# 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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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_w$6.7 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

 