is assumed that subduction zone in this region are aseismic. However, a tsunamigenic normal fault type earthquake occurred in 1771 around the Yaeyama Islands and its source region was estimated in the shallower part of the Ryukyu Trench from the tsunami heights (Nakamura 2009a). Recently, very low frequency earthquakes (VLFEs) were detected from a broadband seismic network along the trench (Ando et al. 2012). On the other hand, Heki and Kataoka (2008) reported that slow slip events (SSEs) had repeatedly occurred with a recurrence interval of about six months along the southwestern Ryukyu Trench. They estimated simple time-independent fault model for the SSEs assuming a planar rectangular fault with spatially uniform slip around the Iriomote Island by analyzing GNSS data at eight GEONET stations. However, the spatio-temporal evolution of SSEs has not been investigated.
We have developed four GNSS stations in the Yaeyama Islands in 2010 in addition to eight GEONET stations to clarify the characteristics of the subduction zone along the southern part of the Ryukyu Trench. Because no large earthquakes recently occurred in this region, it is expected that the GNSS observations contain signals of SSEs that are not contaminated by earthquakes although some meteorological phenomena such as typhoon may affect the observations. In this study, we apply a geodetic time-dependent inversion scheme to these GNSS data to clarify the spatio-temporal evolution of the SSEs and its relation to VLFEs.
Data period used in this study is between March 2010 and July 2013. GNSS data from the 12 stations are processed with the GIPSY-OASIS II software. As a result, 5 SSEs were detected during the period. First of all, we remove the trend from each time-series. Then we conduct a geodetic time-dependent inversion using the detrended time-series to infer the spatio-temporal evolution of slip during each event. For this purpose, we employ a modified Network Inversion Filter (NIF) which is based on the Monte Carlo mixture Kalman Filter (MCMKF, Fukuda et al. 2004, 2008). This method is an improved version of the standard NIF (Segall & Matthews, 1998) and is able to extract slow slip signals without oversmoothing or undersmoothing of estimated slip.
The estimated temporal evolution of moment rate suggests that the first event initiated around 10 August 2010 and lasted for about 40 days and the moment magnitude is estimated as about 6.75. The main slip region locates at the northwestern part of the Iriomote Island and the maximum magnitude of slip is about 10 cm, which is consistent with Heki & Kataoka (2008). The resolution of slip below the Iriomote Island is improved by adding the four new observations, and hence no slip is inferred at the southeastern part of the Iriomote Island at depths of about 30 km where some amount slip is inferred without the four new stations. We find that the passage of a typhoon in the summer of 2010 affected the GNSS position estimates. We thus removed the data during that period to avoid the estimated slip to be affected by the typhoon. In the presentation, we will also show the results for the four other SSEs between 2010 and 2013 and compare the spatio-temporal evolution among the five SSEs.

キーワード：slow slip event、Ryukyu Trench、time-dependent inversion、GNSS
Keywords: slow slip event, Ryukyu Trench, time-dependent inversion, GNSS

傾斜・ひずみデータによるスロースリップイベントの自動検出
Automated detection of slow slip events from tilt and strain data

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In subduction zones such as Nankai and Cascadia, various types of slow earthquakes have been detected using dense geodetic and seismic observation networks. Kimura et al. [2011] developed an automated detection method for the identification and location of short-term slow slip events (SSEs) within the Nankai region using continuous tilt data observed at NIED Hi-net stations. Recently, AIST has constructed a borehole strainmeter network around the Shikoku and Kii peninsula regions, and these strainmeters are generally more sensitive to short-term SSEs than the Hi-net tiltmeters [Itaba, et al. 2010]. In this study, we apply the automated detection method of SSEs not only to the tiltmeter data but also to the strainmeter data in order to enhance the detection capability and improve the accuracy in the SSE model.
We evaluated the capability of detecting short-term SSEs in Shikoku using the strength of the white and random-walk noises estimated for each geodetic time-series data [Kimura et al. 2011]. The comparison between the capability using tiltmeter data and that using both the tiltmeter and strainmeter data indicated that the addition of the strainmeters enhances the detection limit by 0.1-0.2 in the magnitude of SSEs in the Bungo channel and western and central Shikoku regions. On the other hand, in the eastern Shikoku region, the detection capability does not change significantly because strainmeter stations are relatively far from short-term SSE source area.

キーワード：スロースリップイベント、ひずみ計、傾斜計
Keywords: Slow slip event, strainmeter, tiltmeter

スロー地震に関連する地殻比抵抗変化検出を目指したMT法モニタリング
Magneto-telluric monitoring for probing changes in crustal resistivity associated with slow earthquakes

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In southwest Japan, various slow earthquakes such as deep low-frequency tremor, deep very-low-frequency earthquake, and short-term slow slip events occur at the subducting plate interface (e.g. Obara, 2002, Scinence; Ito *et al*., 2007, Science; Hirose and Obara, 2005, EPS). To understand their mechanisms by probing the associated structural changes around the plate interface, we have been carrying out continuous magneto-telluric (MT) observations in western Shikoku, Japan since 2008. MT survey along the dip direction of subducting Philippine Sea plate revealed an existence of low-resistivity structure in the lower crust in this region (Yamashita and Obara, 2009, AGU). Two observational sites KBN and SGW were installed on the survey line. The observation at SGW terminated and representative observation at IKT, which is about 10 km away from the survey line, has started in 2010. Qualities of the data recorded at these sites are relatively fine. However, to further improve the quality, we are applying a data processing method same as Honkura *et al*. (2013, Nat. commun.); we use only data whose coherency between electric and magnetic field is higher than a threshold. Using the high-quality data, we estimate daily MT parameters, apparent resistivities and phases at nine frequencies from 0.00055Hz to 0.141Hz. As a result of the careful data analysis, we found some temporal changes in MT parameters. They should not be originated from a noise but the structural change in crust, because amounts of the changes in apparent resistivity and phase over nine frequencies are consistent with the theoretical relation in MT method. In addition, those temporal changes are common among two observational sites. We further found that the changes in the MT parameters looked correlated with the activity of the deep low-frequency tremor beneath the observational sites. Based on the surveyed resistivity structure, we will further investigate amount and location of the resistivity changes.

キーワード：スロー地震、地殻比抵抗、MT法モニタリング
Keywords: Slow earthquake, Crustal resistivity, Magneto-telluric monitoring

地震波異方性モニタリングの試み：S波スプリッティングパラメータの連続測定
Continuous measurements of S-wave splitting parameters for monitoring of seismic anisotropy

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我々は，地震波異方性という新たな観点から，スロー地震群における誘発性や同期性などの相関関係のメカニズム解明に取り組んでいる．地震波異方性は，媒質の応力状態や構造，物性の影響を反映する事が知られている．したがって，スロー地震を用いた異方性解析を行うことで，その震源域および波線が通過した領域の応力状態や構造，物性などの情報が得られると期待される．そこで，石瀬・西田（2015 JpGU）では，スロー地震のひとつである深部低周波地震に着目し，これを用いた地震波異方性解析を実施した．具体的には，気象庁によって検定された深部低周波地震のS波相にAndo et al.，(1983 JGR）によるS波偏向異方性解析を適用し，四国地方北東部における深部低周波地震の震源域における異方性の時間変化の検出を試みた．しかし，解析領域の深部低周波地震の活動度が低調であったため，異方性の時間変化を明らかにするには至らなかった．そこで，微動シグナルがS波成分に卓越すると考えられるので，微動が発生している間の連続的はS波異方性が得られると期待されるという考えの下，石瀬・西田（2015 SSJ）では，石瀬・西田（2015 JpGU）で解析した低周波地震を含む深部低周波微動を対象にS波スプリッティングパラメータを連続的に測定し，微動活動に伴うS波異方性の時間変化を検出することを試みた．なお，類似の手法により北米のCascadia沈み込み帯の地殻異方性が報告されている(Bostock and Christensen, 2012 JGR)．本研究では，四国地方東部を対象に実施した比較的規模の大きな深部低周波微動活動（例えば2015年12月26日～2016年1月5日）に伴うS波スプリッティングパラメータの連続測定について報告する．異方性の連続測定は，時間窓を60秒，時間ステップを30秒と設定し，2-8 Hzのバンドパスフィルタ処理を施した波形記録にS波スプリッティング解析を連続的に適用することで，「速いS波の振動方向」と「分裂したふたつのS波の到達時間差」の時間連続的な値を得た．これと同時に，入射波についての情報を得るためにpolarization解析を実施し，入射波の到来方向と入射角を推定した．この際，Bostock and Christensen（2012 JGR）に倣い，S波入射を仮定した．以上に従い，四国地方東部のHi-netおよび京都大学の地震観測点で記録された連続波形の解析を実施した．その結果，微動信号が強い（活発な微動活動が発生している，微動源と観測点が近い）ことにより異方性パラメータの測定値のばらつきが小さくなり，異方性測定の信頼性が高まることが示された．また，Polarization解析についても同様に，S波の入射を仮定しているため，微動信号が強いことにより信頼性の高い推定が実施される．事実，本研究で解析した微動エピソードでは，微動源の移動過程を示していると推測される入射波の到来方向および入射角の時間変化が，強い微動信号を記録している複数の観測点で同期して発生している様子が観測された．対象領域の異方性の特徴については，測定された速いS波の振動方向は各観測点に特有の方向近傍に分布する事が示された．その方向は，北西―南東から北東―南西方向の間にあり，四国地方の地質学的なリニアメントの走行と近い．このことは，当該地域における異方性観測は，観測点近傍の異方性の影響を受けやすいということを意味しており，微動源の異方性の検出は困難となる．しかし，その「時間変化」は微動源近くの観測点において明瞭に観測されている．ただし，この変化は入射波の到来方向や入射角の時間変化と同期しているため，この異方性の時間変化は波線経路の違いに起因する異方性の空間変化に対応すると解釈される．よって，我々が目指す微動発生領域における異方性の時間変化を明らかにするには，過去のデータにまでさかのぼり，レトロスペクティブ解析を通して，より多くのケーススタディが必要である．

＃謝辞：解析には，防災科学技術研究所のHi-netおよび京都大学の連続波形記録を使用させていただきました．

キーワード：地震波異方性モニタリング、深部低周波微動

Keywords: monitoring of seismic anisotropy, deep low frequency tremor

Laboratory-observed slow frictional slip instabilities in Tohoku plate boundary fault zone samples

Laboratory-observed slow frictional slip instabilities in Tohoku plate boundary fault zone samples

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The plate boundary megathrust at the Japan Trench has exhibited remarkable slip behavior that has drastically changed our understanding of fault slip behavior. The 2011 Tohoku-Oki earthquake produced an extraordinarily large amount of coseismic slip (several 10’s of meters) up to the seafloor, on a portion of the megathrust previously thought to be aseismic. Additionally, this region is also known to generate slow earthquakes. One of these slow earthquakes occurred with the rupture area of the 2011 Tohoku earthquake; this event was observed one month before the 2011 earthquake and was likely ongoing during the earthquake. This shows that the Japan Trench megathrust does not exhibit strictly stable slip and thus failure can occur in a variety of styles. During Integrated Ocean Drilling Program Expedition 343, the Japan Trench Fast Drilling Project (JFAST), samples of the plate boundary fault zone in the Tohoku region were recovered ~7 km from the Japan Trench axis, within the region of largest coseismic slip during the 2011 Tohoku earthquake. We sheared these samples in laboratory friction experiments utilizing a slip velocity of 2.7 nm/s, equal to the convergence rate between the Pacific and North American plates (85 mm/yr). One key observation is that infrequent strength perturbations occurred which are interpreted to be laboratory-generated slow slip events (SSE). For intact samples, these events have stress drops of ~50-120 kPa that occurs over several hours. The stress drop matches the estimated stress drop of the SSE that occurred prior to the 2011 Tohoku earthquake. Peak slip velocities of the laboratory SSE reach 10-25 cm/yr, comparable to observations in natural subduction zone SSEs worldwide. Displacement records indicate a slip deficit accumulation prior to the laboratory SSEs which is recovered during the subsequent stress drop. The laboratory SSEs tended to occur more frequently in intact samples rather than powdered samples, suggesting that the intense scaly fabric is favorable for the SSEs. Velocity-stepping tests also reveal velocity-weakening frictional behavior, suggesting that the laboratory SSEs are slip instabilities or quasi-instabilities. This is supported the observation that in powdered samples, very large SSEs appear at 16 MPa effective normal stress whereas they are mostly absent at 7 MPa. This is consistent with critical stiffness theory, in which increased effective normal stress is associated with an increased likelihood of slip instability.

キーワード：スロースリップ、岩石実験、2011年東北地方太平洋沖地震
Keywords: Slow slip, rock experiment, The 2011 Tohoku-Oki Earthquake

