Seismic imaging in the trench axis area of Japan and Kuril trenches off Hokkaido

*中村 恭之[1]、白井 太朗[1]、小平 秀一[1]、三浦 誠一[1]
*Yasuyuki Nakamura[1], Taro Shirai[1], Shuichi Kodaira[1], Seiichi Miura[1]

1. 国立研究開発法人海洋研究開発機構
1. Japan Agency for Marine Earth Science and Technology

We conducted a seismic reflection survey off Hokkaido area to obtain detailed seismic reflection profiles around the Japan and Kuril trench axis in December 2016. Seven seismic lines, 4 in the northernmost Japan Trench and 3 in the westernmost Kuril Trench, were acquired during YK16-17 cruise using a 192-channel 1200-m-long streamer cable and 380 inches^3 cluster guns. Seismic images obtained in the northern Japan Trench show the landward dipping reflections in the frontal prism. Thickness of the sediment on the incoming Pacific plate is variable between ˜ 200 –500 ms (two-way travel time). The thickness of the incoming sediment is thick as ˜ 700 ms (two-way travel time). Stratified trench fill sediments are imaged in the Kuril Trench sections, which were not observed in the Japan Trench profiles. The stratified trench fill sediments might be related to the Kushiro Canyon located at the north of the obtained profiles.

3-D resistivity distribution around an intra-plate slow earthquake area in northern Hokkaido, Japan: relationship between serpentine and slow earthquake

*市原 寛[1]、茂木 透[2]、内田 利弘[3]、山谷 祐介[3]、多田 訓子[4]

*Hiroshi Ichihara[1], Toru Mogi[2], Toshihiro Uchida[3], Yusuke Yamaya[3], Noriko Tada[4]

1. 神戸大学、2. 北海道大学、3. 産業総合研究所、4. 海洋研究開発機構
1. Kobe University, 2. Hokkaido University, 3. AIST, 4. JAMSTEC

A slow earthquake of Mw 5.4 is estimated in the Dohoku area, northern Hokkaido Island (Ohzono et al., 2015). Because most of slow earthquakes have been reported in the vicinity of plate boundaries, study of the intra-plate events is important to understand the slow earthquakes. In this study, we estimated a resistivity distribution based on the 3-D inversion of magnetotelluric (MT) data at 45 sites in the Dohoku area. The inverted resistivity model shows the following features. 1) A surface conductive layer is distributed in the most part of the study area. The thickness of the conductor increases toward westward and reaches approximately 5 km at the Japan Sea side. The conductive layer is interpreted as Tertiary-Quaternary sedimentary rocks. 2) An ultra-conductive area (0.1-10 ohm-m, 0-10 km depth) is distributed around the fault of the slow earthquakes. Based on the surface geological distribution and magnetic anomaly (GSJ, 2005), the conductor possibly reflects serpentine-related geological unit associated with the slow slip events. However, a careful interpretation is required because a serpentinite sampled from a few ten meters depth at about 10 km south of the study area is not so conductive (10-100 ohm-m) (Okazaki et al., 2011). This possibly indicates that conductive fluid from deep earth fills pores of serpentine and decreased resistivity.

Stress drops of earthquakes on the Pacific plate off south-east of Hokkaido, Japan: Implications for the spatial heterogeneity of frictional properties

*山田 卓司[1]、齋藤 悠[2]、谷岡 勇市郎[3]、河原 純[1]
*Takuji Yamada[1], Yu Saito[2], Yuichiro Tanioka[3], Jun Kawahara[1]

1. 茨城大学理学部、2. 北海道大学大学院理学院、3. 北海道大学大学院理学研究院附属地震火山研究観測センター
1. Faculty of Science, Ibaraki University, 2. Graduate School of Science, Hokkaido University, 3. Institute of Seismology and Volcanology, Faculty of Science, Hokkaido University

We analyzed stress drops of 721 earthquakes with the magnitude of 4.0 to 5.0 off south-east of Hokkaido, Japan and investigated the spatial heterogeneity of the difference of shear strength and dynamic stress level on the Pacific plate. We deconvolved observed P and S waves with those of collocated small earthquakes and derived the source effect of the earthquakes. We then estimated corner frequencies of the earthquakes and calculated stress drops by using a circular fault model. The values of stress drop showed a spatial pattern consistent with slip distributions of historical large earthquakes. This suggests that frictional properties on the plate interface show little temporal change and their spatial pattern can be monitored by stress drops of moderate-sized earthquakes. The spatial heterogeneity would give clues for estimating the slip pattern of a future large earthquake and discussing a policy for the disaster mitigation, especially for regions where slip patterns of historical large earthquakes are unclear.

キーワード：Stress drop、Frictional properties on the Pacific plate、Spatial heterogeneity
Keywords: Stress drop, Frictional properties on the Pacific plate, Spatial heterogeneity
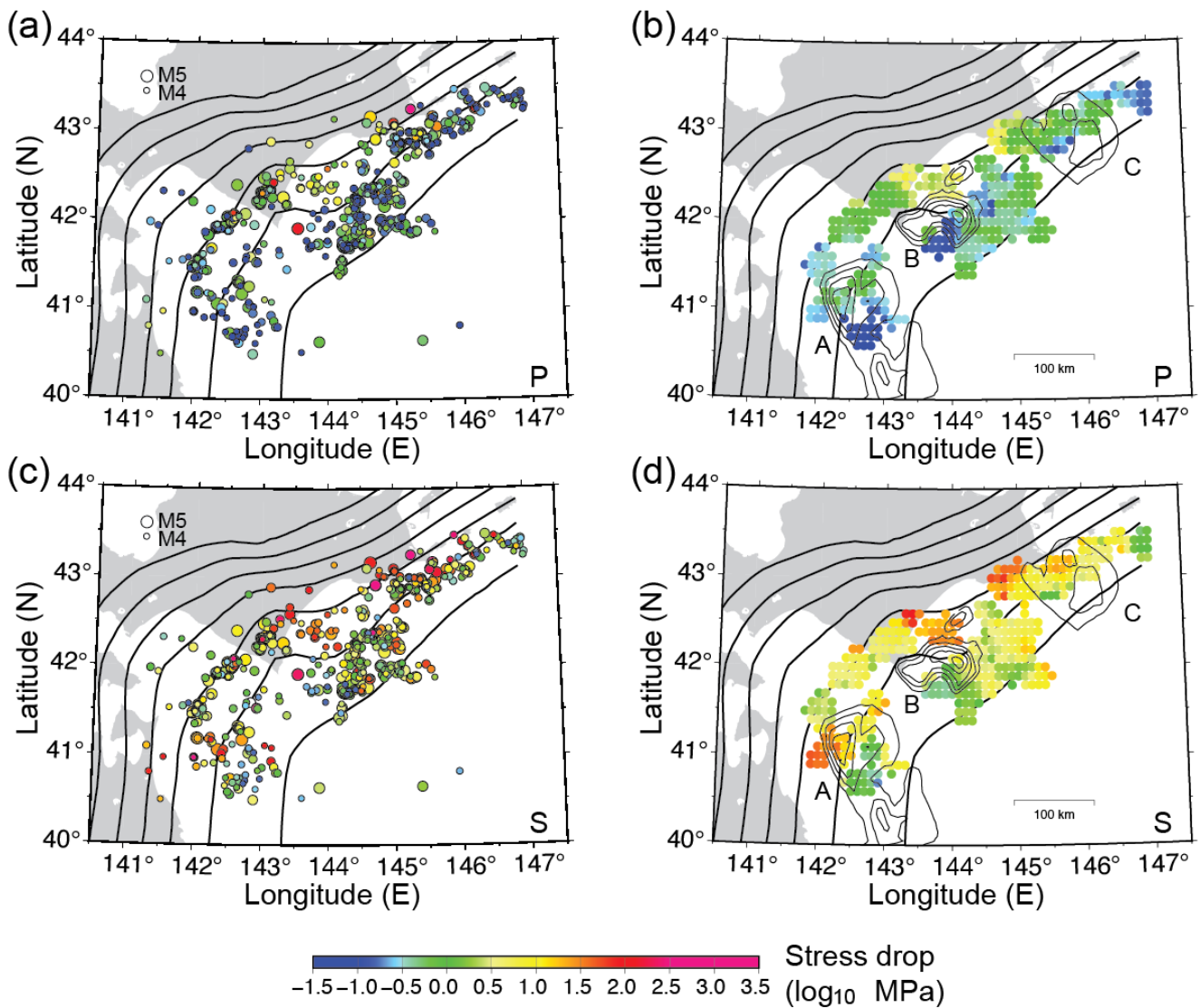
Figure 1. (a) Stress drops for individual earthquakes estimated from P waves. Scale and colour of circles indicate earthquake magnitude and value of stress drop, respectively. Thick lines show the surface depth of subducting Pacific plate (Kita et al. 2010). (b) Spatially smoothed stress drop derived from (a) at grid points with an interval of 0.1 degree in latitude and longitude. A value at each grid point was calculated as an average of stress drops of earthquakes within 15 km of the epicentral distance from the grid point. We did not put any values at grid points with less than four earthquakes within 15 km of the epicentral distance. Thin contours A through C show coseismic displacements for the 1968 Tokachi-oki (Nagai et al. 2001), the 2003 Tokachi-oki (Yamanaka and Kikuchi 2003), and the 1973 Nemuro-oki earthquakes (Yamanaka 2006), respectively with an interval of 1 m. (c) Stress drops estimated from S waves. (d) Map view of spatially smoothed stress drop derived from (c).

東日本で発生する中規模繰り返し地震の震源過程解析
Source process of moderate size repeating earthquakes in eastern Japan

*奥田 貴[1]、井出 哲[1]、内田 直希[2]
*Takashi Okuda[1], Satoshi Ide[1], Naoki Uchida[2]

1. 東京大学大学院理学系研究科地球惑星科学専攻、2. 東北大学大学院理学系研究科附属地震・噴火予知研究観測センター
1. Department of Earth and Planetary Science, University of Tokyo, 2. Research Center for Prediction of Earthquakes snd Volcanic Eruptions Graduate School of Science, Tohoku University

In the Tohoku-Hokkaido subduction zone, several small to moderate earthquakes have occurred repeatedly at almost the same location, radiating almost identical waveforms every time. This phenomenon has been understood as repeated rupture of a patchy structure surrounded by aseismic slip area on the plate boundary (e.g., Matsuzawa et al., 2002, Igarashi et al., 2003). A typical example is the Kamaishi-Oki repeating earthquake sequence of about M4.9 recurring at almost 5.6-year interval. Many smaller earthquakes occurred in clusters in and around the slip area of the main events, suggesting some hierarchical structure in the source region. Such hierarchical structure is considered as a source of diversity in earthquake process, and may control foreshock activities. The lack of aftershocks (Uchida et al., 2012) also suggests that the rupture of main events releases almost all accumulated strain energy around this structure.

Despite a seemingly reasonable interpretation for the Kamaishi sequence, the universality of this interpretation has not been proved. It is not obvious whether similar characteristics are observed for other repeating earthquake sequences. Therefore, this study investigates several repeating sequences of moderate (M4˜5) earthquakes, to discuss the applicability of the above interpretation in the Tohoku-Hokkaido subduction zone. We focus on sequences occurred almost beneath the coastline, where seismic activity looks isolated near the bottom of the seismogenic layer. Relatively good station coverage gives high resolution for source imaging. The study regions are Katori in Chiba prefecture, Mito-Oki, Naka-Oki in Ibaraki prefecture, Futabagun-Oki and Iwaki-Oki in Fukushima prefecture, and Kushiro-Oki, Urakawa and Hidaka-Oki in Hokkadio.

In each study region, we selected M > 1 earthquakes from the JMA catalog since 2002, and relocate them using the Network Cross Correlation Method (Ohta & Ide, 2008). Data are velocity records of 1 Hz short-period seismometers in vertical component at stations operated by the National Research Institute for Earth Science and Disaster Resilience (NIED), the Japan Meteorological Agency (JMA), Earthquake Research Institute (ERI), University of Tokyo, Hokkaido University, and Tohoku University. The original sampling frequency is 100 Hz, and we used 2-8 Hz bandpass filter.

In the Kushiro-Oki region, earthquakes of M˜4.9 occurred fairly regularly at ˜6.6 year recurrence interval. Figure 1(b) shows the relocated hypocenters by circles of approximate source size calculated using the formula of Eshelby (1957), assuming the stress drops of the earthquakes are 3 MPa. The cluster of small earthquakes are located inside the source are of the main event, suggesting some hierarchical structure. Magnitude of these small earthquakes increased before the main events, and seismic activity is relatively low after main events. Similar behavior is observed in the other seven regions.

We also estimate the slip distribution of the main events in repeating earthquake sequences using an empirical Green's function (EGF) method. Data is the same as the relocation analysis, except that 1-8 Hz bandpass filter is used. Figure 1(e) shows an example of tentative results for the Kushiro-Oki region. EGF event is a small earthquake occurred inside the slip area of the main event. The snapshots indicate that the location of the initial rupture of the main event is a little shallower than that of the EGF event (cross).

References: Igarashi, T., T. Matsuzawa, and A. Hasegawa, JGR, 2003; Matsuzawa, T., T. Igarashi, and A. Hasegawa, GRL, 2002; Ohta, K., and S. Ide, EPS, 2008, Uchida, N., T. Matsuzawa, W. L. Ellsworth, K. Imanishi, K. Shimamura, and A. Hasegawa, GJI, 2012.

キーワード：繰り返し地震、階層構造
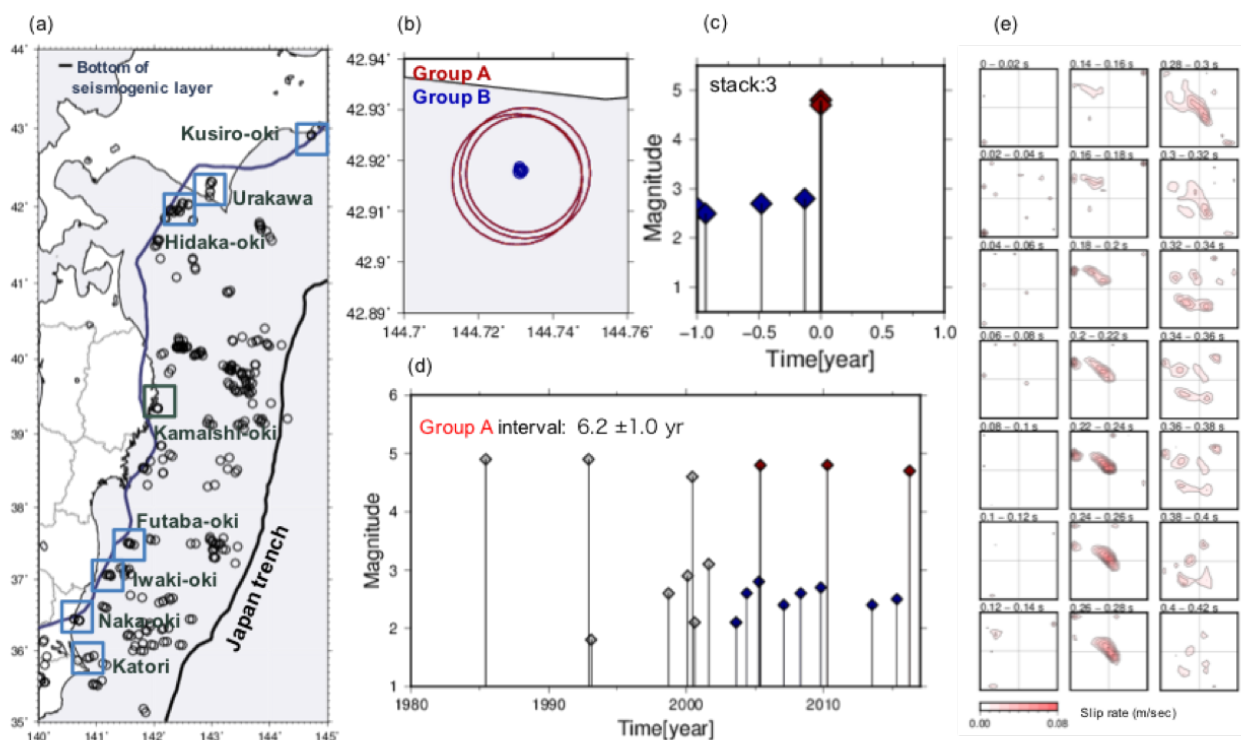Keywords: Repeating earthquake, Hierarchical structure

Figure 1. Source process analysis of Kushiro-oki repeating earthquake.
(a) Study region. (b) the location of hypocenter and the size of circle shows the approximate source size calculated using the formula of Eshelby (1957), assuming the stress drops of the earthquakes are 3 MPa. (c) MT diagram for one year before and after the M ~ 4.9 sequence. The data for 2005, 2010 and 2015 earthquakes are collapsed based on the occurrence time of the each earthquake. (d) MT diagram for Kushiro-Oki region. (e) Slip evolution of the 2010 earthquake.

2012年東北沖スラブ内ダブレット地震の震源断層モデルから検討した2011年東北沖地震による太平洋プレート内応力場の変化
Finite fault model of the 2012 intraslab earthquake doublet and its implication for coseismic stress change in the Pacific plate associated with the 2011 Tohoku-Oki earthquake

*久保田 達矢[1]、日野 亮太[1]、太田 雄策[1]、稲津 大祐[2]、鈴木 秀市[1]

*Tatsuya Kubota[1], Ryota Hino[1], Yusaku Ohta[1], Daisuke Inazu[2], Syuichi Suzuki[1]

1. 東北大学大学院理学研究科、2. 東京海洋大学
1. Graduate School of Science, Tohoku University, 2. Tokyo University of Marine Science and Technology

　2012年12月7日に日本海溝軸のごく近傍の太平洋スラブ内で，深い震源を持つ逆断層型地震 (サブイベント1，57.8 km，Mw 7.2，Global CMT) と浅い震源をもつ正断層型地震 (サブイベント2，19．5 km，Mw 7.2) からなるダブレット地震が発生した．この地震の震源周辺では，スラブの沈み込みに伴う折れ曲がりによって浅部と深部それぞれで水平引張・圧縮の応力場が発達していることが知られている (e.g., Gamage et al., 2009, JGR) が， Obana et al. (2012, GRL) は，2011年東北地方太平洋沖地震後のこの周辺のスラブ内で発生した小地震の震源分布から，正断層型地震が発生する深さ範囲の下限が東北沖地震前よりも深くなったことを明らかにし，スラブ内応力場が変化した可能性を指摘した．2012年の地震の2つのサブイベントの発震機構解は，それらが発生した深さにおける応力場を反映し，それらの破壊の深さ方向の広がりは東北沖地震後の引張・圧縮場の深さ方向の広がりと一致する考えられるため，各サブイベントの断層モデルを詳細に推定することで，東北沖地震後のスラブ内応力場を詳細に推定できると期待される．

　このダブレット地震は2つのサブイベントがほぼ同時に発生しているため，地震波形記録からではサブイベントの震源過程を分離し，震源断層モデルを精度良く推定することが難しいと考えられる．しかし，地震波による解析が特に難しいと考えられる後続のサブイベント2は浅い震源を持ち，津波を効率良く励起することから，津波データを解析することでサブイベント2の断層モデルの推定精度の大幅な改善が期待できる．このダブレット地震による津波は，沖合に設置された多数の海底圧力計によって明瞭に捉えられており，本研究では，こうした沖合での津波波形データの詳細な解析により2つのサブイベントの震源断層の深さ方向の広がりを推定し，その結果を東北沖地震以前の地震活動と比較することにより，東北沖地震前後でのスラブ内応力場の変化を議論する．

　断層モデルの推定に先立って，津波波形記録の逆解析により地震時の初期海底変動分布 (津波波源分布) を推定した．得られた分布は大きな沈降域と隆起域をひとつずつ持つ分布が得られた．この分布をGlobal CMT解から期待される各サブイベントの海底変動分布と比較したところ，沈降域はもっぱらサブイベント2によって生じていると考えてよいことがわかった．そこで，得られた波源分布の沈降域を説明できるようなサブイベント2の震源モデルを余震分布 (Obana et al., 2014, EPS; 2015, AGU FM) を参考にしながら推定した．その後，津波波源分布モデルからサブイベント2による地震時変動の寄与を差し引いてサブイベント1による海底変動分布を抽出し，これと遠地実体波記録を併用してサブイベント1の断層モデルを求めた．最終的に得られたサブイベント2の断層下端の深さは35 –40 km，サブイベント1の断層上端の深さは45 –50 kmと推定された．これは，東北沖地震前のスラブ内の正断層型地震発生域の下限 (約25 km) および逆断層型地震発生域の上限 (約40 –45 km) よりも5 –10 km深く，東北沖地震の影響によって地震活動の深さ分布が変化したことが明らかになった．このような変化が起こる理由として東北沖地震による静的応力変化が考えられるが，この領域での太平洋プレートの折れ曲がりによる応力の鉛直勾配を，プレートの曲率と弾性定数から概算すると15 MPa/km程度となるが，この状態では，東北沖地震による静的応力変化の大きさ (~10 MPa) によるプレート内応力中立面の深さ変化は数km程度にしかならず，ここで推定した東北沖地震前後の地震活動域の深さの変化を説明できない．東北沖地震後に観測された地震活動域の深さ変化は，東北沖地震による静的応力変化に加

え，東北沖地震後にスラブ内断層の破壊強度が低下したことにより，正断層型の地震活動が東北沖地震前に発生していなかった深さ (~35 –40 km) において活発になったことも要因である可能性が示唆される.

キーワード：津波、2011年東北沖地震、スラブ内地震
Keywords: tsunami, The 2011 Tohoku-Oki earthquake, intraslab earthquake

Seafloor displacement in the northern Japan Trench examined by bathymetric surveys after the 2011 Tohoku-oki earthquake

*富士原 敏也[1]、dos Santos Ferreira Christian[2]、Bachmann Katharina[2]、Strasser Michael[3]
、Wefer Gerold[2]、Sun Tianhaozhe[4]、金松 敏也[1]、小平 秀一[1]

*Toshiya Fujiwara[1], Christian dos Santos Ferreira[2], Katharina Bachmann[2], Michael Strasser[3], Gerold Wefer[2], Tianhaozhe Sun[4], Toshiya Kanamatsu[1], Shuichi Kodaira[1]

1. 海洋研究開発機構地震津波海域観測研究開発センター、2. MARUM, Center for Marine Environmental Sciences, University of Bremen、3. Institute of Geology, University of Innsbruck、4. School of Earth and Ocean Sciences, University of Victoria
1. Research and Development Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, 2. MARUM, Center for Marine Environmental Sciences, University of Bremen, 3. Institute of Geology, University of Innsbruck, 4. School of Earth and Ocean Sciences, University of Victoria

Maximum tsunami height caused by the 11 March 2011 Tohoku-oki earthquake (M_W 9.0) was observed at the coast of Sanriku, the northern Tohoku at ~39.5N [The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011]. Therefore, in order to explain the tsunami source, some papers have introduced additional large fault slip of the megathrust up to ~40 m near the Japan Trench [e.g. Satake et al., BSSA 2013]. Alternatively, others preferred to put a large change in seafloor elevation, ~100 m uplift and down-drop, associated with a submarine landslide along the lower trench slope [e.g. Tappin et al., Marine Geology 2014].

After the earthquake, we have carried out multibeam bathymetric surveys in the rupture zone. Survey tracks were aligned along the tracks obtained before the earthquake across the Japan Trench, and we analyzed the difference in bathymetry before and after the earthquake in the area near the trench. For the analysis, apparent offsets of the absolute values of depth soundings and the uncertainty of ship position were examined on the seaward side because the seaward was thought to have suffered little change from the earthquake.

The extraordinary coseismic seafloor displacement caused by the 2011 earthquake was indeed detected by the bathymetric surveys. For the survey track crossing the trench axis at 38.1N, off the coast of Miyagi Tohoku, near the epicenter, there were large relative differences landward extended up to the trench axis, suggesting the earthquake fault rupture reached the trench axis [Fujiwara et al., Science 2011; JpGU 2015; Kodaira et al., Nature Geosci. 2012].

Eventually, we had an opportunity to survey the bathymetry near the Japan Trench off Sanriku between 39.2 and 39.5N by the German research vessel Sonne in 2012 and the last year 2016 (SO219A, SO251A cruises). We acquired two survey tracks. One survey track was on the track of the JAMSTEC R/V Kairei in 2010 (KR10-12 cruise) crossing the trench axis at 39.2N and extending to the landward trench middle slope (~143.5E, 39.3N), ~50 km from the trench axis (SO219A-KR10-12). And the other was on the track of the R/V Kairei KR07-08 cruise in 2007 crossing the trench axis at 39.5N and extending to the landward trench middle slope (~143.5E, 39.4N) (SO251A-KR07-08).

As the result of comparison of the bathymetry before and after the earthquake, horizontal and vertical seafloor displacements were within the error of the analysis because the results may incorporate errors of several meters in vertical displacement and about 20 m in horizontal displacement. Very large fault slip or very large submarine landslide is unlikely at least on the two survey tracks.

キーワード：2011 Tohoku-oki earthquake、tsunami、Japan Trench、Sanriku、multibeam
　　　　　bathymetry、seafloor displacement
Keywords: 2011 Tohoku-oki earthquake, tsunami, Japan Trench, Sanriku, multibeam bathymetry, seafloor
　　　　　displacement

Direct and precise geodetic measurement across the Japan Trench after the 2011 Tohoku-oki earthquake

*山本 龍典[1]、日野 亮太[1]、木戸 元之[2]、本荘 千枝[2]
*Ryusuke Yamamoto[1], Ryota Hino[1], Motoyuki Kido[2], Chie Honsho[2]

1. 東北大学大学院理学研究科、2. 東北大学災害科学国際研究所
1. Graduate School of Science, Tohoku University, 2. International Research Institute for Disaster Science, Tohoku University

The 2011 Tohoku-oki earthquake (Tohoku Earthquake: M_w 9.0) caused over 50 m coseismic slip. After then many geodetic observations such as on-shore GNSS, GPS/Acoustic (GPS/A), and others, have been carried out. Especially, GPS/A played important roll to reveal large off-shore coseismic displacement and subsequent postseismic deformation, which can be interpreted by viscoelastic relaxation (Sun et al., 2014, Nature; Watanabe et al., 2014, GRL; Tomita et al., 2015, GRL) and/or afterslip. Because GPS/A observation alone cannot reveal the afterslip of megathrust in the shallow dip of the trench, "direct-path acoustic ranging", which can measure precise relative distance (e.g., ˜ mm/yr precision for 1 km baseline) between two stations, was used across the trench. It periodically measures two-way travel-time and is corrected the calculated sound velocity after the recovery. Prior to this study, the same observations were conducted twice; they were 2013 (˜150-days) (Osada et al., 2014, JpGU) and 2014-2015 (˜250-days) (Yamamoto et al., 2016, JpGU), respectively. These observations proved the capability to measure as long as ˜10 km baseline and found no significant relative motion across the trench.

In September 2015, we installed five instruments at the same, the region of large coseismic slip (e.g., Iinuma et al., 2012, JGR) and recovered in September 2016 (˜360-days observation). The result shows no significant movement across the trench axis like as in the previous surveys. This result shows fully locked state and may clarify the absence of postseismic slip in the shallower part in this area and at least 2013-2016.

In March 2017, we plan to install five instruments across the Japan Trench off-Fukushima, where instead large postseismic slip (e.g., Sun and Wang, 2015, JGR; Iinuma et al., 2016, Nature Comm.). This auxiliary observation may reveal spatial variation of convergence rate along the trench axis.

宮城県沖スロー地震震源域周辺の地殻構造
Seismic structure around the SSE event source in northeastern Japan forearc deduced by an airgun-ocean bottom survey

*東 龍介[1]、日野 亮太[1]、望月 公廣[2]、村井 芳夫[3]、八木原 寛[4]、佐藤 利典[5]、篠原 雅尚[2]
*Ryosuke Azuma[1], Ryota Hino[1], Kimihiro Mochizuki[2], Yoshio Murai[3], Hiroshi Yakiwara[4], Toshinori Sato[5], Masanao Shinohara[2]

1. 東北大学大学院理学研究科地震・噴火予知研究観測センター、2. 東京大学地震研究所、3. 北海道大学、4. 鹿児島大学、5. 千葉大学
1. Recearch Center for Prediction of Earthquake and Volcanic Eruption, Graduate School of Science, Tohoku University, 2. Earthquake Research Institute, University of Tokyo, 3. Hokkaido University, 4. Kagoshima University, 5. Chiba University

Various kinds of slips have been observed along the plate boundary (PB) in the Japan Trench subduction zone. The 2011 Tohoku-oki earthquake ruptured the large area of PB fault along the Japan Trench, and a huge slip (> 40 m) happened at 37.5–38.5N in the Miyagi-oki region. Prior to the Tohoku-oki earthquake, slow slip events (SSE) also happened in 2008 and 2011 at 37.7–38.7N (Ito et al., 2012). Faults hosting slow slip events are often characterized by low seismic velocity anomalies (e.g., Obara and Kodaira, 2009). Although it is expected that the distribution of the interplate low velocity material can be identified by strong seismic reflectivity of the interface, a detail structure in the Miyagi-oki SSE source area remains unknown. To clarify a structural characteristic near the PB, which would provide useful information to understand the occurrence mechanism of SSE, we made an airgun-OBS (Ocean Bottom Seismmometer) survey in the SSE source area.

The survey was carried out in 2014. Survey lines with 180 km length were slightly oblique to the Japan Trench axis and overwrapped the SSE source area at the southern section. We deployed 17 and 20 OBSs along each line with 10 and 8 km intervals. An airgun array with a total volume of 100 liter was shot with 50 m intervals along those lines.

To obtain a seismic velocity structure beneath each line, we performed a tomographic inversion using first arrival traveltimes (Fujie et al., 2013). Results of checkerboard resolution test indicated that velocity anomalies with > ˜ 15 km and ˜ 4 km in horizontal and vertical sizes can be resolved down to ˜ 25 km in depth. To investigate spatial distribution of reflectors with their intensities, we applied a traveltime mapping method (Fujie et al., 2006) to observed reflected arrivals. This method directly projects picked arrival times of observed reflection signals onto corresponding reflection points in a depth-distance domain.

The P-wave velocity (Vp) model estimated by the tomographic inversion showed distinct variation of Vp in the overriding plate; high Vp of > ˜ 4 km equivalent to the island arc crust material was estimated to the south of 39 N, whereas low Vp of < ˜ 3 km/s corresponding to unconsolidated sedimentary layer distributed in the northern part of the survey line. On the reflection mapping images, the PB was imaged as a continuous reflector at depths from 8 km to 14 km, where Vp is ˜ 5 km/s. This reflector is more distinctive beneath the island arc crust than that beneath the sedimentary layer. Since the Vps of the island arc upper crust and the oceanic layer 2 may not be different significantly, the distinctive reflections from the PB suggest the existence of a low Vp channel layer along the PB. The spatial extent of high-Vp overriding crust and the highly reflective PB, identified to the south of 39N, almost coincides with the SSE source location estimated by Ito et al. (2012). Therefore, our survey results suggest that the Miyagi-oki SSE source area is characterized by the presence of low-Vp channel layer along the PB beneath the high Vp overriding crust.

キーワード：地殻構造、プレート境界反射強度、スロースリップイベント
Keywords: Crustal structure, interplate reflectivity, Slow slip event

A coupled model of stress-driven frictional afterslip and viscoelastic relaxation following the 2011 Tohoku-oki earthquake

*福田 淳一[1]、Johnson Kaj[2]

*Jun'ichi Fukuda[1], Kaj M. Johnson[2]

1. 東京大学地震研究所、2. Indiana University

1. Earthquake Research Institute, University of Tokyo, 2. Indiana University

Postseismic deformation following the 2011 Mw9.0 Tohoku-oki earthquake has been captured by both on-land GNSS and seafloor GPS/Acoustic networks. Previous studies have shown that the observed postseismic displacements can be reproduced as a sum of contributions from viscoelastic relaxation of coseismic stress changes in the upper mantle and afterslip on the plate interface surrounding the coseismic rupture. In most previous studies, viscoelastic relaxation and afterslip were modeled separately and afterslip was estimated kinematically. In this study, we develop a three-dimensional coupled model of stress-driven frictional afterslip and viscoelastic stress relaxation in order to investigate the frictional properties on the plate interface, upper mantle rheology, and the relative contributions of the viscoelastic relaxation and afterslip to the overall postseismic deformation following the 2011 Tohoku-oki earthquake.

We assume that afterslip is governed by a rate-strengthening friction law that is characterized with a friction parameter (a-b) σ. Viscoelastic relaxation of the upper mantle is modeled with a biviscous Burgers rheology that is characterized with the steady-state and transient viscosities. We calculate the evolution of afterslip and viscoelastic relaxation using an assumed coseismic slip model as the initial condition.

We examine the effects of the friction parameters, mantle viscosities, elastic thickness of the slab and upper plate, and coseismic slip distribution on the model prediction and explore the range of the parameters that can fit the observed postseismic displacements. We also examine if afterslip overlaps regions that ruptured seismically during M6.3-7.2 earthquakes from 2003 to 2010. We find that significant overlap between afterslip and the historical M6.3-7.2 coseismic rupture areas are required to fit the horizontal displacements.

キーワード：余効変動、余効すべり、摩擦、粘弾性緩和、2011年東北沖地震
Keywords: postseismic deformation, afterslip, friction, viscoelastic relaxation, 2011 Tohoku-oki
　　　　　　earthquake

Distribution of earthquakes around the subducted seamount off Ibaraki in response to the largest Mw7.8 aftershock of the 2011 Tohoku-oki earhtquake

*望月 公廣[1]、米島 慎二[1,2]、山田 知朗[1]、篠原 雅尚[1]

*Kimihiro Mochizuki[1], Shinji Yoneshima[1,2], Tomoaki Yamada[1], Masanao Shinohara[1]

1. 東京大学地震研究所　地震予知研究センター、2. 石川島播磨重工業（株）
1. Earthquake Prediction Research Center, Earthquake Research Institute, University of Tokyo, 2. Ishikawajima-Harima Heavy Industries Co., Ltd.

M7 class earthquakes have repeatedly occurred ˜100 km offshore of the Ibaraki prefecture at fairly constant time interval of 20 years. It has been revealed that there exists a subducted seamount up-dip of the source region of such repeating M7 earthquakes (Mochizuki et al., 2008). Therefore, the seamount itself does not appear to be an asperity of the large earthquakes.

The region coincides with the southern limit of the fault region of the 2011 Tohoku-oki earthquake, where its largest aftershock with Mw7.8 occurred 30 minutes after the main shock. Spatio-temporal distribution of seismicity following such large earthquakes provides important information for understanding changes of the state of the stress caused by such a large fault slip and mechanisms of earthquake generation in relation to the topographic features of the plate interface.

We collected one-year long seismic data using ocean bottom seismometers equipped with 3-component 1 Hz velocity sensors. Data were recorded at a 200 Hz sampling frequency. We installed a dense OBS array using 35 instruments around the subduction front of the subducted seamount at a spatial interval of ˜6 km for about a year from October, 2010, through September, 2011. In the middle of the observation period, the 2011 Tohoku-oki earthquake and its largest aftershock occurred. The epicenter of the largest after shock is located only ˜30 km to the west (donw-dip) of the array, and its rupture propagated up-dip toward the seamount. Recent studies on its rupture propagation (Honda et al., 2013; Kubo et al., 2013) revealed that the rupture stopped before it reached the subducted seamount so that its rupture area occupies the area in subduction front of the seamount. In spite of such severe situation for seismic observation, we successfully recovered data from 31 stations.

More than 20000 earthquakes around the OBS array were recorded. Visual identification and manual picking of P and S arrivals through the records of ˜30 stations are unrealistic. Therefore, we applied an automatic picking method that we developed by referring to Grigoli et al. (2014). The observed waveforms were converted to characteristic functions that have high sensitivity to arrivals of seismic phases. Having 3-D seismic velocity structure around the region that has been compiled by referring to the existing seismic profiles, the characteristic functions were migrated according to the travel times from the stations to the grid points in the structure volume, and then they were stacked. We determined the hypocenter of each event by finding the maximum stacked value among the grid points.

The resulted distribution of the earthquakes shows two primary layers of seismicity. The upper layer may represent distribution of small scale faults above the seamount. We found seismically quiet region in front of the subducted seamount that appears consistent with the rupture area of the largest aftershock.

キーワード：2011 東北沖地震、最大余震、余震分布、沈み込む海山

Keywords: 2011 Tohoku-oki earthquake, largest aftershock, aftershock distribution, subducted seamount

紀伊半島東部における地震波減衰構造の推定
Three dimensional attenuation structure beneath the eastern part of Kii Peninsula, southwest Japan, derived from small earthquake spectra

津村 紀子[1]、*中浴 広樹[1]、梅山 恵理[1]、水野 直希[1]、蔵下 英司[2]、加藤 愛太郎[2]、酒井 慎一[2]、飯高 隆[2]、岩崎 貴哉[2]

Noriko Tsumura[1], *Hiroki Nakasako[1], Eri Umeyama[1], Naoki Mizuno[1], Eiji Kurashimo[2], Aitaro Kato[2], Shin'ichi Sakai[2], Takashi Iidaka[2], Takaya Iwasaki[2]

1. 千葉大学大学院理学研究科、2. 東京大学地震研究所
1. Grad. Sch. of Sci., Chiba Univ., 2. ERI, Univ. of Tokyo

Low Frequency earthquakes (LFEs), one of slow earthquakes that occur in subduction zones, have been observed in the southwest Japan, especially in the Kii Peninsula. Clusters of LFEs are distributed along the isodepth contour of 30 to 40 km of the subducting Philippine Sea plate's surface and more concentration is seen in the eastern part. Previous studies for seismic velocity and conductivity structures suggested that occurrence of such LFEs is closely related to the existence of fluid.

Q value, the parameter of seismic attenuation, has been used to study LFE because its values vary sensitively to the presence of fluid. For instance, Tsumura et al.(2016) estimated a three-dimensional attenuation structure in the Kii Peninsula, and revealed that a high Qp zone exists near LFE cluster in the western part of the study area. In the eastern part of the Kii Peninsula where LFE's activity is high, however, a detailed attenuation structure has not been estimated. Therefore in this study, we applied the inversion method (Tsumura et al., 2000) to estimate P wave attenuation structure there.

Adding to the data recorded in routine seismic stations, we used the data of the three dense seismic arrays which were settled in perpendicular or parallel direction in the east, the west and the south part of Kii Peninsula. The array length were about 90km (or 60km) with 1km station interval. Observation period were from December 2009 to May 2010 (for the E-W line in the south), from December 2010 to June 2011 (for the N-S line in the west), and from May 2015 to December 2015 (for the E-W line in the east). We selected 302 earthquakes which were recorded at 172 seismic stations and calculated 11133 spectra for P arrivals of time window ls for taking into account ray distribution. The sampling frequency is 100 or 200 Hz for the permanent stations and 200 Hz for the temporary stations. Furthermore, in order to express a three-dimensional Q structure, we divided the study region into 9, 11, and 6 portions in latitude, longitude, depth- direction respectively.

Derived Qp images show that a low Qp zone is seen at the depths of 30 to 40km in which high activity of the DLFEs in the eastern part of the Kii Peninsula. On the contrary, we can find patch-like high Qp zones were distributed in the same depth range at the western part of the Kii Peninsula. These high Qp zones coincide with the regions where the DLFE clusters exist. Both of these high and low Qp zones corresponds to the lower Vp and high Vp/Vs regions derived from travel time tomography. Although seismic velocities derived from travel time tomography and conductivity structures indicate that the existence of fluid in the source regions of LFEs, we can see the difference between attenuation parameters estimated for the eastern and western parts of the Kii Peninsula. These results may reflect the different physical properties of the eastern and the western parts and it affects the difference of LFEs' activity in each side of the Kii Peninsula.

キーワード：地震波減衰、低周波地震、紀伊半島

Keywords: seismic attenuation, low frequency earthquake, Kii Peninsula

Heterogeneous structure in and around the slow-earthquake source region beneath the eastern Kii Peninsula, SW Japan

*蔵下 英司[1]、飯高 隆[1]、津村 紀子[2]、岩崎 貴哉[1]
*Eiji Kurashimo[1], Takashi Iidaka[1], Noriko Tsumura[2], Takaya Iwasaki[1]

1. 東京大学地震研究所、2. 千葉大学
1. Earthquake Research Institute, the University of Tokyo, 2. Chiba University

The Nankai trough region, where the Philippine Sea Plate (PHS) subducts beneath the SW Japan arc, is a well-known seismogenic zone of interplate earthquakes. Recently, various slip types, including episodic tremors and very low-frequency earthquakes, have been recognized at or near the up-dip and down-dip limits of seismogenic zone (e.g., Obara, 2002; Ito and Obara, 2006). Obara(2002) suggested fluids as a source for tremor. Previous studies indicate the fluid pressure on a plate interface is one of the key factors to understand the fault slip process (e.g., Saffer and Tobin, 2011). Seismic reflection characteristics and seismic velocity variations can provide important information on the fluid-related heterogeneity of structure around plate interface. In 2006, active-source seismic experiment was conducted to obtain the subduction structure beneath the eastern part of the Kii Peninsula (Iwasaki et al., 2008). Iwasaki et al. (2008) revealed the geometry of the subducting PHS. However, little is known about the deeper part of the plate boundary, especially Vp/Vs structure in and around the source region of the slow-earthquake. Passive seismic data is useful to obtain a deep image including the S-wave velocity. Therefore, we conducted passive seismic experiment in the eastern part of the Kii Peninsula. Ninety portable seismographs were installed on a 90-km-long line nearly parallel to the direction of the subduction of the PHS with approximately 1 km spacing. Each seismograph consisted of a 1.0-Hz 3-component seismometer and an offline recorder. Waveforms were continuously recorded during the period from May 26, 2015 to December 8, 2015. The continuously recorded data obtained by the offline recorders were processed in the laboratory subsequent to the observations. First, they were divided into event files, each of which had waveform data that started from an origin time determined by the Japan Meteorological Agency. In order to obtain a high-resolution velocity model, a well-controlled hypocenter is essential. Due to this, we combined the seismic array data recorded by the offline recorders with the telemetered seismic data. We used 116 telemetered seismic stations in the present study. P- and S-wave arrivals for the 275 local earthquakes were picked, yielding 17,957 P-wave and 15,442 S-wave arrival times that were used in our analysis. To investigate the earthquake locations and three dimensional Vp and Vp/Vs structures, the double-difference tomography method (Zhang and Thurber, 2003) was applied to the P- and S-wave arrival time data obtained from 275 local earthquakes. The initial 1-D velocity model used in the present study was obtained by resampling the 1-D velocity model calculated by the joint hypocenter determination technique (Kissling et al., 1994). The final 3-D velocity structures are resolved down to 50 km depth. Hypocenter distribution associated with the underthrusting of the PHS is located beneath the subducting oceanic Moho. Most low-frequency earthquakes (LFEs) are located within subducting oceanic crust. Reported strong reflector interpreted to be the top of the PHS (Iwasaki et al., 2008) well corresponds to the top of the LFE zone. LFEs are also located in and around the low Vp and high Vp/Vs zone. The low Vp and high Vp/Vs zone generally suggests the existence of fluid (e.g., Zhao et al., 1996). The obtained fluid-related heterogeneous structure is clearly correlated with the source region of the LFE. These results indicate the occurrence of the LFEs may be associated with fluids. Previous research has indicated that zones of high pore-fluid pressure are marked by high reflectivity and/or high Vp/Vs (e.g., Kodaira et al., 2004). These studies suggest that fluids dehydrated from the PHS may control the degree of plate coupling.

キーワード：フィリピン海プレート、地震波トモグラフィー、速度構造、低周波地震
Keywords: Philippine Sea plate, Seismic tomography, Velocity structure, Low-frequency earthquake

キーワード：フィリピン海プレート、地震波トモグラフィー、速度構造、低周波地震
Keywords: Philippine Sea plate, Seismic tomography, Velocity structure, Low-frequency earthquake

Lateral variation of low S-wave velocity zone in the Nankai accretionary prism derived from Rayleigh admittance

*利根川 貴志[1]、荒木 英一郎[1]、木村 俊則[1]、中村 武史[2]、中野 優[1]、鈴木 健介[1]

*Takashi Tonegawa[1], Eiichiro Araki[1], Toshinori Kimura[1], Takeshi Nakamura[2], Masaru Nakano[1], Kensuke Suzuki[1]

1. 海洋研究開発機構、2. 防災科学技術研究所
1. Japan Agency for Marine-Earth Science and Technology, 2. National Research Institute for Earth Science and Disaster Resilience

A cabled seafloor network (DONET: Dense Oceanfloor Network System for Earthquake and Tsunamis) has been constructed on the accretionary prism at the Nankai subduction zone of Japan since March 2010. DONET contains 22 stations in DONET1 (eastern network) and 29 stations in DONET2 (western network), and the their observation periods exceed more than 5 years and 10 months, respectively. In this study, using Rayleigh waves of microseisms and earthquakes, we calculate the Rayleigh admittance (Ruan et al., 2014, JGR) at the seafloor for each station, i.e., an amplitude transfer function from pressure to displacement, particularly for the frequencies of 0.1–0.2 Hz (ambient noise) and 0.04–0.1 Hz (earthquake signal), and estimate one-dimensional S-wave velocity (Vs) structure beneath stations in DONET.

Each station contains broadband seismometers and absolute and differential pressure gauges. We calculated the displacement seismogram by removing the instrument response from the velocity seismogram for each station. The pressure record observed at the differential pressure gauge was used in this study because of a high resolution of the pressure observation. In addition to Rayleigh waves of microseisms in ambient noise, we collected waveforms of Rayleigh waves for earthquakes with an epicentral distance of 15–90º, M>5.0, and focal depth shallower than 50 km. In the frequency domain, we smoothed the transfer function of displacement/pressure with the Parzen window of ±0.01 Hz. In order to determine one-dimensional Vs profiles, we performed a nonlinear inversion technique, i.e., simulated annealing.

As a result, Vs profiles obtained at stations near the land show simple Vs structure, i.e., Vs increases with increasing depth. However, some profiles at the toe of the acceretionary prism in southwest and southeast of the Kii Peninsula have a low-velocity zone (LVZ) at a depth of 5–7 km within the sediment. The Vs reduction is approximately at most 30 %. On the other hand, such Vs reductions cannot be seen south of the Kii Peninsula. Park et al. (2010) reported a large reduction in P-wave velocity within the region of DONET1 (eastern network and southeast of the Kii Peninsula), but our result shows the LVZ in the regions of both DONET1 and 2 (2: western network and south-southwest of the Kii Peninsula). This indicates lateral variation of low Vs zone at the toe of the Nankai accretionary prism. We will discuss the spatial relationship between the LVZ distribution and the active regions of very low frequency earthquakes.

キーワード：低速度域、付加体、水平方向の不均質
Keywords: Low velocity zone, Accretionary prism, Lateral variation

Low velocity zones along subducting plates: comparative study between southwest Japan and Cascadia subduction zones

*悪原 岳[1]、Bostock Michael[1]、加藤 愛太郎[2]
*Takeshi Akuhara[1], Michael G. Bostock[1], Aitaro Kato[2]

1. Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia、2. 東京大学地震研究所
1. Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, 2. Earthquake Research Institute, University of Tokyo

Low velocity zones (LVZs) along subducting oceanic plates are a ubiquitous feature of subduction zones worldwide. The LVZ has been interpreted as a hydrated oceanic crust from its high Vp/Vs ratio and is thought to affect generation of episodic tremor and slip (ETS) events. Southwest (SW) Japan and Cascadia subduction zones are well-investigated in terms of the LVZ properties. However, a direct comparison of LVZ properties between these subduction zones is difficult due to the difference in analysis methods: tomographic methods are often used in SW Japan, versus receiver function methods in Cascadia. In this study, we solve for LVZ properties beneath SW Japan through receiver function inversion analysis. This analysis optimizes model parameters (thickness, Vp/Vs ratio, dip angle and strike of layered structure) such that synthetic waveforms reproduce observed waveforms recorded by a linear array of seismographs installed in the Tokai region in 2008 (Kato et al., 2010, GRL). The results show that the LVZ is characterized higher Vp/Vs ratios (> 2.0) than previous estimates from tomographic analyses. In addition, the Vp/Vs ratio shows along-dip variation, culminating where ETS and long-term slow-slip events occur. This suggests that high pore fluid pressure plays an important role in generating ETS and long-term slow-slip events. A detailed look at high-frequency receiver function waveforms suggests that the LVZ is likely to be composed of two layers. Such high Vp/Vs ratios (> 2.0) and two-layer structure of the LVZ are also reported for Cascadia. However, whether along-dip variation of Vp/Vs ratio exists or not is still open question for Cascadia. Further efforts to reveal such variations at Cascadia is left for future study. Detailed comparison of LVZ properties may lead to improved understanding of ETS mechanisms.

キーワード：沈み込み帯、低速度層、レシーバ関数解析
Keywords: Subduction zone, Low velocity zone, Receiver function analysis

熊野沖南海トラフにおける三次元地震探査データの最新解析結果
Improved 3D seismic image in Nankai Trough off Kumano

*白石 和也[1]、Moore Gregory[2]、山田 泰広[1]、木下 正高[3]、真田 佳典[1]、木村 学[4]
*Kazuya Shiraishi[1], Gregory Moore[2], Yasuhiro Yamada[1], Masataka Kinoshita[3], Yoshinori Sanada[1], Gaku Kimura[4]

1. 海洋研究開発機構、2. ハワイ大学、3. 東京大学地震研究所、4. 東京海洋大学
1. Japan Agency for Marine-Earth Science and Technology, 2. University of Hawaii, 3. ERI, The University of Tokyo, 4. Tokyo University of Marine Science and Technology

　熊野沖南海トラフでは、国際深海科学掘削計画（IODP）プロジェクトとして、地球深部探査船「ちきゅう」による地震発生帯深部掘削計画が継続されている。その事前調査として2006年に取得された三次元地震探査データは、巨大分岐断層や前縁部スラスト帯の三次元的構造を明らかにし、南海トラフ付加体形成の理解に大きく貢献した。しかし、この地域の複雑な地質構造に対しては、当時の最新技術では多重反射波やノイズに対する信号比や深部の空間分解能を十分に上げられず、熊野海盆下の付加体内部の詳細構造はいまだ明らかではなかった。そこで、2006年から10年の間には、海中多重反射波あるいは各種ノイズの除去処理、速度異方性を考慮した深度イメージング技術など、格段の進歩を遂げてきた三次元地震探査データの解析技術を用いてデータ再処理を実施し、速度モデルの再構築と深度イメージングを行った。

　取得データの大きな問題は、掘削対象とする深度約5,000m以深の構造からの信号を被覆する海中多重反射波と、流速4–4.5knotにおよぶ黒潮による受振ケーブルのフェザリングの影響であった。海中多重反射波および波浪やフェザリングに伴うノイズに対して、複数の処理手法を最適に組み合わせて適用することで効果的に除去するに成功した。ケーブルフェザリングによる重合数の不均一は反射波イメージを劣化させるので、この課題に対しては、四次元トレース内挿による重合数の規格化とノイズ抑制が図られた。そして、近年の技術革新の一つであるゴースト除去処理を含む信号の広帯域化は、低周波帯域のシグナル強調、波形の先鋭化による浅部の高分解能化に寄与した。このような最新のデータ処理を行ったのち、新たにTTI異方性を考慮した深度領域の速度モデル構築と重合前深度マイグレーションが行われた。速度モデル構築は、ビームマイグレーションを用いた反射波トモグラフィにより、データに依拠する速度モデルの更新が行われた。

　新たに得られた高分解能な反射波イメージによって、前縁部スラスト帯では主逆断層の形成に伴う微細な変形構造が、ノッチの浅部では堆積構造と急傾斜な正断層の存在が明らかである。また、熊野海盆下の付加体内部は、異方性深度マイグレーションにより複雑な断層褶曲構造からの反射波はより正確な位置へイメージングされたと期待される。海中多重反射波が効果的に抑制された分岐断層の上盤側には、深部の地層境界の存在を示唆する反射波群が確認される。また、分岐断層の海側延伸部には、下盤側へ派生した反射波群も確認できる。分岐断層は既存解析に比べて下方へ凸に湾曲した形状を示し、その上部には1.5〜2.0km厚さの最大値が5,000m/sを超える高速度帯の存在が示唆されている。ただし、ストリーマ長（4.5km）を超える深度域であるため、異なる仕様の地震探査記録も併用しながら、今後の詳細な評価が必要であると考える。再解析により新たに得られた三次元データボリュームは、変形構造や物性に関する詳細な解析を行うことで、南海トラフプレート沈み込みに伴う付加体内部構造の解明、「ちきゅう」による地震発生帯深部掘削の成功に大きく貢献する。

キーワード：南海トラフ地震発生帯、三次元地震探査
Keywords: Nankai Trough seismogenic zone , 3D seismic survey

Connecting faults and fractures with clay formation and fluid movement in the accretionary prism of the Nankai Trough: NanTroSEIZE IODP Expeditions 338/348, Site C0002

*Maria Jose Jurado[1], Anja Schleicher[2]

1. Institute of Earth Sciences Jaume Almera-CSIC, Barcelona, Spain, 2. Helmholtz Center Potsdam German Research Center for Geosciences GFZ, Potsdam, Germany

During the International Ocean Discovery Program (IODP) Expeditions 338 and 348, which is part of the NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) project, three deep riser holes were drilled south of the Kii Peninsula at Site C0002. The site is located in the Kumano forearc basin above the seismogenic portion of the plate boundary thrust. Hole C0002F (Expedition 338) was drilled down to 2004.5 mbsf. Hole C0002N/C0002P (Expedition 348) was drilled down to 3058.8 mbsf. Hemipelagic mudstone and sand/silt sediments are the predominant lithologies (Moore et al., 2014; Tobin et al., 2015). A complete set of logging while drilling (LWD) data, including borehole images, was collected during IODP Expeditions 338/348. Also rock-cuttings and spot cores. Distinct sections of intense fracturing and faulting within the very clay-dominated lithology were characterized on LWD borehole oriented images and other geophysical logs (Boston et al.,2016). The intense deformation of the generally homogenous lithology is characterized by bedding that dips steeply (60-90°). Smectite and illite are the most common clay minerals. Underwood and Song (2016) documented the abundance of smectite expandability of clay minerals in both holes. However, the properties and the role these minerals play in influencing fluid flow specifically in fractures, faults and folds within the accretionary prism is still not well understood.

The main focus of this contribution is on the analysis and potential link between structure development and the associated formation of clay minerals in the accretionary prism. We analyzed the relationship between the fractures, faults and the changes in clay mineralogy as derived from post-cruise cutting sample analyses. The comparative analysis of clay mineralogy reveals an increase of intensity observable in smectite and illite at specific depth intervals that are related to fault and fracture zones at 2350-2400 mbsf, at 2600-2800 mbfs, and also at 2150 mbsf. This increased intensity reflects an increase in the amount of smectite and illite in those areas, that could be related to due to abundant fluid-rock interaction processes. The connection between structures characterized on borehole images and the changes in clay mineralogy for Hole C0002P suggests that mineralogical changes are associated to structures of the Nankai accretionary prism. This is critical for a better understanding of clay-fluid interaction and mechanical properties during fault displacements and seismogenesis. We interpret a defined connection between the occurrence of fracture and/or faults in the accretionary prism and the abundance of illite and smectite clay minerals. Ongoing postcruise research on hole C0002 N and C0002P (Expedition 348) should confirm these results.

References
-Boston B., Moore G.F., Jurado M.J., Sone H. (2016) Deformation of the Nankai Trough inner accretionary prism: the role of inherited structures, Geochem. Geophys. Geosyst., 17, doi: 10.1002/2015GC006185.
-Moore G. F., Kanagawa K., Strasser M., Dugan B.,. Maeda L, Toczko S., and the IODP Expedition 338 Scientific Party (2014) IODP Expedition 338: NanTroSEIZE Stage 3: NanTroSEIZE plate boundary deep riser 2 Sci. Dril., 17, 1-12, 2014, www.sci-dril.net/17/1/2014/, doi:10.5194/sd-17-1-2014.

-Tobin H., et al. (Eds.) (2015) Site C0002, in Proceedings of integrated Ocean Drilling Program, vol. 348, Integr.Ocean Drill. Program, College Station, Tex., doi: 10.2204/iodp.proc.348.103.2015.
-Underwood, M.B., and Song, C., 2016. Data report: clay mineral assemblages in cores from Hole C0002P, IODP Expedition 348, Nankai Trough accretionary prism. In Tobin, H., Hirose, T., Saffer, D., Toczko, S., Maeda, L., Kubo, Y., and the Expedition 348 Scientists, Proceedings of the Integrated Ocean Drilling Program, 348: College Station, TX (Integrated Ocean Drilling Program). http://dx.doi.org/10.2204/iodp.proc.348.202.2016

Keywords: Nankai Trough Seismogenic Zone, Clay-fluid interaction, Accretionary prism, Borehole imaging, Logging while drilling

室戸-足摺沖隆起帯の浅部活構造
Active shallow structures of Muroto-off Ashizuri uplifted ridges, SW Japan

*芦 寿一郎[1]、大出 晃弘[1]、高下 裕章[1]、山口 飛鳥[2]、池原 研[3]
*Juichiro Ashi[1], Akihiro Ohde[1], Hiroaki Koge[1], Asuka Yamaguchi[2], Ken Ikehara[3]

1. 東京大学大学院新領域創成科学研究科／大気海洋研究所、2. 東京大学大気海洋研究所、3. 産業技術総合研究所
1. GSFS/AORI, UTokyo, 2. Atmosphere and Ocean Research Institute, UTokyo, 3. National Institute of Advanced Industrial Science and Technology

　室戸岬から足摺岬沖には室戸海丘，西室戸海丘，足摺海丘といった高まりが逆L字型に断続的に連なる．反射法地震探査記録では，東側を逆断層で切られ，西側が緩やかな非対称な背斜構造からなり，後期鮮新世から第四紀初め頃に隆起し始めたとされる（岡村・上嶋，1986，地調海洋地質図）．この逆L字型の隆起帯はフィリピン海プレートが南海トラフに斜めに沈み込むことで形成されたと考えられている（杉山，1989，地調月報）．

　本研究では，隆起運動にともなう海底表層の堆積・変形構造を捉えるため，KH-15-2, KH-16-5白鳳丸航海において深海曳航式サブボトムプロファイラー（SBP）探査を行った．チャープ方式を用いた装置（EdgeTech DW-106）を無人探査機NSSを用いて海底面上15 m前後で探査することにより，高解像度のSBP断面を取得することができた．

　探査地点は，室戸岬南方45kmの西室戸海丘と足摺岬沖70kmの無名の海丘（本研究では足摺南海丘と仮称）である．西室戸海丘は，北東－南西方向に伸びた複数の高まりからなり，探査は南東から北西に向かって行った．南峰の南東側の堆積盆では，北西に向かって地層が傾動しており深部ほど傾斜が大きい．南峰の北西側の堆積層は北西に向かって大きく傾動しており，南峰の南東側の崖には100m程度の変位が存在するとみられる．また，北東－南西方向の深い谷地形が南峰の北西斜面に発達する．一方，北峰は堆積層の反射面がほとんど見られず．南峰より古い時代の地層が露出しているものとみられる．両者の間の小海盆の地層は北峰の相対的な隆起を示唆する．南足摺海丘は南斜面に北東－南西方向の線状構造が発達する．調査はそれを横断する南東から北西に向けて行ない，海底面まで変形の達する高角の断層と撓曲に挟まれたホルスト状の地形が捉えられた．本高解像度浅部構造探査により，室戸岬から連続する隆起帯に沿う，最近のテクトニクスを反映した特徴的な堆積と変形が捉えられた．

キーワード：活断層、活褶曲、外縁隆起帯、サブボトムプロファイラー、自航式深海底サンプル採取システム
Keywords: active fault, active fold, outer ridge, subbottom profiler, Navigable Sampling System

Unsolving the formation of a massive bivalve colony grave at the eastern Nankai subduction zone from a geological and geochemical view

*Kazuhiro Yagasaki[1], Juichiro Ashi[1], Yusuke Yokoyama[1,2,3], Yosuke Miyairi[1], Shin'ichi Kuramoto[4]

1. Atmosphere and Ocean Research Institute, The University of Tokyo, 2. Dept. of Earth and Planetary Science, The University of Tokyo, 3. Dept. of Biogeochemistry, Japan Agency for Marine-Earth- Science and Technology (JAMSTEC), 4. Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Cold seep activity in the Nankai and Tokai regions are common, supporting wide varieties of chemosynthetic communities. This study focuses on an extinct *Calyptogena* spp. bivalve colony covering an area over 47,000 m^2 discovered on the south slope of the Daini Tenryu Knoll off Tokai. The unusual size and the condition of these shells raises questions on the process involved in forming a chemosynthetic community this size. Methane seeps are known to be ephemeral allowing for possibilities that the colony was gradually formed over time. Yet the sheer volume of dead shells may suggest that past major geological events may have disrupted the underlying methane hydrate layer that is known to be found in this region. ^{14}C radiocarbon dating was adopted on shells found at the colony (600 m) off Tokai using a Single-Stage Accelerated Mass Spectrometer (AMS) at AORI, UTokyo (Yokoyama et al., 2007, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms), revealing three ^{14}C age groups (ca. 1400, 1912 and 6000 cal BP). Suitable calibration model was created for this environment using δ13C DIC measurements of the shell (3‰) and the gill (-39‰) suggesting that the bivalve incorporates carbon from different sources for growth. The δ13C DIC value of porewater collected from the sediments below the bivalve colony also matches the gill measurements collected in this study (Tomonaga et al., 2016, Blue Earth Symposium). Seawater ^{14}C DIC depth profile of the region were also measured at 50-100m intervals to observe for any abrupt changes near the colony. Geological analyses of sub-bottom profile (SBP) data below and around the colony region using ROV Navigable Sampling System (NSS) highlights multiple areas with steep and shallow faults facing in a NE-SW direction which matches the major Kodaiba thrust that exists in the region. Majority of these faults feature further south of the colony. The region directly below the colony revealed a depression which may have been a result from a past tectonic activity possibly disrupting the underlying structure which could have provided the necessary passage for hydrocarbon rich fluids to pass through to support such a large colony.

Keywords: Cold seeps, Active fault, Radiocarbon dating, Bivalve shells

熊野前弧海盆堆積物のビトリナイト反射率測定から得られた断層に関連する高温流体循環の可能性
Thermal fluid migration in the Kumano forearc basin, Nankai Trough, estimated through vitrinite reflectance measurement

*川端 訓代[1]、坂口 有人[2]、濱田 洋平[3]、北村 有迅[1]、斎藤 実篤[4]

*Kuniyo Kawabata[1], Arito Sakaguchi[2], Yohei Hamada[3], Yujin Kitamura[1], Saneatsu Saito[4]

1. 鹿児島大学大学院理工学研究科、2. 山口大学理学部、3. 海洋研究開発機構高知コア研究所、4. 海洋研究開発機構海洋掘削科学研究開発センター

1. Graduate School of Science and Engineering, KAGOSHIMA UNIVERSITY, 2. Deaprtment of Geosphere Sciences, Yamaguchi University, 3. Kochi institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology, 4. Research and Development Center for Ocean Drilling Science, Japan Agency for Marine-Earth Science and Technology

Sediment analysis and the thermal history of the Kumano forearc basin and slope basin sediments in the Nankai Trough were studied through chemical and mineral composition analyses and the vitrinite reflectance measurement of sediments from Integrated Ocean Drilling Program Sites C0004, C0007, and C0009. The immobile component ratio (TiO_2/P_2O_5) suggests that the depositional source of sedimentary rock underlying the Kumano forearc basin (Unit IV of Site C0009) is different from those in the Kumano forearc basin (Unit III of Site C0009). The results support that Unit IV is not a basin sediment but a part of an old accretionary prism. The source of Unit IV is similar to that of the Shikoku basin sediment currently situated in the accretionary toe and subduction input, based on mineral composition analysis. The similarity is well explained by sediment transport from the East China Sea. In the Kumano forearc basin, a paleothermal anomaly was detected at Site C0009 using vitrinite reflectance measurement. The anomaly peak is 200 m wide with a maximum temperature of 79 ºC. Estimation of reflectance increase through vitrinite reaction promotion suggests that 80–100 ºC thermal fluid had passed with at least 100 ky, thus causing the anomaly. The thermal fluid upwelling might relate to ancient splay fault activity near Site C0009. The thermal anomaly zone in the Kumano forearc basin at Site C0009 coincides with the currently fluid conduit zone. These results indicate that massive fluid circulation occurs spatially and temporally through a large thrust in the subduction zone.

キーワード：南海トラフ、ビトリナイト反射率、熊野前弧海盆、高温流体
Keywords: Nankai Trough, Vitrinite reflectance, Kumano forarc basin, Thermal fluid

遠地地震によって誘発された深部低周波微動の活動特性
Activity of deep low frequancy tremor triggered by teleseismic earthquakes.

*栗原 亮[1]、小原 一成[1]、竹尾 明子[1]、前田 拓人[1]
*Ryo Kurihara[1], Kazushige Obara[1], Akiko Takeo[1], Takuto Maeda[1]

1. 東京大学地震研究所
1. Earthquake Research Institute, The University of Tokyo

Deep low frequency tremor in subduction zone is sometimes triggered by surface waves from teleseismic earthquakes. This type of tremor is called as triggered tremor. Amplitude of triggered tremor seems to be modulated by each phase of surface wave trace of teleseismic earthquake. Such triggered tremor has been observed in the ambient tremor zone where short-term slow slip events episodically occur. However, triggered tremor is not distributed in the entire source area of ambient tremor, but is rather concentrated in several spots. In this study, we investigated finer spatiotemporal characteristics of triggered tremor in order to reveal its activity.

We applied matched filter technique (Shelly et al., 2007) to detection of triggered tremor episodes in northern Kii and western Shikoku area, where triggered tremor episodes were observed at many times. The data obtained at NIED Hi-net stations were used in this analysis. We used waveforms of low frequency earthquake based on the JMA hypocenter catalog as templates of tremor. We analyzed continuous waveform data for one hour from the origin times of 67 teleseismic events with magnitude larger than 7.5 which occurred after Dec. 26, 2004.

Triggered tremor episodes were detected at 9 teleseismic events in northern Kii and at 15 teleseismic events in western Shikoku. Triggered tremor episodes were detected in one spot at northern Kii, and in two spots at western Shikoku. The areas where triggered tremor episodes occurred are not same at some teleseismic events. Along-dip migrations of triggered tremor were observed in both areas. Migration speed of triggered tremor is 5–20 km/h in northern Kii and about 40–100 km/h in western Shikoku. In northern Kii, the directions of migrations are same in all cases. In western Shikoku, both up-dip and down-dip migrations were observed.

Although migration speed of our result is much faster than that of episodic tremor and slip, about 10 km/day, tremor episodes having migration speed similar to our result has been reported during non-triggered tremor in previous studies. In northern Kii, migration of triggered tremor is similar to rapid tremor reversal (RTR) and rapid tremor forward (RTF) (Houston et al., 2011). Then, migration of triggered tremor may correspond to RTR and RTF. In western Shikoku, migration of triggered tremor is similar to rapid streak (Ghosh et al., 2010).

Ghosh et al. (2010) proposed two models about rapid streak. The first one is the apparent velocity model. The second model is effect of fluid. If we try to explain the observed migration in western Shikoku by the apparent velocity model with an assumption of actual migration velocity of 20 km/h obtained on northern Kii, the initiation of the background slip must be located at longer than 20 km away from the streak because apparent velocity at tremor streak would be about 60 km/h. However, the triggered tremor is excited at the same time as the arrival of the surface wave. Therefore, the apparent velocity model is not suitable for migration of triggered tremor and the fluid model might remain as one of reasonable models. However, another model may be reasonable for migration of triggered tremor. This is tremor asperity model, which predicts occurrence of real high-speed rupture due to existence of strong tremor asperities.

キーワード：深部低周波微動、誘発微動

Keywords: Deep low frequency tremor, triggered tremor

キーワード：深部低周波微動、誘発微動

Keywords: Deep low frequency tremor, triggered 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
Development and evaluation of modified envelope correlation method for deep tectonic tremor

*水野 尚人[1]、井出 哲[1]
*Naoto Mizuno[1], Satoshi Ide[1]

1. 東京大学大学院理学系研究科地球惑星科学専攻
1. Department of Earth and Planetary Science, The University of Tokyo

　深部微動の震源決定のための新たな手法を開発し、南海沈み込み帯の微動活動に適用した。新手法は微動震源決定手法として広く用いられているエンベロープ相関法を、最尤法の観点から整理したものである。相互相関関数を直接的に目的関数とし、各観測成分を分散の逆数によって重みづけることで、エンベロープ相関法と最尤法は同値となる。この定式化に従い、重み付きの相互相関関数を最大化する震源決定アルゴリズムを開発した。本手法では複数のイベントがほぼ同時に起こった場合、それぞれが尤度の極大値として現れる。

　重み付きの相互相関関数の平均（ACC）は、微動の震源位置を変数とする非線形関数である。この関数の最大化は二段階に分けて行う。まず始めに深さを30kmに固定し水平方向に0.2度刻みでグリッドサーチを用いて局所解を列挙し、それらを震源位置の候補とする。それらの局所解を初期値として3次元的な位置を推定するために勾配法を用いる。この結果、5分間のタイムウィンドウ内で複数の震源が決定されることがある。分解能をそれぞれの震源が分離して検出できるために必要な距離として定義すると、観測された震源ペアの距離の分布からこれは約100kmであると推定された。理論波形を用いて震源間の距離に応じて両方を検出できる割合を計算したところ、観測から推定された分解能と同様の結果が得られた。本手法を西日本の4年間の連続波形に用いたところ、従来の手法よりも微動の決定数が27%向上した。これは複数の震源を同時に決定することと重みづけによる精度向上によるものである。

　震源周囲の尤度の分布は、観測点配置に由来するバイアスを取り除いても、異方性を持っている場合が多い。ACCを走時差の二次関数で近似したところ、ACCが変化しにくい方向が沈み込み方向とおおむね一致する。このことは、震源が沈み込み方向に伸びていることを示唆する。ACCの感度は微動の継続時間が長くなるにしたがって低下し、これが継続時間の平方根におおよそ比例する。この結果は微動の継続時間内で活動領域が拡散的な移動をしていることを示唆する。これらの特徴は微動震源地域の構造の不均質性を反映していると考えられる。微動活動の様式から、微動震源となる脆性な領域は沈み込み方向に並んでいると考えられていたが、この結果はそれを支持するものであり、さらに小さなスケールでも微動の発生様式には異方性が存在することを示唆する。

キーワード：深部微動、震源決定手法
Keywords: Deep tectonic tremor, Location method

Estimated seismic tremor energy for small amplitude tremors

*片上 智史[1]、伊藤 喜宏[2]、太田 和晃[2]
*Satoshi Katakami[1], Yoshihiro Ito[2], Kazuaki Ohta[2]

1. 京都大学大学院理学研究科地球惑星科学専攻、2. 防災研究所　京都大学
1. Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto university, 2. Disaster Prevention Research Institute, Kyoto University

Various types of slow earthquakes, such as tectonic tremor [Obara, 2002] and slow slip events [e.g. Rogers and Dragert, 2003] have been recently observed at both the updip and downdip edges of the coseismic slip areas [Obara, 2002; Yamashita et al., 2015]. The frequent occurrence of slow earthquakes may help us to reveal the physics underlying megathrust events as useful analogs [Kato and Obara, 2016]. Maeda and Obara. [2009] estimated spatiotemporal distribution of seismic energy radiation from low-frequency tremors. They applied their method to only the tremors, whose hypocenters had been decided with multiple station method. However, a lot of tremors with small amplitude could be prone to underestimate on their detection. The events with small amplitude should not ignored to reveal slow earthquake activity and to understand strain condition around a plate boundary in subduction zones.

Here, we apply the modified frequency scanning method (mFSM) at a single station to NIED Hi-net data in the southwestern Japan. The original frequency scanning method [Sit et al., 2012] proposed a tremor detection method of calculating envelope waveform ratios through different bandpass filters of broadband data in the Cascadia margin. We modified this analysis for short period seismic Hi-net data recorded in the Southwest Japan. Three bandpass filters of 2–8 Hz, 10–40 Hz, and 0.25–1.0 Hz, corresponding to the dominant frequency band of tremors, local earthquakes, and seasonal noise, respectively. In addition, we removed the regular earthquake events by considering these envelope waveform shapes are similar to exponential curve in 2–8Hz band. We do not use three minutes continuous seismic data when correlation coefficient value is greater than 0.8 between envelope waveform and given simple exponential function.

Our results with mFSM is corresponded to those with multiple method in Southwest Japan. On the other hand, our results include small amplitude tremors which can not be detected with multiple methods. We also estimated their seismic tremor energy including small amplitude tremors which were detected by mFSM at each sites. Amplitudes observed at each site was corrected using the site amplification factors estimated with the coda normalization method and the Euclidean distance between the tremor source and the station, The estimated energy in this analysis may indicates more realistic strain release rate around the plate boundary.

キーワード：スロー地震、地震エネルギー
Keywords: slow earthquake, seismic energy

Locating triggered tremors using envelope back projection

*須田 直樹[1]、北 佐枝子[1]

*Naoki Suda[1], Saeko Kita[1]

1. 広島大学大学院理学研究科地球惑星システム学専攻
1. Department of Earth and Planetary Systems Science, Graduate School of Science, Hiroshima University

Surface waves radiated from large teleseismic earthquakes sometimes trigger a series of deep non-volcanic tremors with intervals of 20-30 seconds, which are dominant periods of surface waves [e.g. Miyazawa & Brodsky 2008]. Dynamic stress perturbation due to surface waves in the tremor source region is as low as a few kPa, indicating the tremor source fault is quite sensitive to the stress change. Not all the large surface waves, however, induce triggered tremors. Necessary conditions for triggered tremor are still unknown.

Most of previous studies used the envelope correlation method (ECM) [e.g. Obara 2002] or a method derived from ECM [Wech & Creager 2008] to locate triggered tremors. Time resolution in tremor location is therefore limited by data length used in ECM in those studies. The method with higher time resolution is required because tremor is phenomenon whose time scale is approximately one second. The back-projection method is possible to give higher time resolution because it uses only amplitude information. The source-scanning algorithm [Kao & Shan 2004] is a kind of back-projection method, but not fully applied to triggered tremors. In this study, we applied the envelope back-projection method to records of triggered tremors to determine high-resolution space-time transition of tremor sources.

We focused on triggered tremors in the western Shikoku region of the Nankai subduction zone. We set 2629 source grids with the horizontal interval of 2 km on the model plate boundary [Baba et al. 2002; Nakajima & Hasegawa 2007; Hirose et al. 2008]. Theoretical traveltimes were computed using the 1-D seismic velocity model JMA2001 [Ueno et al. 2002]. We used records from 60 seismic stations of Hi-net, F-net, JMA, GSJ, ERI, Kochi and Kyushu Universities. Records of ground velocity were bandpass-filtered between 2 and 10 Hz and then envelopes were computed using three-component records. We obtained site amplification factors for 2-10 Hz using the coda normalization method [Takemoto et al. 2012] and used them in the analysis. We back-projected squared envelope amplitudes averaged in 0.5 second to the source grids to create back-projection maps with a time interval of 0.5 second. We used only the data from the stations whose epicentral distances are less than 60 km. Tremor epicenter was determined as a weighted average of source locations whose back-projection value is greater than or equal to 90 % of the maximum value.

We searched for clearly triggered tremors in the western Shikoku region between 2004 and 2016 and found them for 9 large earthquakes. Most of envelope peaks were able to be identified as space and time peaks in back-projection maps, and epicenters were determined. The results show that the triggered tremors in the western Shikoku region form two clusters, which correspond to the well-known clusters of tectonic tremor in this region. The western cluster is known as the tremor sweet spot in which tectonic tremors occur most frequently. It has an elongated shape along the NW-SE direction: NW and SE parts correspond to deep and shallow source regions, respectively. Most of the tremors belong to this cluster are located in the shallower part, though some were located in the deeper part. The triggering by the 2004 Sumatra earthquake is particular because triggered tremors occurred widely along the western cluster. Other detailed source characteristics and results for other regions will be shown in the

presentation.

キーワード：非火山性微動、誘発、バックプロジェクション、南海沈み込み帯
Keywords: non-volcanic tremor, triggering, back-projection, Nankai subduction zone

地震波異方性モニタリング手法を用いた低周波微動活動の検出
Detection of tectonic tremor using a monitoring method of seismic anisotropy

*石瀬 素子[1]、西田 究[1]、望月 公廣[1]
*Motoko Ishise[1], Kiwamu Nishida[1], Kimihiro Mochizuki[1]

1. 東京大学地震研究所
1. Earthquake Reseach Institute, University of Tokyo

We have been investigating temporal variations in seismic anisotropy around the source region of low-frequency tremor, one of the families of slow earthquakes associated with the Nankai trough mega-thrust earthquake [e.g., Ishise and Nishida, 2015 JpGU, 2015 SSJ, 2015 AGU]. Seismic anisotropy has close relationships with stress state and physical properties of the medium such as water content. Therefore, a temporal change in seismic anisotropy is a good proxy for the temporal and spatial evolution of tremor activity, which is related to temporal changes in the stress state and various physical properties.

In this study, we investigated tremor episodes in the eastern part of Shikoku by applying the monitoring method of seismic anisotropy. As a result, we detected that temporal variations in anisotropy and polarization directions of incoming waves occasionally indicate an event with a characteristic temporal pattern. Further, we found that the spatio-temporal distribution of the detected events includes all located spatio-temporal distribution of tremor activities in the study area [e.g., world tremor database, Idehara et al., 2014]. Therefore, we interpreted that the events with characteristic temporal patterns are manifestations of tremor activity and assumed that the monitoring method can be used to detect tremor activity.

As briefly mentioned above, we estimate back azimuth and incident angle of incoming wave from the polarization direction through this monitoring. Therefore, given the depth of tremor source regions from other studies, we could determine the source location of tremor with the aid of known back azimuth and incident angle of the incoming wave. Under an ideal situation, even source locations of the tremor may be possible using only a single-station data. This method is complementary to conventional source location determination methods that require observation of coherent seismic signals at several stations [e.g., Obara, 2002]. Then, it is expected that the tremor detection method with the seismic anisotropy monitoring provides a detailed spatio-temporal distribution of tremor activities. In addition, this tremor detection method is feasible for a study of offshore tremor activity, because the quality and quantity of marine observation data is limited in various aspects compared with those of land-based observation data. This will eventually discover some unknown phenomena.

Then, we started to study on offshore tremor activity by applying the seismic anisotropy monitoring method to ocean bottom seismometer data. As a first step, we applied the monitoring method to seismograms of an offshore seismic network, DONET, off southwest Japan along the Nankai trough, and examined the efficiency and validity of the offshore tremor study. In this presentation, we show a preliminary result of the investigation of tremor activity associated with the Mw 6.0 earthquake offshore the Kii Peninsula of southwest Honshu, Japan on 1 April 2016.

キーワード：低周波微動、地震波異方性モニタリング、微動検出方法
Keywords: low frequency tremor, seismic anisotropy monitoring, tectonic tremor detection method

Improvement of a system for monitoring very-low-frequency earthquakes

*浅野 陽一[1]、松澤 孝紀[1]
*Youichi Asano[1], Takanori Matsuzawa[1]

1. 国立研究開発法人防災科学技術研究所
1. National Research Institute for Earth Science and Disaster Resilience

We have improved a system for detecting and locating regular and very-low-frequency earthquakes (VLFEs) based on array-signal-processing technique. Using this system, we have analyzed filtered seismograms (pass band: 0.02-0.05 Hz) observed by high-sensitivity accelerometers (tiltmeters) in the approximately 700 NIED Hi-net and have revealed spatiotemporal distribution of VLFEs in and around Japan [Asano et al, 2008]; however, critical error of event location have been found in the surrounding areas of the tiltmeter network due to ill-conditioned station coverage. Therefore we have tried to analyze not only tiltmeter data but also additional data observed at seven F-net and three temporary stations in the surroundings such as southern Kyushu and Ryukyu areas. We separated these ten stations into three arrays and applied semblance technique to the continuous seismograms observed during the periods of May. 26-27, 2015 and Feb. 12-14, 2017, when VLFEs were located in Hyuga-nada, southeast off Kyushu, by the routine system only analyzing tiltmeter data. Estimated directions of coherent seismic waves at northern two arrays suggest that these VLFEs were widely distributed from off Amami to Hyuga-nada. On the other hand, incident wave directions at southwestern array far from these VLFEs were east for most of all VLFEs probably due to guided wave along the Ryukyu trench. These present results show that data observed at the neighbor arrays not so far from the VLFEs are useful to reject ill-conditioned VLFE epicenters and can constrain them in the future.

キーワード：very-low-frequency earthquake、array
Keywords: very-low-frequency earthquake, array

立体アレーとHi-netを使った東海地域深部低周波地震の高精度な震源決定
Precise hypocenter determination of deep low-frequency earthquakes in the Tokai area of the Nankai subduction zone using a 3D array and Hi-net

*鈴木 貞臣[1]、大久保 慎人[2]、今西 和俊[3]、中島 淳一[4]
*Sadaomi Suzuki[1], Makoto Okubo[2], Kazutoshi Imanishi[3], Junichi Nakajima[4]

1.（公財）地震予知総合研究振興会 東濃地震科学研究所、2. 高知大学、3. 独立行政法人　産業技術総合研究所、4. 東京工業大学
1. Tono Research Institute of Earthquake Science (TRIES), Association for the Development of Earthquake Prediction, 2. Kochi University, 3. Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), 4. Tokyo Institute of Technology

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 Nankai 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 only conventional 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 by using a 3D array (6 km x 4 km area) with 14 seismic stations in the Tokai area 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 calculated the semblance distributions for their seismic waves of 75 LFEs to identify P and S phases and obtained their propagation parameters (back azimuths and incident angles) . Using the back azimuths and incident angles of S waves, and S-P times with high quality result, we calculated the preliminary hypocenters of 15 LFEs by using a shooting method. Referring to those identified P and S phases we manually picked the arrival times of not only both P and S waves of the 3D array stations but also S waves and rarely P waves of Hi-net stations. Using the arrival times we relocated precise hypocenters of the 15 LFEs. Those hypocenters distribute in the depth range from 26 km to 34 km (red stars in Fig.1) approximately along the plate interface (Hirose et al., 2008) inclining in depth from 30 km to 32 km. The errors of those hypocenters estimated from residuals of the arrival times are 0.2-0.9 km in horizontal and 0.4-0.8 km in depth, respectively. By using the same procedure as we explained for LFEs, we also relocated precise hypocenters of 13 regular earthquakes occurring in the subducting Philippine Sea plate. Those regular earthquakes belong to the intra-slab events which are normal-fault or strike-slip type earthquakes, with the T–axis oriented in an E-W direction (e.g. Miyoshi and Obara, 2010). Those hypocenters distribute in the depth range from 35 km to 45 km (light blue squares in Fig.1). We found that the hypocenters of LFEs did not overlap with the regular earthquakes in depth. In Fig. 2 we compared the depth distributions of LFEs and the regular earthquakes with a simple model of inter-plate structure under Tokai area. From Fig.2 we may conclude that LFEs occur not only along a thin subduction interface (less than about 1(?) km in width) but also in the nearly whole layer of oceanic crust and several km width in wedge mantle. And the total depth range of the LFEs obtained from the standard deviation is about 5 km. This distribution of LFEs may support the undrained condition model (Nakajima and Hasegawa, 2016) of enhanced pore-fluid pressure for LFE activity. (Acknowledgment) National Research Institute for Earth Science and Disaster Prevention (NIED) , Japan Meteorological Agency (JMA)
(References)

Hirose F, Nakajima J, Hasegawa A (2008) Three-dimensional seismic velocity structure and configuration of the Philippine Sea slab in southwestern Japan estimated by double-difference tomography, J. Geophys. Res., 113:B09315. doi:10.1029/2007JB005274.

Kato A, Iidaka T, Ikuta R, Yoshida Y, Katsumata K, Iwasaki T, Sakai S, Thurber C, Tsumura N, Yamaoka K, Watanabe T, Kunitomo T, Yamazaki F, Okubo M, Suzuki S, and Hirata N (2010) Variations of fluid pressure within the subducting oceanic crust and slow earthquakes, Geophys. Res. Lett., 37:L14310. doi:10.1029/2010GL043723.

Miyoshi T, Obara K (2010) Double seismic zone within the ridge-shaped slab beneath southwest Japan, Earth Planets Space, 62, 949-954.

Nakajima J, Hasegawa A (2016) Tremor activity inhabited by well-drained conditions above a megathrust, Nature Communications 7, doi:10.1038/ncomms13863.
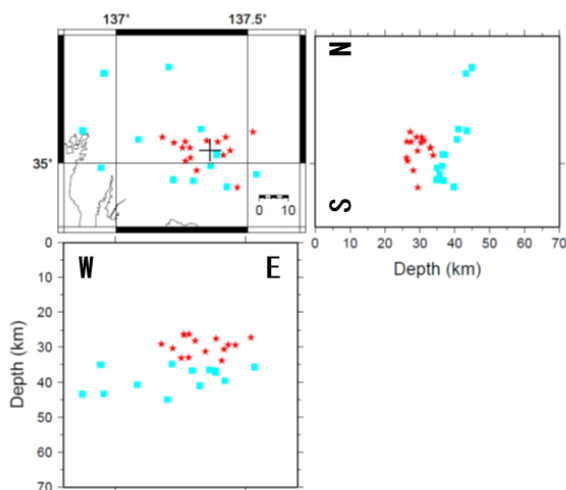
Fig.1. Hypocenter distribution of LFEs (red stars) and regular earthquakes (light blue squares) determined by using the data of a 3D array and Hi-net.
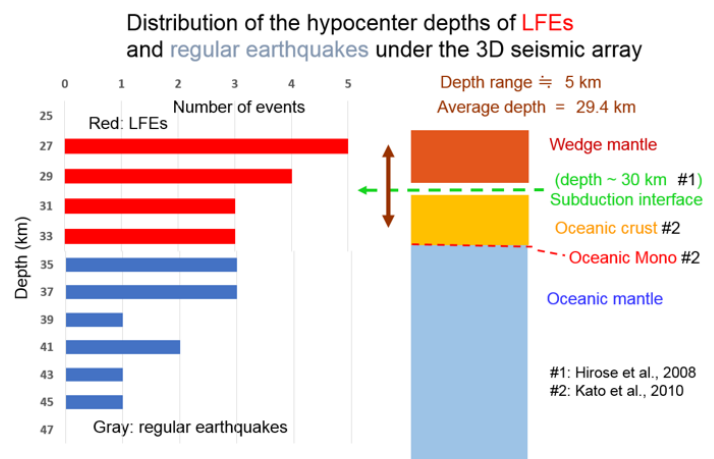

Fig.2. Comparison of hypocenter-depth distributions (left) with schematic inter-plate structure (right).

Quality control of tilt and strain data for automated detection of slow slip events within the Nankai subduction zone, Japa

*木村 武志[1]、板場 智史[2]、松澤 孝紀[1]、木村 尚紀[1]
*Takeshi Kimura[1], Satoshi Itaba[2], Takanori Matsuzawa[1], Hisanori Kimura[1]

1. 防災科学技術研究所、2. 産業技術総合研究所
1. NIED, 2. AIST

In the Nankai subduction zone, a large amount of high-quality geodetic and seismic data enables us to study the slow earthquakes such as the slow slip events (SSEs) and the nonvolcanic deep low-frequency tremors in detail. In order to reveal the source physics of various interplate slip phenomena, it is important to understand the relationship among members of slow earthquakes. Source models of short-term SSEs estimated from geodetic data objectively and independently of seismic slow earthquake catalog (e.g., Kimura et al., 2011) are essential to clarify the relationship. We have developed an automated method to detect SSEs from tilt and strain data, and in order to apply the method to data with the length of one year or longer, it is necessary to treat temporal changes of background noise levels appropriately. To assume incorrect noise parameters is possible to cause a miss detection or an excessive detection.

In this study, we evaluate temporal changes in noise levels of geodetic data. We assumed that continuous geodetic data contains background linear trend, random-walk noise and white noise, and estimated the noise strengths for a 30-day moving time-window using maximum likelihood method. Typical strengths of the random-walk and white noises are approximately 1.0-5.0 $nrad/hr^{0.5}$ and 1.0-5.0 nrad, respectively, for tilt data, and 0.5-1.0 $nstrain/hr^{0.5}$ and 0.5-1.0 nstrain, respectively, for strain data. The random-walk noise strengths of tilt data at MASH station in Kii Peninsula had been 1.0-2.0 $nrad/hr^{0.5}$ and almost constant from 2001 to 2012. They were increasing in 2013 and reached 10-20 $nrad/hr^{0.5}$. This increase in noise levels lowered the detection capability for SSEs in Kii Peninsula.

This work was supported by JSPS KAKENHI Grant Number JP16H474.

A stress-constrained geodetic inversion method for spatiotemporal slip of a slow slip event with earthquake swarm

田中 拓[1]、*廣瀬 仁[2,1]
Taku Tanaka[1], *Hitoshi Hirose[2,1]

1. 神戸大学大学院理学研究科、2. 神戸大学都市安全研究センター
1. Graduate School of Science, Kobe University, 2. Research Center for Urban Safety and Security, Kobe University

Geodetic inversions have been performed by using GNSS data and/or tiltmeter data in order to estimate spatio-temporal fault slip distributions. They have been applied for slow slip events (SSEs), which are episodic fault slip lasting for days to years (e.g., Ozawa et al., 2001; Hirose et al., 2014). Although their slip distributions are important information in terms of inferring strain budget and frictional characteristics on a subduction plate interface, inhomogeneous station coverage generally yields spatially non-uniform slip resolution, and in a worse case, a slip distribution can not be recovered.

It is known that an SSE which accompanies an earthquake swarm around the SSE slip area, such as the Boso Peninsula SSEs (e.g., Hirose et al., 2014). Some researchers hypothesize that these earthquakes are triggered by a stress change caused by the accompanying SSE (e.g., Segall et al., 2006). Based on this assumption, it is possible that a conventional geodetic inversion which impose a constraint on the stress change that promotes earthquake activities may improve the resolution of the slip distribution.

Here we develop an inversion method based on the Network Inversion Filter technique (Segall and Matthews, 1997), incorporating a constraint on a positive change in Coulomb failure stress (Delta-CFS) at the accompanied earthquakes. In addition, we apply this new method to synthetic data in order to check the effectiveness of the method and the characteristics of the inverted slip distributions.

We model a horizontal square fault with its area of 80 x 80 km^2 at 15 km depth in a half-space. This fault is divided into 64 square subfaults with each dimension of 10 x 10 km^2. We define the four subfaults at the center of the modeled fault as "slip patch" where slip lasts for five days and evolves to 50 cm. 49 GNSS stations are located on grid points on the surface with 20 km spacing. Theoretical surface displacement time-series at each GNSS station are calculated based on Okada's (1992) formulation. Pseudo observation data are generated by adding Gaussian noise with its standard deviation of 1 mm in horizontal components and 3 mm in vertical components, respectively, to the calculated displacements. These data are inverted with or without the Delta-CFS constraint, and both of the estimated slip distributions are compared. We test two GNSS station distributions: (a) all of the 49 stations are included; (b) reduced 28 stations which cover only a half area of the fault. The triggered earthquake hypocenters are located at the center of each subfault around the assumed slip patch where Delta-CFS is calculated. The same focal mechanism of these earthquakes is assumed as that of the SSE for the stress calculation. In case (a), because the station coverage is sufficient to reproduce the given slip distribution, the difference between the inversion results with and without the Delta-CFS constraint is small. In case (b), where the observation condition is worse than (a), the inversion result with the Delta-CFS constraint has larger slip (closer to the assumed slip amount) on the slip patch and smaller smearing on the surrounding subfaults than that without the Delta-CFS constraint.

These show that there is a case in which the reproduction of a slip distribution is better with earthquake information than without it. That is, it is possible to improve the reproducibility of a slip distribution of an SSE with this new inversion method if an earthquake catalog for the accompanying earthquake activity can be used when insufficient geodetic data are available.

キーワード：Delta-CFS、地殻変動、GNSS、群発地震、プレート境界
Keywords: Delta-CFS, crustal deformation, GNSS, earthquake swarm, plate interface

Estimation of the spatiotemporal evolution of the slow slip events in the Tokai region, central Japan, since 2013 using GNSS data

*坂上 啓[1]、福田 淳一[2]、加藤 照之[2]、西村 卓也[3]
*Hiromu Sakaue[1], Jun'ichi Fukuda[2], Teruyuki Kato[2], Takuya NISHIMURA[3]

1. 京都大学大学院理学研究科、2. 東京大学地震研究所、3. 京都大学防災研究所
1. Graduate School of Science, Kyoto University, 2. Earthquake Research Institute, The University of Tokyo, 3. Disaster Prevention Research Institute, Kyoto University

In the Tokai region, central Japan, the previous long-term slow slip event (L-SSE) was very slow and long-term aseismic slip, observed on the subducting Philippine Sea Plate (PSP) from 2000 to 2005. In addition, many short-term slow slip events (S-SSEs) accompanied by low frequency tremors (LFTs), have been detected using not only tiltmeter and high sensitivity seismograph from the NIED Hi-net but also GNSS from the GEONET recently. Although several previous studies have reported the spatiotemporal evolution of L-SSEs, there are few previous studies that estimated the spatiotemporal evolution of S-SSEs. In this study, we applied a time-dependent inversion method to GNSS data to obtain the spatiotemporal evolution of an L-SSE and S-SSEs on the PSP beneath the Tokai region, since 2013.

GNSS data from January 1, 2008 to December 31, 2015 were used in this study. The GIPSY-OASIS II software was used to estimate daily coordinates of 222 GNSS stations from the GEONET in the Tokai region. It is well known that GNSS time series have many systematic signals that do not result from SSEs. These systematic signals include, for example, seasonal variations and post-seismic deformation of the 2011 Tohoku-oki earthquake (Mw9.0). After removing these systematic signals, we applied a modified Network Inversion Filter (NIF) [Fukuda et al., 2008]. The original NIF [Segall & Matthews, 1997] assumes a constant hyperparameter for the temporal smoothing of slip rates and thus often results in oversmoothing of slip rates. The modified NIF assumes a time-variable hyperparameter, so that changes in slip rates are effectively extracted from GNSS time series.

The results indicate that the moment magnitude and maximum cumulative slip of the L-SSE were estimated to be Mw~6.5 and ~6.5 cm from January 1, 2013 to December 31, 2015, respectively. In addition to the L-SSE, we found several periods of slip acceleration that can be regarded as S-SSEs, but we discuss only S-SSEs which are larger than the estimation error. The biggest S-SSE in analysis period occurred at the end of January, 2014 around the Ise Bay. Maximum cumulative slip of this S-SSE was estimated to be~1.1 cm from January 17, 2014 to February 1, 2014, respectively. We also found several other S-SSEs that occurred around the Ise Bay in the down-dip area of the L-SSE. These S-SSEs are correlated with LFTs, suggesting that LFTs were triggered by the S-SSEs.

Our results suggest that the slip peaks of the L-SSE and S-SSEs do not overlap and that the temporal variation of moment in the central area of the L-SSE is smooth and is not affected by the S-SSEs. In addition, LFTs [Obara et al., 2010] do not occur near the center of the L-SSE. In order to further investigate the relationship among the L-SSE, S-SSEs, and LFTs, we additionally processed data from GNSS stations constructed by the Japanese University Consortium for GPS Research and operated by Earthquake Research Institute at the University of Tokyo and allied universities. We will present results of joint analyses of these additional data and the GEONET data in the presentation.

キーワード：スロースリップ、GNSS、東海地方
Keywords: SSE, GNSS, Tokai region

三重県南東沖の浅部低周波微動活動の特徴とその監視
Episodic shallow tremor off southeast Mie prefecture and its monitoring

*案浦 理[1]、橋本 徹夫[1]、鎌谷 紀子[1]、勝間田 明男[2]
*Satoshi Annoura[1], Tetsuo Hashimoto[1], Noriko Kamaya[1], Akio Katsumata[2]

1. 気象庁、2. 気象研究所
1. Japan Meteorological Agency, 2. Meteorological Research Institute

We analyzed long-term continuous seismic records (from September 2015 to April 2016) of DONET deployed off southeast Mie prefecture and we investigated activity of shallow tremor near the trough axis with the envelope correlation method. We found that shallow tremor was active only in two periods of October 2015 and April 2016 and their durations were about 6 days and 2 weeks respectively.
In the episode of April 2016, migration property was observed. Because of the migration properties, it is inferred that slow slip events were related to activities of shallow tremor similar to the case of deep tremor. We observed three migrations with different speed (from several km per day to 20 km per hour). Triggering property was also observed after M7.3 Kumamoto Earthquake on 16 April. This is also the same with well-known triggering property of deep tremor by teleseismic wave.
This shallow tremor is sensitive to stress perturbation because it was triggered by teleseismic wave as is the case with deep tremor. Furthermore, shallow tremor in this research was located in the vicinity of the initiation points of past megathrust earthquakes in Nankai (M7.9 Showa-Tonankai earthquake in 1944 and M8.0 Showa-Nankai earthquake in 1946). Therefore, monitoring this tremor activity will be very important to reveal stress accumulation process of megathrust earthquakes.
We are now developing automatic monitoring system to detect shallow tremor in JMA. The system first determines candidate hypocenters of tremor using envelope correlation method and then excludes false detection such as regular earthquakes or artificial explosions by detecting spike-shaped waveform. We will introduce this method in the system as well.

キーワード：浅部微動、南海トラフ、沈み込み帯
Keywords: episodic shallow tremor, Nankai Trough, subduction
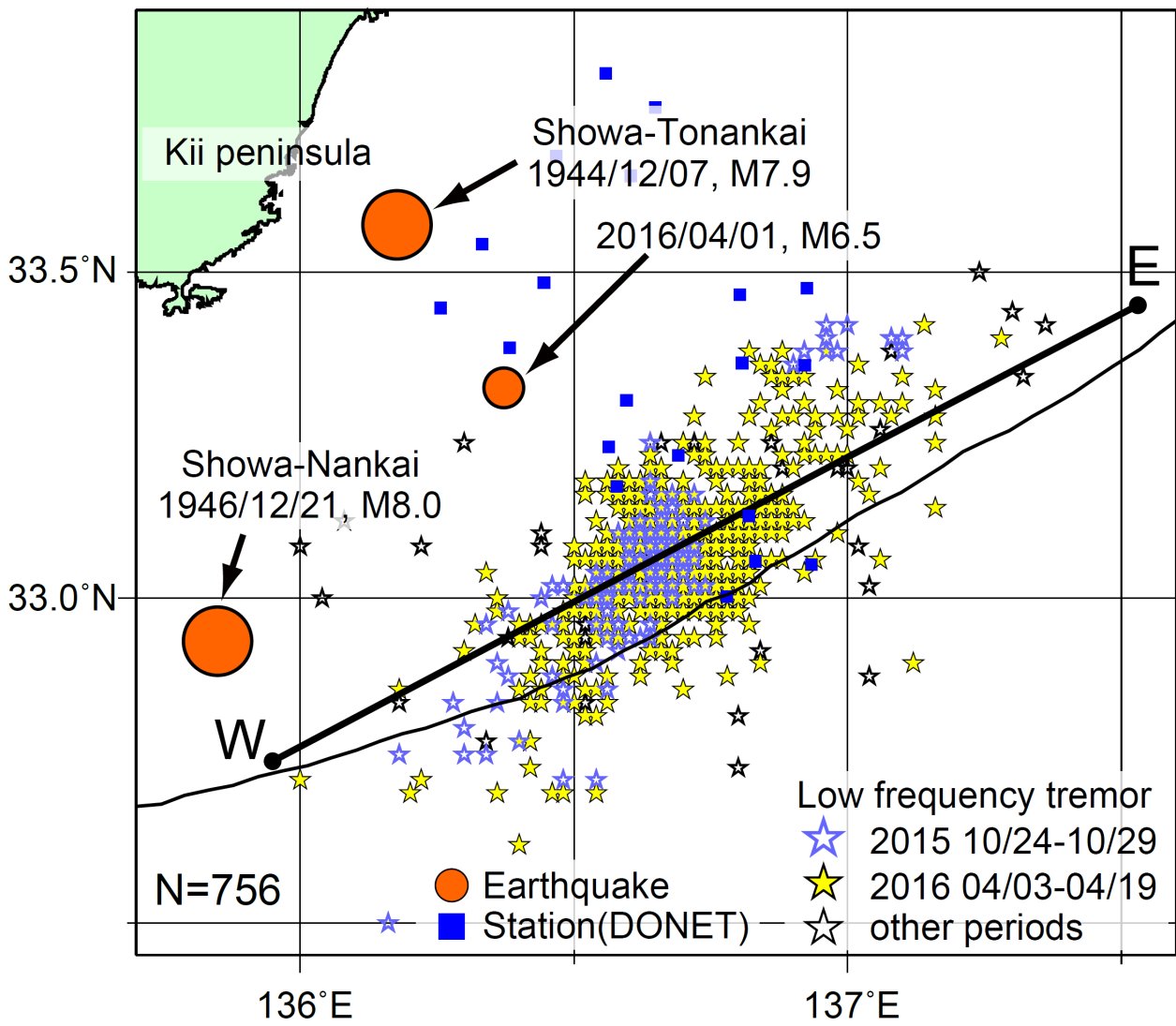
Shallow Slow Slip Event Off the Kii Peninsula in April 2016, Japan

*板場 智史[1]、案浦 理[2]、橋本 徹夫[2]、鎌谷 紀子[2]、勝間田 明男[3]

*Satoshi Itaba[1], Satoshi Annoura[2], Tetsuo Hashimoto[2], Noriko Kamaya[2], Akio Katsumata[3]

1. 産業技術総合研究所　活断層・火山研究部門、2. 気象庁　地震火山部、3. 気象研究所　地震津波研究部
1. Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, 2. Seismology and Volcanology Department, Japan Meteorological Agency, 3. Meteorological Research Institute, Japan Meteorological Agency

On 1 April 2016, an earthquake (Mw=5.9, hereafter mainshock, USGS) occurred off the Kii Peninsula, Japan. The mainshock occurred around the expected focal region of the so-called Tonankai earthquake. After the mainshock, strain and pore-pressure changes caused by the slow slip event (SSE) were observed by the three borehole strainmeters of AIST. The source region of this SSE is located on the plate interface at southeast side of the mainshock. An equivalent magnitude of this SSE is Mw 6.0, and duration is about 7 days. From after just a few days from the mainshock, in and around this SSE source region, intensive activity of shallow low frequency tremor has been observed for about two weeks, it is assumed that these shallow tremor events were induced by this SSE.
In off the Kii Peninsula, VLF and Low Frequency Earthquake has been often observed, but SSE had not been observed by geodetic method. The slip deficit rate of this SSE source region is about 3 cm / year (Yokota *et al.*, 2016), and the plate convergence rate is 5.0 to 6.5 cm / year (Heki and Miyazaki, 2001). Therefore, in addition to this case, there is a possibility that SSE frequently occurred in this region.

References

Heki, K. and S. Miyazaki, Plate Convergence and Long-Term Crustal Deformation in Central Japan,. *Geophys. Res. Lett.*, **28**, 2313-2316, 2001.
Yokota, Y., T. Ishikawa, S. Watanabe, T. Tashiro, and A. Asada, Seafloor geodetic constraints on interplate coupling of the Nankai Trough megathrust zone, *Nature*, **534**, 374-377, doi:10.1038/nature17632, 2016.

キーワード：SSE、スロー地震、低周波地震
Keywords: SSE, Slow earthquake, Low frequency earthquake

Shallow tremor activity around the source areas of the Nankai and Tonankai earthquakes by using LTBMS and DONET

*鈴木 健介[1]、荒木 英一郎[1]、木村 俊則[1]、町田 祐弥[1]、Demian Saffer[2]、高橋 成実[3]、小平 秀一[1]
*Kensuke Suzuki[1], Eiichiro Araki[1], Toshinori Kimura[1], Yuya Machida[1], Demian M. Saffer[2], Narumi Takahashi[3], Shuichi Kodaira[1]

1. 海洋研究開発機構、2. The Pennsylvania State University、3. 防災科学技術研究所
1. Japan Agency for Marine-Earth Science and Technology, 2. The Pennsylvania State University, 3. National Research Institute for Earth Science and Disaster Resilience

Several studies reported the activities of the non-volcanic tremors, Slow Slip Events (SSE) and the Very Low Frequency earthquakes (VLF) had occurred along the Nankai trough, southwest Japan (e.g., Obara, 2002; Obara and Hirose, 2006; Sugioka et al., 2012). SSEs were accompanied by tremors and VLFs, and those migrated with various pattern in response to SSEs (e.g., Obara 2011; Yamashita et al., 2015). Although tremors were well detected at the plate interface deeper than the source areas of mega-thrust and large earthquakes along the Nankai trough, tremors were little detected at the shallower part except for off southern Kyushu at where Yamashita et al. (2015) reported by the means of ocean bottom observation. It is considered as a reason why the shallow tremors along the Nankai trough were rare to be detected that S/N ratios of those signals are low because of the long distance between those sources and the onshore seismic network.

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) installed the cabled observation system called Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) in the source areas of the Nankai and Tonankai earthquakes, southwest Japan, to monitor earthquakes and tsunamis (Kaneda et al, 2015; Kawaguchi et al., 2015). In addition, JAMSTEC installed the borehole observation system called Long-Term Borehole Monitoring System (LTBMS) for seismic, geodetic, and hydrological observation in the seafloor targeting on the seismogenic faults along the Nankai trough as a part of the NanTroSEIZE by IODP program (e.g., Kopf et al., 2011), which is connected to DONET system. LTBMS and DONET stations can cover from coast to trough axis and are connected to land stations with fiber optic cables. The digitized data of them are continuously transferred in real-time to our laboratory at JAMSTEC. Therefore, we can continuously monitor the tremor activity occurred at shallow part of the source areas of the Nankai and Tonankai earthquakes. In this study we purpose to investigate the characteristics of the shallow non-volcanic tremor activity around the source areas of the mega-thrust earthquakes.

We detected non-volcanic tremors that occurred between Jan. 2011 and Dec. 2016, around the source areas of the mega-thrust earthquakes by applying the envelope correlation method (Ide, 2010, 2012) to the records of the broadband seismometers deployed to LTBMS and DONET stations. Shallow tremors have stably occurred around the aftershock area of the 2004 off Kii peninsula earthquake that occurred near the trough axis. Episodic shallow tremors were activated after the large earthquakes such as the off Mie earthquake (Mw = 6.0) on 1 April 2016. In addition, some episodic shallow tremor activities were observed without the large earthquakes. Several tremor activities were synchronized with deviations of the pore pressure deployed to LTBMS.

Investigation of tidal-induced poroelastic responses at IODP Sites C0010 and C0002 along the Kumano Transect - SE Japan

*Alexander Rösner[1], Achim Kopf[1], Earl E. Davis[2], Demian M. Saffer[3], Chihiro Kinoshita[3], Sean Toczko[4]

1. MARUM, Univ. of Bremen, 2. Pacific Geoscience Centre, Geological Survey of Canada, Canada, 3. Department of Geology Pennsylvania State Univ., USA, 4. JAMSTEC, Yokohama, Japan

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a multi-expedition Integrated Ocean Drilling Program (IODP) project along the Nankai Trough subduction zone with the purpose of better understanding subduction-zone earthquakes and seismogenic processes. Long-term pressure and temperature monitoring along the Kumano transect produced valuable data records, which constrain potential fluid flow paths and help to identify regions of strain accumulation/release. Simultaneous pressure and temperature records are available for IODP Site C0002 and IODP Site C0010.

The recent IODP Exp. 365 in April 2016 recovered an autonomous borehole observatory named "GeniusPlug". The GeniusPlug was recovered from Site C0010, were it was installed within the megasplay fault zone at 407 mbsf. The GeniusPlug observatory was equipped with temperature loggers and two pressure sensors. One pressure sensor is used as hydrostatic reference, while the other measures formation pressure. The GeniusPlug recording has a sampling period of 30 sec from November 2010 –April 2016. Complementary formation pressure data at various depths (PPI 940 mbsf, PPII 920 mbsf, PPIII 770 mbsf) and a hydrostatic reference are available via the C0002 long-term borehole monitoring system (LTBMS) installed in November 2010. Hence, formation pressures can be compared via monitoring at the megasplay fault zone and the inner accretionary prism/deep Kumano Basin.

Amplitude and phase of formation pressure variation have been determined relative to tidal pressure variations at the hydrostatic reference. Mean formation pressure amplitudes are reduced to 62 - 74 % and not shifted in phase. Theory of porous media response to periodic loading allows the calculation of frame bulk modulus, specific storage, hydraulic diffusivity and strain sensitivity. This approach allows investigation of formation-scale hydraulic and mechanical properties for the fractured mega splay fault sediments in C0010, and the inner accreted sediments of Unit IV at C0002 and the Kumano Basin sediments of Unit II at C0002.

Keywords: Poroelastic properties, Borehole observatory, Fluid pressure, NanTroSEIZE

Tidal modulation of slow slip detected using tiltmeters in Nankai subduction zone

*上田 拓[1]、菊地 淳仁[2]、井出 哲[2]、松澤 孝紀[3]
*Taku Ueda[1], Junji Kikuchi[2], Satoshi Ide[2], Takanori Matsuzawa[3]

1. 東京大学理学部地球惑星物理学科、2. 東京大学大学院理学系研究科、3. 防災科学技術研究所
1. Department of Earth and Planetary Physics, University of Tokyo, 2. Department of Earth and Planetary Science, University of Tokyo, 3. National Research Institute for Earth Science and Disaster Resilience

Episodic tremor and slip events have now been observed at many subduction zones worldwide. It has been shown that tectonic tremors are controlled by tides and passing surface waves, suggesting high sensitivity to small stress disturbances. Hawthorne and Rubin (2010) has detected that the slow slip events are also controlled by tides by using borehole strainmeters in Cascadia subduction zone. We address whether tidal modulation of slow slip is a general phenomenon by using tiltmeters in Nankai subduction zone, following the procedures proposed by Hawthorne and Rubin (2010).

We use tiltmeters at two stations of Hi-net operated by National Research Institute for Earth Science and Disaster Resilience. A set of analysis windows are selected to include slow slip events occurred from January 2001 to January 2013. Tilt record includes large undesired signals due to local deformation caused by the ocean loading and body tides. Therefore, we estimated local deformation empirically using tilt data without slow slip signals, and subtracted it from the original data to obtain signals caused by slow slip. The processed signals are modeled as a summation of sinusoids at four tidal periods and a linear trend, and simultaneously fit for all analysis windows.

The tidal modulation of the tilt rate is significant at 12.4 h (M2) period, at the 99% confidence level, which is consistent with the result of Hawthorne and Rubin (2010). The phase of maximum tilt rate at the M2 period appears to correspond to the maximum shear stress in the direction of plate motion on the plate interface right beneath each station.

Reference: Hawthorne, J. C., and A. M. Rubin (2010), J. Geophys. Res., 115, B09406.
Yabe, S., Y. Tanaka, H. Houston, S. Ide (2015), J. Geophys. Res. Solid Earth, 120, 7587-7605.

歪計を用いたスロースリップイベントの潮汐応答性解析
Tidal modulation of slow slip events in the Nankai subduction zone detected by borehole strainmeter

*菊地 淳仁[1]、井出 哲[1]、松本 則夫[2]
*Junji Kikuchi[1], Satoshi Ide[1], Norio Matsumoto[2]

1. 東京大学大学院理学系研究科地球惑星科学専攻、2. 産業技術総合研究所地質調査総合センター地震地下水研 究ク ゛
ルーフ ゜
1. Department of Earth and Planetary Scinence, The University of Tokyo, 2. Tectono-Hydrology Research Group,
Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST)

　日本の南西部、紀伊半島から四国地方にかけての南海トラフ沈み込み帯ではスロースリップイベント(SSE)が
度々発生している。SSEはプレート境界の摩擦特性が変わる遷移領域で発生すると考えられる。また隣接する
巨大地震発生領域の応力を変化させるので、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、
SSEが潮汐応答を示すことが知られている。本研究では、微動カタログを用いて検出した豊後水道での短期
SSEに対して、産業技術総合研究所(Advanced Industrial Science and Technology, AIST)のボアホール歪計の
データを用いて、Cascadiaの先行研究と同様の統計解析を試みた。豊後水道SSEにおいても先行研究と同様に
潮汐応答が確認できたが、応答をしめす分潮がCascadiaでは最大振幅を持つ半日潮であったのに対し、豊後水
道では一日潮であった。この結果は、SSEがどれかの分潮に依存するといったような単純なものではないこと
を示しており、合算の潮汐応力を考慮する必要性を示唆するものである。そこで本研究では、プレート境界で
の滑りレートと合算の潮汐応力との比較を試みた。SSEによる歪変化が微動活動によって説明可能か検討を
行ったところ、豊後水道ではSSEによる歪と微動活動から合成した歪のパターンが定性的に一致していた。そ
こで微動の震源がSSEの滑り地点を代表していると仮定し、SSEの滑り地点の時間変化を推定した。SSEの滑り
地点と観測点の位置関係が観測歪に与える影響を定量的に見積もることで、歪データからプレート境界上での
滑りレートを計算し、合算の潮汐応力との比較を行ったところ、プレート境界上での滑りレートと剪断潮汐応
力の間に正の相関が見られた。この結果は、SSE発生領域における摩擦特性が速度強化摩擦則であることを示
唆するものである。この結果は、測地データによって初めて得られたSSE発生領域における速度強化摩擦則の
証拠である。同様の手法を他の地域にも適用することで、沈み込み帯における摩擦特性の包括的な理解につな
がる。

キーワード：スロースリップイベント、歪計、潮汐応力、滑りレート、速度強化摩擦則
Keywords: Slow Slip Event (SSE), strainmeter, tidal stress, slip rate, velocity strengthening friction law

Tidal response in shallow micro low-frequency tremors

*片上 智史[1]、山下 裕亮[2]、八木原 寛[3]、清水 洋[4]、伊藤 喜宏[5]、太田 和晃[5]

*Satoshi Katakami[1], Yusuke Yamashita[2], Hiroshi Yakiwara[3], Hiroshi Shimizu[4], Yoshihiro Ito[5], Kazuaki Ohta[5]

1. 京都大学大学院理学研究科地球惑星科学専攻、2. 京都大学防災研究所地震予知研究センター宮崎観測所、3. 鹿児島大学大学院理工学研究科附属南西島弧地震火山観測所、4. 九州大学大学院理学研究院附属地震火山観測研究センター、5. 京都大学防災研究所
1. Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto university, 2. Miyazaki Observatory for Disaster Prevention Research Institute, Kyoto University, 3. Nansei-toko Observatory for Earthquakes and Volcanoes, Faculty of Science, Kagoshima University, 4. Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University, 5. Disaster Prevention Research Institute, Kyoto University

Various types of slow earthquakes, such as tectonic tremor [Obara, 2002], low-frequency earthquake [Katsumata and Kamaya, 2003] and slow slip events [e.g. Rogers and Dragert, 2003] have been recently observed at both the updip and downdip edges of the coseismic slip areas [Obara, 2002; Yamashita et al., 2015]. Here, we show micro low-frequency activity with very weak amplitudes detected using the modified frequency scanning method (mFSM) at a single station [Sit et al., 2012], and successfully detected micro low-frequency tremors (mLFTs) that have not been previously reported. These mLFTs are the almost same as ordinary tectonic tremors, but we define them here in this matter in order to discuss the differences and distinguish the tremor amplitudes, which have amplitudes that are one tenth of the amplitude of tremor detected by the envelope correlation method [Yamashita et al., 2015].
We also evaluated tidal response of the tremor activity at each site. The clear response to tides of slow earthquake activity at depth is well known [Ide, 2010], but the relationship between shallow slow earthquakes and tides is still debatable. We calculated the sea surface change due to the Earth using a computational model, and evaluated the relationship between shallower tremor activity and tidal stress changes ocean loading tides from the model NAO.99b [e.g. Matsumoto et al., 2010]. We used perturbation of the tides at each OBS site and statistically evaluated the relationship based on the Schuster p test. We consequently found high tidal responses of shallow tremors especially latter part of tremor migration which reported Yamashita et al., (2015). Specifically, mLFTs have clear response to tides.
We suggest two different occurrence mechanisms for slow earthquake activity off south-eastern Kyushu. The start of the tremors is mainly modulated by larger stress changes, such as from nearby, slow slip events, and later controlled by ambient shear stress perturbations such as tides. In other words, tremor, especially mLFTs could have been induced under the neutral stress regime by tidal stress perturbation.

キーワード：スロー地震、浅部沈み込み帯、潮汐応答性
Keywords: slow earthquake, shallower part of the subduction zone , tidal responses

Fortnightly tidal modulation of shallow very low frequency earthquakes in Hyuga-nada and off Cape Ashizuri

*田中 佐千子[1]、浅野 陽一[1]、松澤 孝紀[1]、小原 一成[2]
*Sachiko Tanaka[1], Youichi Asano[1], Takanori Matsuzawa[1], Kazushige Obara[2]

1. 防災科学技術研究所、2. 東京大学地震研究所
1. National Research Institute for Earth Science and Disaster Resilience, 2. Earthquake Research Institute, The University of Tokyo

We investigated correlations between fortnightly tides and shallow very low frequency (VLF) earthquakes in Hyuga-nada and off Cape Ashizuri. We focused on three active swarms in 2003, 2010, and 2015, for which strong correlations with semidiurnal tides have been observed (Tanaka et al., 2011, 2015). We detected and located VLF earthquakes by applying a cross correlation technique (Asano et al., 2015) to the seismograms recorded by the F-net broadband seismograph network. For each event, we calculated tidal Coulomb stresses with a friction coefficient of 0.2 (Tanaka et al., 2002), and assigned a fortnightly tidal phase at the time of occurrence from the smoothed stress amplitude envelope (Curchin and Pennington, 1987). For the fault plane, we assumed a landward-dipping reverse fault from a well-determined focal mechanism solution by using the centroid moment method (Ito and Obara, 2006). Based on the distribution of tidal phases, we tested whether they concentrate near some particular angle or not by using the Schuster's test. In this test, the result is evaluated by p-value, which represents the significance level to reject the null hypothesis that the VLF earthquakes occur randomly irrespective of tidal phase angle. As a result of analysis, we observed significantly small p-values for all the three swarms; the p-values for 2003 (N = 423), 2010 (N = 1506), and 2015 (N = 739) swarms are 4E-16, 7E-52, and 7E-15, respectively. The frequency distributions of tidal phases exhibit a peak where the tidal stress amplitude is at its maximum. 65%, 68%, and 69% of the events occurred during the half (50%) of tidal phase range with large stress amplitudes. These results indicate that the occurrence of VLF earthquakes is strongly modulated by fortnightly tidal stress variations and is well correlated with large tidal stresses.

キーワード：浅部超低周波地震、地球潮汐、トリガー作用
Keywords: shallow very low frequency earthquakes, Earth tides, triggering

Small-scale along-dip variations of deep low frequency tremor activity detected in western Shikoku, southwest Japan

*疋田 朗[1]、竹尾 明子[1]、前田 拓人[1]、加藤 愛太郎[1]、松澤 孝紀[2]、小原 一成[1]

*Hikita Akira[1], Akiko Takeo[1], Takuto Maeda[1], Aitaro Kato[1], Takanori Matsuzawa[2], Kazushige Obara[1]

1. 地震研究所/東京大学、2. 防災科学技術研究所
1. Earthquake Research Institute / The University of Tokyo, 2. National Research Institute for Earth Science and Disaster Resilience

It is reported that deep low frequency tremor occurs more episodically at the updip part of the tremor region compared to the downdip part in Shikoku in southwest Japan (Obara et al., 2010, 2011) and Cascadia (Wech and Creager, 2011). In this study, we focused on the updip cluster in western Shikoku analyzed in Obara et al. (2010) in order to investigate tremor activity in a finer scale along the dip direction.

We detected tremor activity by using the matched filter technique (Shelly et al., 2007) in western Shikoku. The continuous waveform data from 2013 to 2015 at 12 Hi-net stations operated by National Research Institute for Earth Science and Disaster Resilience are used after applying band-pass filter of 2 to 8 Hz. As template events, we selected several low frequency earthquakes located within a streak-like tremor cluster along the dip direction of the subducting plate from the catalog of Japan Meteorological Agency (JMA). We used the time window of four seconds from one second before the arrival time of S-wave detected by JMA at each station. We applied two thresholds for detection: 8 and 8.5 times of median absolute deviation for the distribution of correlation sums.

We found stepwise tremor activities at all spots corresponding to episodic tremor and slip (ETS), which recurs at intervals of about half a year in western Shikoku. At the northern (deeper) part, the number of detected events during ETS was smaller, and small tremor bursts were more frequently detected during inter-ETS compared to the southern (shallower) part. This result is consistent with the general trend of tremor activity in wider scale in southwest Japan and Cascadia. For both thresholds, the characteristics of the results are almost the same.

Some tremor episodes were detected only at the up-dip part of the tremor cluster, although individual ETSs are mainly initiated at the deeper part and migrate upwards in western Shikoku (Obara et al., 2011) and Cascadia (Wech and Creager, 2011). This may suggest that some ETSs initiate at the updip part.

キーワード：深部低周波微動、スロー地震、ETS
Keywords: deep low frequency tremor, slow earthquake, ETS

The 1st report of the Network-MT survey in the Western part of Shikoku Island, SW Japan

*上嶋 誠[1]、市原 寛[2]、吉村 令慧[3]、相澤 広記[4]
*Makoto Uyeshima[1], Hiroshi Ichihara[2], Ryokei Yoshimura[3], Koki Aizawa[4]

1. 東京大学地震研究所、2. 神戸大学、3. 京都大学防災研究所、4. 九州大学大学院理学研究院附属地震火山観測研究センター
1. Earthquake Research Institute, The University of Tokyo, 2. Kobe University, 3. Disaster Prevention Research Institute, Kyoto University, 4. Institute of Seismology and Volcanology, Faculty of Science, Kyushu University

In the Bungo channel region at the western margin of the Nankai megathrust rupture zones, the long-term slow slip events (SSE) repeatedly occurred about every 6 or 7 years. They activated deeper episodic tremors and slips (ETS) in the transition zone between locked and steady state slip zones along the sliding zones on the plate interface. The SSE also activated shallow very low frequency earthquakes (VLFE) off the Cape Ashizuri. All of these activities are releasing accumulated stress between the subducting Philippine Sea Plate and the SW Japan without generating a megathrust rapid rupture. Since the last major SSE occurred in 2010, we have not observed the major SSE yet and we will soon have the next one (in 2017 or 2018).

In order to examine mechanism of the SSE and/or concurrent ETS activities, especially to clarify influence of interstitial fluids on occurrence of the events, or to detect movement of the fluids associating with the events, we have started the Network-MT survey in the western part of the Shikoku Island facing the Bungo channel since April, 2016. In the Network-MT method, we use metallic telephone line network of the Nippon Telegraph and Telephone Corp. to measure temporal variation of the electrical potential difference with long baselines of from several kilometers to 10 and several kilometers. We selected 17 areas in the western part of Ehime and Kochi prefectures and installed 3 or 4 electrodes in the respective areas. By using those electrodes and metallic telephone lines, we measure the potential differences in 3 or 4 directions in the respective areas. The electrical potential differences measured in this way are known to be less affected by small scale near-surface lateral resistivity heterogeneities (e.g. Uyeshima, 2007). We also measure geomagnetic field at two stations in the target region. With the aid of the BIRRP code (Chave and Thomson, 2004), we estimated the frequency-domain response functions between each voltage difference and two component horizontal magnetic fields. From these response functions, we can estimate the regional deep resistivity structure. As the first report of this survey, in this presentation, we will show stability of the long-term electric field time series and discuss on the spatial distribution of the Network-MT response functions.

キーワード：南海沈み込み帯、ネットワークMT観測、スロースリップイヴェント、非火山性微動とすべり運動、比抵抗構造探査

Keywords: Nankai Subduction Zone, Nework-MT survey, slow slip event, episodic tremor and slip, resistivity structure prospecting

Large-scale electrical resistivity structure around the long-term Slow Slip Events beneath the Bungo Channel region, southwest Japan

*吉村 令慧[1]、山崎 健一[1]、小川 康雄[2]、中川 潤[1]、川崎 慎吾[1]、小松 信太郎[1]、米田 格[1]、大内 悠平[3]、岡崎 智久[3]、鈴木 惇史[4]、齋藤 全史郎[4]、臼井 嘉哉[4]、寺石 眞弘[1]

*Ryokei Yoshimura[1], Ken'ichi Yamazaki[1], Yasuo Ogawa[2], Jun Nakagawa[1], Shingo Kawasaki[1], Shintaro Komatsu[1], Itaru Yoneda[1], Yuhei Ouchi[3], Tomohisa Okazaki[3], Atsushi Suzuki[4], Zenshiro Saito[4], Yoshiya Usui[4], Masahiro Teraishi[1]

1. 京都大学防災研究所、2. 東京工業大学理学院火山流体研究センター、3. 京都大学大学院理学研究科、4. 東京工業大学理工学研究科
1. Disaster Prevention Research Institute, Kyoto University, 2. Volcanic Fluid Research Center, School of Science, Tokyo Institute of Technology, 3. Graduate school of Science, Kyoto University, 4. Graduate school of Science and Engineering, Tokyo Institute of Technology

Recent geodetic observations detect recurrent slow slip events (SSEs), which occurred beneath the Bungo Channel and southwest Shikoku Island, with interval of approximately 6 years (e.g. GSI, 2010). In order to reveal a large-scale three-dimensional resistivity structure around SSEs region, we carried out wideband magnetotelluric (MT) surveys around the western part of Shikoku Island. We also plan to establish a permanent long-term MT monitoring network that aims to detect temporal changes of resistivity structure during SSE cycle. As of June, 2016, MT surveys were performed at 31 sites by using Phoenix wideband MT instruments. In the most of sites, high quality MT responses were obtained using the BIRRP code (Chave and Thomson, 2004) for the period range 300 Hz to 10,000 sec. The spatial distributions of the phase tensor ellipses and the induction vectors suggest that resistivity contrasts are located surrounding SSEs. In this presentation, we show the results of the data analysis and preliminary inverted three-dimensional model around the transition zone between SSEs and stick-slip regions.

キーワード：スロースリップイベント、豊後水道、比抵抗構造
Keywords: slow slip events, Bungo Channel, resistivity structure
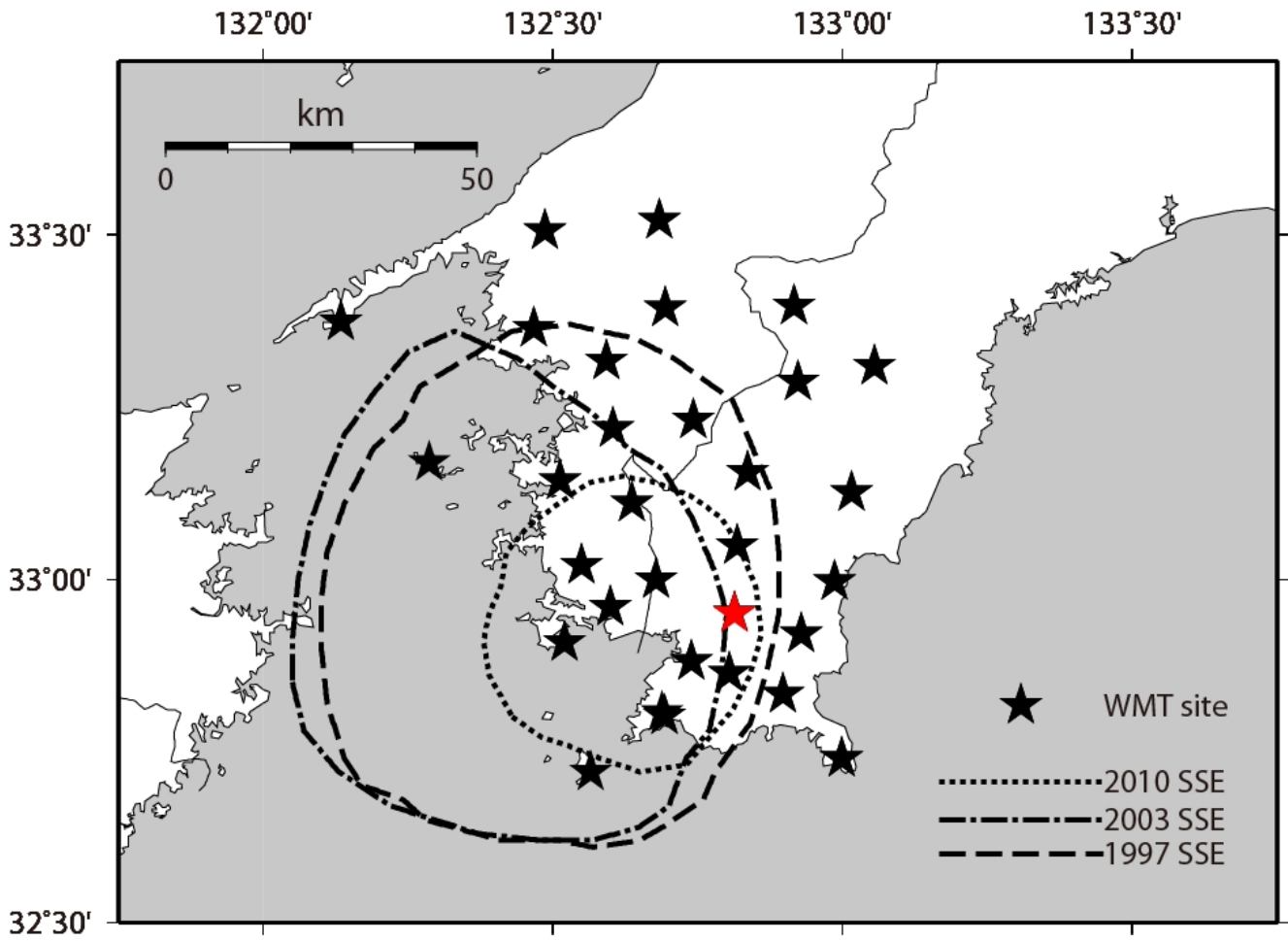
Simultaneous estimation of a long-term and short-term slow slip events in the Bungo Channel region with MCMKF-based inversion

*横井 貴稔[1]、宮崎 真一[1]、坂上 啓[1]、福田 淳一[2]

*Takatoshi Yokoi[1], SHINICHI MIYAZAKI[1], Hiromu Sakaue[1], Jun'ichi Fukuda[2]

1. 京都大学理学研究科、2. 東京大学地震研究所
1. Graduate School of Science, Kyoto University, 2. Earthquake Research Institute, The University of Tokyo

We estimated space-time evolution of slow slip events (SSE) in the Bungo Channel region with the Monte Carlo Mixture Kalman Filter (MCMKF) based Network Inversion Filter [Fukuda et al.,2014]. The Bungo Channel region is well known site where long-term SSEs (duration is about one year) repeatedly occur with the recurrence interval of about 6-7 years. In addition, short-term SSEs (duration is several to ten days) have been reported by analyzing tiltmeter data. In this study, we use GNSS time series of GEONET stations proceeded by GIPSY [Takuya Nishimura, pers. comm.] between Jan. 1, 2009 and Dec. 31,2012 to estimate both long-term SSE and short-term SSEs simultaneously. MCMKF-based inversion has an advantage that the temporal smoothing parameter is temporally variable and chosen to follow the temporal variation of fault slips. In the light of this advantage, we estimated both long-term SSE and short-term SSEs simultaneously.

First we pre-processed GNSS time series; we estimate secular velocities, annual and semi-annual variations, coseismic steps and post-seismic deformation based on the least-square method, and subtract them from the original time series.

We employ the plate configuration by Hirose et al. [2008], and select the area of about 200km long to the east and 280km long to the north as the model region. We subdivide it to 719 subfaults, and represent the slip by a series of 24 depleted basis functions. Finally we performed the MCMKF-based inversion to infer cumulative slips and slip velocities. The estimated cumulative slip distribution is consistent with previous studies [e.g. Yoshioka et al., 2015 for the long-term SSE and Nishimura, 2014 for short-term SSEs].

This study may be the first case where both a long-term SSE and short-term SSEs have been estimated simultaneously from GNSS time series.

疎性モデリングで得られた豊後水道長期的スロースリップイベントのすべり分布
Spatial distribution of long-term slow slip events beneath the Bungo Channel under sparsity constraints

*中田 令子[1]、日野 英逸[2]、桑谷 立[3]、吉岡 祥一[4]、岡田 真人[5]、堀 高峰[1]
*Ryoko Nakata[1], Hideitsu Hino[2], Tatsu Kuwatani[3], Shoichi Yoshioka[4], Masato Okada[5], Takane Hori[1]

1. 海洋研究開発機構地震津波海域観測研究開発センター、2. 筑波大学システム情報系、3. 海洋研究開発機構地球内部物質循環研究分野、4. 神戸大学大学院理学研究科、5. 東京大学大学院新領域創成科学研究科
1. R & D Center for Earthquake and Tsunami, Japan Agency for Marine-Earth Science and Technology, 2. University of Tsukuba, 3. Department of Solid Earth Geochemistry, Japan Agency for Marine-Earth Science and Technology, 4. Kobe University, 5. The University of Tokyo

　豊後水道下の深さ20－40 kmのプレート境界面では、長期的スロースリップイベント（Long-term slow slip event, L-SSE）が繰り返し観測されている。1997年・2003年・2010年に発生した豊後水道L-SSEに関しては、すでにABICを用いたインバージョン解析等が行われており、すべりの中心は3回ともほぼ同じ場所で、すべりの中心から外側へむかって緩やかに変化するすべり域が推定されている[e.g., Yoshioka et al., 2015]。このL-SSE領域の浅部延長上では、過去に1946年南海地震（M8.0）や1968年日向灘地震（M7.5）が発生している。一方深部では、繰り返し間隔・継続期間ともにL-SSEより短いETS（episodic tremor and slip）と呼ばれる異なる時間的特徴を示すスロー地震が起きている。これら一連の現象は全て、フィリピン海プレートの沈み込みに伴って発生すると考えられており、プレート境界面上での地震発生メカニズムを理解するうえで、L-SSEとの位置関係を正確に把握することは非常に重要である。

　本研究では、豊後水道L-SSEのすべり分布をより詳細に調べるため、スパースモデリングの一種であるgeneralized fused lasso（一般化結合正則化）[Tibshirani et al., 2005]を用いる。この数理モデルは、近年、情報科学だけでなく医学や天文学などの自然科学分野でも広く用いられているが、測地データのインバージョン解析に用いた例は報告されていない（はずである）。

　Yoshioka et al. [2015]と同じGEONETデータを用いてインバージョン解析を行ったところ、すべり域内部ですべり量が階段状に変化する不連続な境界があることが明らかになった。また、すべり域の境界も、これまでよりも大きな空間勾配（急な空間変化）であることが示された。なお、この不連続な変化と同等な変化をすべりデータとして同じ観測点配置で解析すると、少し変化の仕方が緩くなること、さらに、なめらかな分布を仮定すれば、なめらかな分布が得られることを確認している。したがって、すべり量の急な変化は、解析手法や観測点分布に起因するものではない。今回得られたL-SSEのすべり分布に見られる境界は、地震発生帯の下限・深部低周波微動の上限および下限の位置とほぼ一致していた。これらは、長期的SSE域の浅部延長上で起きている地震発生帯および深部延長上で発生しているETSに至る、異なる時間的特徴を持った様々な地震発生メカニズムの系統的な理解に役立つ重要な知見となり得る。

Radiation Efficiency of Earthquakes in the Philippine Sea slab

*足立 夢成[1]、中島 淳一[1]、松澤 暢[2]

*Yumenari Adachi[1], Junichi Nakajima[1], Toru Matsuzawa[2]

1. 東京工業大学、2. 東北大学
1. Tokyo Institute of Technology, 2. Tohoku University

Although the Philippine Sea (PHS) slab beneath Kyushu is subducting to a depth of >400 km, earthquakes in Kyushu are limited to a depth of ˜200 km. The termination of intraslab earthquakes may be related to a change in physical or material properties of the PHS slab at a depth of 200 km. This study estimates radiated energy and radiation efficiency of earthquakes occurring in the depth of 60 ˜ 200 km beneath Kyushu, and discusses the depth variation in radiation efficiency.

Precise estimates of the static stress drop and radiated energy are essential to calculate the radiation efficiency. Although the static stress drop depends on the corner frequency and the radiated energy depends on the quality factor, there is a strong trade-off between the corner frequency and quality factor and so it is not easy to determine the two parameters simultaneously. Therefore, in this study, the corner frequency is first estimated by the coda wave spectral ratio method, and the quality factor is then obtained from the shape of amplitude spectra for S waves using the pre-estimated corner frequency.

The obtained results show that the radiation efficiency changes little with depth. The average value of the radiation efficiency in the PHS slab beneath Kyushu is ˜0.1, which is relatively small compared to that observed at the same depth range in the Pacific slab beneath Tohoku and Hokkaido. We infer that the small radiation efficiency in the PHS slab is due to high temperatures of the slab compared to those in the Pacific slab beneath northern Japan.

キーワード：地震波放射効率
Keywords: Radiation Efficiency

Induced Low Frequency Earthquakes Contributed to Teleseismic Events Along the Ryukyu Islands, Okinawa

*金城 亜祐美[1]、中村 衛[1]、門井 洋平[1]
*Ayumi Kinjyo[1], Mamoru Nakamura[1], Youhei Kadoi[1]

1. 琉球大学理学部
1. Fauclty of Science, University of the Ryukyus

Recently, triggered low frequency earthquakes (LFEs) have been observed during the passage of surface waves from teleseismic earthquakes. The occurrence of the triggered LFE depends on the maximum amplitude of surface wave and its propagation direction (Chao et al., 2011). The triggered LFEs are observed around various places in Japan (Chao et al., 2016), but it has not observed in Ryukyu Trench yet. We investigated the LFEs in the Ryukyu arc by the teleseismic earthquake.
First we picked several teleseismic events witch were Mw>7.5 and >1000km away from Naha. By using F-net data from NIED and short-period seismometers by JMA, we bandpass filtered them at the frequency range 2-8 Hz for horizontal components and 0.02-0.05 Hz for horizontal and vertical components, for the waveforms produced of teleseismic earthquake. Then, we detected the triggered LFEs manually comparing low frequency waveforms (for surface waves) with high frequency ones. Then we compared relation between triggered LFEs and surface wave amplitudes, durations, and wave intrusion directions of teleseismic earthquake. Among 56 teleseismic events, we could observe 18-37 LFEs. Also, LFEs were induced when least 0.1 cm/s of maximum amplitudes intruded. The wave propagation direction might not affect on the occurrence of LFEs; however, the durations of surface waves possibly conditioned to induce LFEs.
We determined the triggered LFEs of three teleseismic earthquakes (Sumatra 2004, Nias 2005, and Sumatra 2012) by using the time differences of S-waves arrival times at each station. The time differences were computed using the Envelope Correlation Method (Obara, 2002), and hypocenter locations were determined by grid-search method (Chao et al., 2013). Thus, some clusters of the LFE hypocenters are distributed at the Trench side and Okinawa Trough side. This suggests that the LFEs were triggered in the subducted plate and backarc area including volcanic zone.

キーワード：低周波地震、琉球海溝、誘発地震、地震相互作用
Keywords: Low Frequency Earthquake, Ryukyu Trench, Triggered Earthquake, Earthquake Interaction

An evidence of existence of transition region from slow-slip area to general earthquake area

*石原 靖[1]、山本 揚二朗[1]、高橋 努[1]、新井 隆太[1]
*Yasushi Ishihara[1], Yojiro Yamamoto[1], Tsutomu Takahashi[1], Ryuta Arai[1]

1. 海洋研究開発機構 地震津波海域観測研究開発センター
1. R&D Center for Earthquake and Tsunami, JAMSTEC

Yaeyama Region, Western Ryukyu Islands, is one of tectonically unique regions which have slow-slip, tsunami earthquake and general earthquakes within one are associating with Philippine Sea plate subduction. Repeating slow slips are detected beneath west off Ishigaki island (Heki and Kataoka, 2008) and Nishimura(2014) analyzes detail of slip distribution of each slow slip carefully. Arai et. al.(2016) reported low frequency seismic signals in shallower area by ocean bottom seismic network. By considering with broadband seismic data, these are one of shallow very low frequency earthquakes. Yamamoto et.al.(2016) identified inter-plate general earthquakes using by ocean bottom seismic and islands' telemetered data and located their hypocenters. They suggested that each event of source type locate in different area. It implies that mechanical property around interface of two plates varies in space. Nishimura(2014) and Yamomoto et.al.(2016) shows that Ishigaki island locates just above boundary between slow slip and general earthquake occurrence area. We try to monitor and review broadband seismic data recorded STS-1 sensor (station: ISG) in Ishigaki island. We identified one very low frequency event signal. In short period network in Yaeyama region, short-term tremor-like signals also observed. The feature is same with deep very low frequency earthquake.
By location using envelopes of seismograms, epicenter is determined just below Ishigaki island. Assuming plate shape model proposed by Yamamoto et.al.(2016), constraint analysis shows also that this event just boundary region below Ishigaki island. It supports results of Yamamoto et. al.(2016) and implies existence of transition region of two areas.

キーワード：低周波地震、スロースリップ
Keywords: low frequency earthquake, slow slip

琉球海溝で発生する超低周波地震の潮汐応答にみられる季節変化
Seasonal variation of tidal response of very low frequency earthquakes in the Ryukyu Trench

*中村 衛[1]
*Mamoru Nakamura[1]

1. 琉球大学理学部
1. Faculty of Science, University of the Ryukyus

　琉球海溝でも超低周波地震が発生し、その活動は潮汐応答性を持つことがわかってきた（Nakamura and Kakazu, 2017）。しかし同時に、潮汐応答の大きさは数年単位で変化している。変化をもたらす要因として内的要因と外的要因の2つがある。内的要因としては超低周波地震の発生場所の変化やプレート面での状態（間隙圧変化）の可能性がある。一方、外的要因としては大気圧や海底圧力によって応力変化に敏感な超低周波地震活動が変化する可能性もありうる。そこで潮汐応答が季節変化をするのかを調べ、潮汐応答が大気・海洋の影響で変化しうるのか計算した。

　解析は2002年から2015年までに南西諸島で発生した超低周波地震（M>3.5）である（Nakamura and Sunagawa, 2015; Nakamura and Kakazu, 2017）。沖縄島付近で2か月間に発生した超低周波地震の時系列を2か月ごとにフーリエ変換して振幅を調べた。その結果、Ｍ２分潮の振幅が夏季に小さく(0.3)、冬季に大きく（0.5）なることが分かった。しかし超低周波地震の月ごとの発生数には明瞭な季節変化は見られなかった。奄美大島付近でも同様で、M2分潮の振幅が冬季にはノイズレベルより高いものの夏季には振幅が小さく、ノイズレベル程度であった。

　そこで、M2分潮の振幅を変化させる変動の原因を探るため、①海洋荷重の季節変化と②大気圧荷重の季節変化で説明できるか試みた。まず①について、海洋大循環モデルを用いた海底圧力計算結果（ECCO Ocean Bottom Pressure）を用いた。月ごとの海底圧力分布が１度メッシュで推定されているので、それを補完して0.25度メッシュで使用した。②については過去の月平均気圧（2.5度メッシュ）を用い、30年間の平均気圧分布からの差分を補完して0.25度メッシュにし、島を含む陸上に荷重として与えた。応力の計算にはSPOTL(Agnew, 2012)のプログラムに半無限媒質での点荷重による地下での応力変化計算式を組み込んだ。断層モデルは琉球海溝で沈み込むプレート面を仮定した。深さは15km、走向、傾斜はSlab1.0 (Hayers et al., 2012)を用いた。計算は奄美大島東沖、沖縄島南東沖、八重山南沖で行った。

　計算の結果、奄美大島付近と沖縄島付近では±20Paおよび±15Paのせん断応力の年周変化が生じた。せん断応力は夏季に負の最大、冬季に正の最大となる。せん断応力の位相とM2分潮の最大・最小の時期は一致することが確認できた。しかし奄美大島付近と沖縄島付近では潮汐によるせん断応力の振幅は600Paおよび400Paなので、大気圧・海洋荷重によるせん断応力増加は±3%の応力変化に相当する。これは超低周波地震活動を約±5%変化させる。潮汐応答変化を説明するには応力変化が小さい（約1/3）が、おおよその傾向は再現できることがわかった。

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

Spatio-temporal evolution of recurrent slow slip events from 2010 to 2013 along the Ryukyu Trench, southwestern Japan

*加納 将行[1]、福田 淳一[1]、宮崎 真一[2]、中村 衛[3]
*Masayuki Kano[1], Jun'ichi Fukuda[1], SHINICHI MIYAZAKI[2], Mamoru Nakamura[3]

1. 東京大学地震研究所、2. 京都大学理学研究科、3. 琉球大学理学部
1. Earthquake Research Institute, the University of Tokyo, 2. Graduate School of Science, Kyoto University, 3. Faculty of Science, University of the Ryukyus

Various types of slow earthquakes, including slow slip events (SSEs, Heki and Kataoka, 2008, Nishimura, 2014), very low frequency earthquakes (VLFEs, Ando et al. 2012, Nakamura and Sunagawa, 2015), and low frequency earthquakes (LFEs, Nakamura, submitted), are detected along the southern part of the Ryukyu Trench, Japan. In this area, Global Navigation Satellite System (GNSS) stations have been newly installed since 2010 by Kyoto University in addition to the stations operated by Geospatial Information Authority of Japan. This study applies a modified Network Inversion Filter to these GNSS time series from March 2010 to February 2013, to estimate the spatio-temporal evolution of slow slip on the plate interface in detail. Five SSEs with Mw 6.6–6.8 and durations of 30–100 days are found during this period. The main slip region of the five SSEs are similar, located beneath the northwestern side of the Iriomote island. In contrast to the similarity in the spatial location, our detailed analysis newly clarifies the difference in the temporal evolution among the events; three SSEs suddenly accelerated to the maximum slip rate, and the other two SSEs showed a slow acceleration for 20–50 days. The spatial relationship among the SSEs, LFEs, VLFEs, and tsunamigenic earthquake, is complementary along the trench, depending on the depth; tsunamigenic region in the shallowest part, weakly coupled region of VLFEs and LFEs with depths shallower than 30 km, and SSEs deeper than 30 km, reflecting the depth variation of physical properties. VLFEs are sometimes activated 10–20 days after the onset of SSEs that initiate with slow acceleration phase, although the number of SSEs is too small to assert this correlation. Since new GNSS stations are planning to be established, additional data and further analyses will possibly make the correlation clear in the future.

キーワード：スロースリップ、琉球海溝、時間依存インバージョン
Keywords: slow slip events, Ryukyu Trench, geodetic time-dependent inversion

名蔵ダム貯水池の水面揺動に関する有限要素固有値解析
ー mHz帯域の未知のスローイベント検出に向けて ー
Finite element eigenvalue analysis of seiche in Nagura dam reservoir: physics-based signal identification for slow seismic event detection

*竿本 英貴[1]、名和 一成[1]、木村 武志[2]
*Hidetaka Saomoto[1], Kazunari Nawa[1], Takeshi Kimura[2]

1. 産業技術総合研究所、2. 防災科学技術研究所
1. National Institute of Advanced Industrial Science and Technology, 2. National Research Institute for Earth Science and Disaster Resilience

　沖縄県石垣島に設置されている広帯域地震計(F-net石垣観測点)の観測記録には、11 mHz程度にピーク周波数を持つ振動が頻繁に記録されている。この観測点は名蔵ダムの近くに設置されているため、貯水池の水面揺動に起因していると推察できる。また、貯水池の水位が低くなる期間中では11 mHzのピーク周波数が低周波側にシフトしていることから、水位に依存して変化する貯水池水面揺動の固有周波数が記録されている可能性がある。自由振動の周波数帯域(mHzオーダー)を利用してスロー地震や氷河地震の探索が試みられている(例えば、Beroza & Jordan, 1990; Ekström et al., 2003)現状を考慮すると、名蔵ダム貯水池の水面揺動についての固有周波数を把握しておくことは、未知のスロー地震関連イベントの計測データに対するノイズ除去の観点から有用である。

　今回の発表では貯水池の形状を正確に表現した上で水面揺動に関する固有周波数を有限要素解析によって求め、貯水池の水面揺動の固有周波数が11 mHzとなる条件を探索した。ここで、水面揺動の支配方程式として線形浅水波方程式を仮定しており、固有値問題の求解には汎用工学ソフトウェアCOMSOL Multiphysicsを用いた。水位を様々に変化させた固有値解析の結果、固有周波数が11 mHz となる5つの固有モードを見出した。満水時の貯水池水深が10 m 程度であることを考慮すれば、5つの候補は、(1)水深が9.5 mの場合の第3固有モードと、(2)水深が12.2 mの場合の第2固有モードの2つに絞られる。どちらのモード(あるいは混合されたモード)が現れているのかを解析のみによって決定することはできないが、南北方向に振動が卓越していることを考慮すれば、(2)のモード形状が現れているものと推察できる。いずれにしても、11 mHzにピーク周波数を持つ振動は名蔵ダム貯水池の水面揺動の固有周波数として説明できることがわかった。
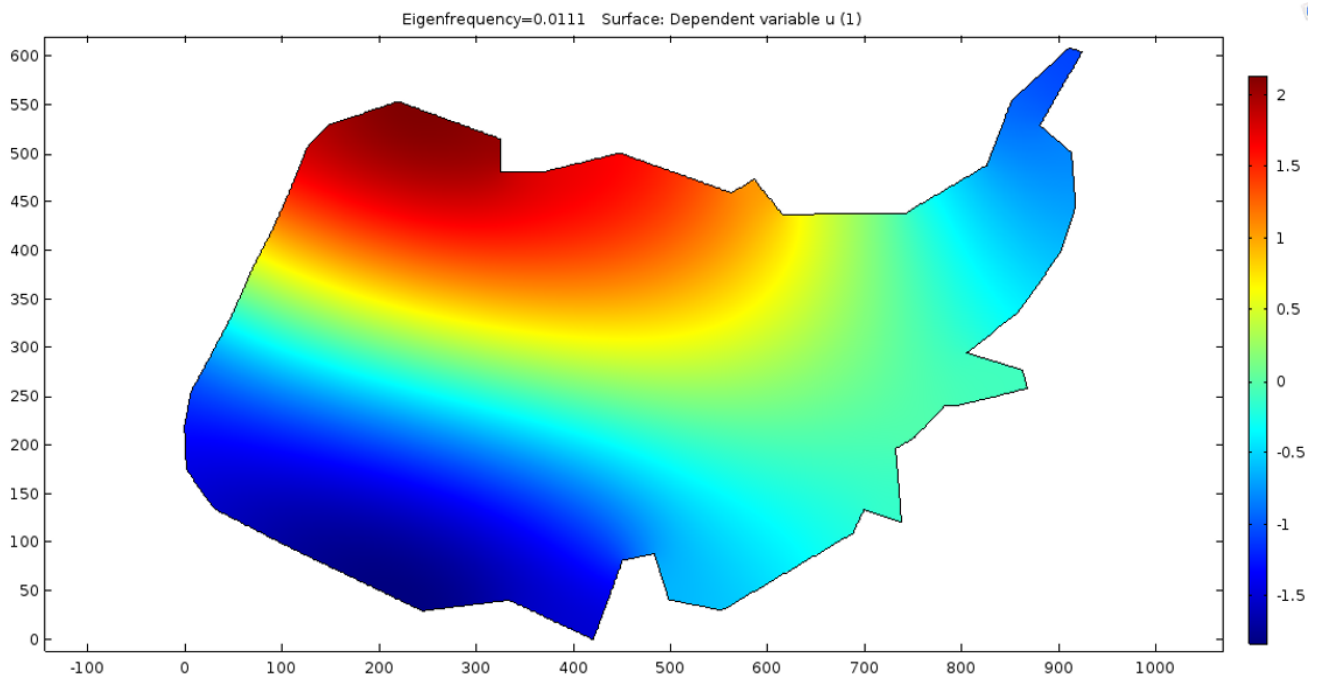
　参考文献:
　Beroza, G.C. and Jordan, T.H.: Searching for Slow and Silent Earthquakes Using Free Oscillations, JOURNAL OF GEOPHYSICAL RESEARCH, 1990.
　Ekström, G., Nettles, M., Abers, G. A.: Glacial Earthquakes, SCIENCE, Vol.302, 2003.

キーワード：振動、セイシュ、固有周波数、有限要素法
Keywords: oscillation, seiche, eigenfrequency, finite element method

Eigenfrequency=0.0111   Surface: Dependent variable u (1)

Sub-slab anisotropy in the western Pacific :
The Izu-Bonin and Mariana regions

*Li-Chen Hsu[1], Cheng-Chien Peng[1], Ban-Yuan Kuo[2], Chin-Wu Chen[1]

1. National Taiwan University, 2. Institute of Earth Sciences, Academia Sinica

Understanding the mechanism of plate subduction helps us put together a whole picture of how the mantle works under plate tectonics. The sub-slab seismic anisotropy serves as a direct tool for illuminating subduction dynamics, implying the flow direction and deformation patterns of subducting slabs.
We measured source-side shear wave splitting with receiver-side correction for the Izu-Bonin and Mariana subduction zones. The initial results show that the deeper slab is associated with larger delay times (dt) in Izu-Bonin region, while delay times of deeper slab in the Mariana are smaller. The fast directions (f) of the two regions seem to be random with respect to the slab contour. However, anisotropy for shallow events in the Izu-Bonin slab is consistent with the relative plate motion. The next step is to consider the radial anisotropy in the receiver-side correction.

The fluid flux and fault rock development along the subduction seismogenic Okitsu Fault, Shimanto accretionary complex, SW Japan

*坂口 有人[1,5]、山口 はるか[2]、高見 良児[3]、金谷 貴正[4]

*Arito Sakaguchi[1,5], Haruka Yamaguchi[2], Ryoji Takami[3], Takamasa Kanaya[4]

1. 山口大学、2. 岡山大学、3. 興和技研株式会社、4. ブラウン大学、5. 海洋研究開発機構
1. Yamaguchi Univ., 2. Okayama Univ., 3. Kowa-giken corporation, 4. Brown Univ., 5. JAMSTEC

The Okitsu Fault is pseudotachylyte bearing ancient seismogenic fault of the Shimanto accretionary complex, SW Japan. This paper discusses the relationship between fluid flux and fault rock development. The structural analysis revealed that the Okitsu Fault develops at the roof thrust of the duplex structure of the Okitsu Mélange. Among the mélange zone, the rock around the Okitsu Fault has suffered high temperature, and the fault zone is characterized by many vein minerals and altered basalt blocks. Hydrothermal activity along the fault zone likely transfer the heat from the deep. The fault rock seems to be developed with fluid flow. The hydro-fracturing, vein mineral precipitation and pressure solution deformations are occurred at thick fault area. This fault thickness may vary with fluid flux. The CO_2 flux along the fault zone is estimated from the alteration grade of the basalt blocks within the fault zone. More than 118 kmol/m^2 of CO_2 fluid flux was obtained in thick fault zone, and it drops in thinner fault zone. Such partial distribution of fluid flux implies that the fluid pathway may have existed at same location historically along the fault. The fluid pathway possibly concern with fault rock asperity.

キーワード：付加体、震源断層、流体
Keywords: accretionary complex, seismogenic fault, fluid

Geological observations supporting a slip model that stress drop varies with characteristic rupture length

*橋本 善孝[1]、大久保 慎人[1]、濱田 洋平[2]
*Yoshitaka Hashimoto[1], Makoto OKUBO[1], Yohei Hamada[2]

1. 高知大学、2. 海洋研究開発機構高知コア研究所
1. Kochi University, 2. JAMSTEC Kochi

There are two slip models for slow earthquakes proposed by Ide et al (2007). One is constant stress drop model in which displacement is proportional to rupture area. This model is common for regular earthquakes. The other is diffusional earthquake model with constant displacement. For slow earthquakes, however, both two models can be adoptable because the average slip amounts of smaller events are unknown.

In this study, two geological observations are introduced to discuss how the observations support the diffusional earthquake model.

One is from a relationship between heat generation rate and slip duration estimated from decreasing pattern of vitrinite reflectance with distance from a micro-fault observed in the Shimanto Belt, an exhumed accretionary complex, SW Japan. The micro-fault has shear zones with thickness of up to 3.7 mm. Magnitude of vitrinite reflectance decays with distance from the fault. The distance which vitrinite reflectance attenuates to background level is about 4-10 cm. On the basis of the decreasing pattern, we estimated 2300-8600 J/m^2/s of heat generation rate and 10000-98000 s of slip duration. The relationship between heat generation rate and slip duration from natural faults follows the scaling relationship for slow earthquakes with -1 of scale exponent.

The other is from roughness analyses on surfaces of natural faults, which shows the Hurst exponent is less than 1 in the relationship between power spectrum density and wave number. An example from the micro-faults in the cores from Taiwan Chelung-pu fault Drilling Project (TCDP). The roughness of surfaces of micro-fault was analyzed by 3D topographic micro-analyzer. The Hurst exponent is about 0.7-0.76. This kind of Hurst exponent has been reported for the natural fault normally ranging on 0.6-0.8. So the result from TCDP case is also consistent with the results from previous studies. Assuming the elastic shear deformation, the Hurst exponent less than 1 indicates that the stress drop is not constant but negatively proportional to fault length.

These two examples support the diffusional earthquake model is suitable for slow earthquakes. The -1 of scale exponent between thermal generation rate and slip duration can be achieved when displacement is constant. The thermal generation rate $Q = \mu' * P_{eff} * D/T$ (μ': effective friction coefficient, P_{eff}: effective vertical stress, D: displacement and T is slip duration) is proportional to T^1, indicating that the D is constant because μ' and P_{eff} can be constant.

The Hurst exponent less than 1 indicates that stress drop is negatively proportional to fault length as described above when elastic frictional shear was assumed. Because stress drop is expressed as $dS = \mu D/L$ (μ: rigidity, L: dimension of fault plane), when D is constant, stress drop is not constant but negatively proportional to L.

In conclusion, these geological observations support the diffusional earthquake model expected in mechanisms for slow earthquakes, which can not be adopt to the regular earthquake.

キーワード：断層岩、スロー地震、スリップモデル
Keywords: fault rocks, slow earthquakes, slip model

九州四万十付加体槇峰メランジュの石英充填剪断脈形成速度とスロー地震発生サイクルの比較検討

Comparison between timescales on formation of quartz-filled shear veins and slow earthquake cycle in the Makimine mélange of the Shimanto accretionary complex, SW Japan

*最首 花恵[1]、氏家 恒太郎[2]、木下 貴裕[2]、大坪 誠[1]
*Hanae Saishu[1], Kohtaro Ujiie[2], Takahiro Kinoshita[2], Makoto Otsubo[1]

1. 産総研、2. 筑波大学
1. AIST, 2. University of Tsukuba

　これまで地球物理学的観測により，スロー地震発生への流体の関与が示唆されている。しかし，その地質学的実態や変形過程は現在もよく分かっていない。深度15 km未満の浅部スロー地震発生域で形成された付加体には，石英で充填された剪断脈が，ある幅（～60 m）で集中して発達している。石英脈形成過程では，石英の析出反応による岩石き裂閉塞が岩石透水率の減少と流体圧の上昇に寄与し，スロー地震の発生に影響を及ぼしている可能性がある。しかし，石英脈形成速度とスロー地震発生周期の定量的な関係は分かっていない。本研究では，九州東部四万十付加体上部白亜系槇峰メランジュ中に発達する石英充填剪断脈の形成速度を計算し，石英脈形成速度とスロー地震発生の時間スケールを比較する。

キーワード：石英充填剪断脈、反応速度、き裂閉塞時間、スロー地震発生周期
Keywords: Quartz-filled shear vein, Kinetics, Sealing time of crack, slow earthquake cycle

前弧マントルコーナーにおける流体移動、流体岩石相互作用、スロー地震
Fluid flow, fluid-rock interaction and slow earthquakes at the forearc mantle corner

*森 康[1]、重野 未来[1]、西山 忠男[2]
*Yasushi Mori[1], Miki Shigeno[1], Tadao Nishiyama[2]

1. 北九州市立自然史・歴史博物館、2. 熊本大学
1. Kitakyushu Museum of Natural History and Human History, 2. Kumamoto University

The forearc mantle corner in subduction zones is a site of deep slow earthquakes such as low-frequency tremors, very low frequency earthquakes and short-term slow slip events. Geophysical observations suggest that these seismic activities are related to updip fluid flow along the slab-mantle interface and quartz deposition in the crust above the mantle corner (*e.g.*, Audet & Bürgmann, 2014, *Nature*, 510, 389–392; Hyndman *et al.*, 2015, *J. Geophys. Res. Solid Earth*, 120, 4344–4358). The geological evidence for the fluid flow has been reported from many subduction-zone mélanges (Bebout & Penniston-Dorland, 2016, *Lithos*, 240–243, 228–258, and references therein).

The question is, how the updip fluid flow is formed and maintained at the slab-mantle interface? Fractures probably play an important role of fluid pathways, but the life span of individual fractures could be short for the rapid sealing by vein minerals. We propose that fluid-rock interaction in subduction-zone mélange would sustain the fluid flow if reaction-enhanced permeability takes place.

We present an example of fluid-rock interaction and reaction-enhanced permeability in subduction-zone mélanges. The Nagasaki metamorphic rocks in Kyushu, Japan, consist mainly of Late Cretaceous schists and contain serpentinite mélanges. The metamorphic pressure and temperature are close to those of the forearc mantle corner (˜0.8 GPa and ˜440 $^{\circ}$C). The serpentinite typically occurs as mélanges, in which metapelitic tectonic blocks have been albitized along the rims and cracks. The albitization is considered to be the result of fluid-rock interaction. The isocon analysis indicates that the albitization involves a loss of rock volume and extraction of silica from the blocks. The volume loss increases along with the reaction progress of the albitization.

Albitization is commonly found in the subduction-zone mélanges of the blueschist to eclogite facies. This suggests that reaction-enhanced permeability widely takes place at the slab-mantle interface. As a result, the subduction-zone mélanges probably become porous media, which act as sustainable channels of the updip flow of fluids (and silica) towards the site of deep slow earthquakes.

キーワード：曹長岩化作用、反応促進型透水性、沈み込み帯メランジュ、スロー地震
Keywords: Albitization, Reaction-enhanced permeability, subduction-zone mélange, Slow earthquakes

Preliminary results of interstitial water geochemistry from IODP Expedition 362: Subduction inputs to the Sumatra subduction zone

*尾張 聡子[1,2]、Marta Torres[7]、Andre Hüepers[6]、Lisa McNeill[3]、Brandon Dugan[4]、Katerina Petronotis[5]、IODP Expedition 362 scientists
*Satoko Owari[1,2], Marta Torres[7], Andre Hüpers[6], Lisa McNeill[3], Brandon Dugan[4], Katerina Petronotis[5], IODP Expedition 362 scientists

1. 千葉大学大学院理学研究科、2. 日本学術振興会特別研究員、3. National Oceanography Centre Southampton University of Southampton、4. Department of Geophysics Colorado School of Mines、5. International Ocean Discovery Program Texas A&M University、6. MARUM University of Bremen、7. College of Earth, Ocean and Atmospheric Sciences Oregon State University
1. Chiba university, 2. JSPS Research Fellow, 3. National Oceanography Centre Southampton University of Southampton, 4. Department of Geophysics Colorado School of Mines, 5. International Ocean Discovery Program Texas A&M University, 6. MARUM University of Bremen, 7. College of Earth, Ocean and Atmospheric Sciences Oregon State University

The Mw 9.2 Sumatra earthquake in 2004 resulted in unexpectedly shallow megathrust slip, which amplified the earthquake magnitude and caused a devastating tsunami. At two sites (Sites U1480 and U1481) International Ocean Discovery Program (IODP) Expedition 362 cored the input sediment with R/V JOIDES Resolution ~250 km seaward of the Sumatra subduction zone to groundtruth the material properties that contributed to the unexpectedly shallow seismogenic slip and a distinctive forearc prism structure of the North Sumatra subduction zone. The recovered sediment comprise a Late Cretaceous to Miocene abyssal-plain environment facies consisting of mixed tuffaceous and pelagic sediments and a series of intercalated pelagic and igneous materials, which is overlain by a thick sequence of siliciclastic sediments (mostly siliciclastic mud, siliciclastic sand and calcareous mud) of the Nicobar fan. Here we present preliminary results from shipboard geochemical analyses of interstitial waters.
The sulfate-methane transition zone (SMTZ) exists at 120 mbsf. Concentrations of ammonium and phosphate have positive peaks above the SMTZ, which reflect the remineralization of organic matter. Low alkalinity and calcium concentration below the SMTZ indicate carbonate precipitation. Release of silica and cations (K^+, Ca^{2+}, Na^+, Al^{3+}) to the interstitial water are indicative of volcaniclastic ash alteration in the upper 20 mbsf. A subsequent depletion of potassium below 400 mbsf to values as low as 1 mM suggest zeolite formation, consistent with observations in the recovered sediment. The high sulfate concentration of 15 mM in pelagic sediment at 1403 mbsf may reflect a presence of sulfate-rich fluid in the basement aquifer. Ongoing post-expedition analyses of interstitial water geochemistry will provide additional insights into fluid-rock interactions and fluid flow processes which will shed light on the evolving properties of the sediment incoming to the North Sumatra subduction zone.

Temporal Variation of Interplate Coupling in Java Subduction Zone Based on 2008-2012 GPS Observations

*Henri Kuncoro[1], Satoshi Miura[1], Irwan Meilano[2], Susilo Susilo[3]

1. Graduate School of Science, Tohoku University, 2. Geodesy Research Division, Institute Technology of Bandung, 3. Geospatial Information Agency of Indonesia

In the southern Java, the Australian plate subducts beneath Sunda Block at almost perpendicular direction on the western part of Java trench and more oblique along the rest of Java trench. There have been several earthquakes, the 2009 West Java (M7.0), the 2010 West Java (M5.9), the 2011 East Java (M5.7) and the 2011 Bali (M6.1) that occurred as a result of interplate coupling along the Java subduction zone. Since they caused coseismic offsets in the coordinate time series at several GPS sites near the epicenter, we divided them into some specific time periods and estimated the temporal variations of the slip deficit rates along Java subduction zone. We carry out the geodetic inversion analyses of the GPS site velocities from 2008 to 2012 located in Java, Bali, Madura, and Lombok (54 national network sites) and 10 IGS stations, together with the azimuth of slip vector from some earthquakes in Java subduction zone using TDEFNODE software (McCaffrey, 2009). We use the Euler pole parameter from previous result (Longitude: 86.876ºW, Latitude: 48.917ºN, and Angular velocity: -0.330º/Myr) in the inversion. We do several checkerboard tests to examine how well the artificial distributions of coupling ratio with 100% and 0% slip deficits can be restored. The results show that TDEFNODE can recover well the most part of fault surfaces in Java subduction zone except for the plate boundary near the trench.

The locking map before and after the 2009 West Java earthquake demonstrates the low coupling rate of ˜30 mm/yr and ˜10 mm/yr, respectively, near the hypocenter. The inversion result before the 2010 West Java earthquake cannot detect the significant coupling rate near the hypocenter because the lack of the data but after that earthquake the coupling rate became ˜10 mm/yr. The locking map before and after the 2011 East Java earthquake and the 2011 Bali earthquake show the unrealistic result since low ability to resolve the coupling rate in the easternmost of Java Subduction zone. Overall the inversion of the GPS data before the 2012 Sumatra earthquake shows the low coupling rate of ˜30 mm/yr in the western part, the coupling rate of ˜40 mm/yr in the middle part, and the very high rate of ˜70 mm/yr in the eastern part.

References:
McCaffrey, R. (2009), "Time-dependent inversion of three-component continuous GPS for steady and transient sources in northern Cascadia", Geophysical Research Letters, 36, L07304, doi:10.1029/2008GL036784

Keywords: Temporal variation, Java Subduction, Interplate Coupling

プレート沈み込み帯に持ち込まれる生物起源堆積物の摩擦強化に関連した剪断の局所化
Shear localization related to frictional strengthening of the biogenic sediments entering subduction zone

*並木 由香[1]、堤 昭人[1]
*Yuka Namiki[1], Akito Tsutsumi[1]

1. 京都大学大学院理学研究科
1. Graduate School of Science, Kyoto University

In subduction zones, various seismic activities such as large earthquakes, episodic slow slip events, or silent earthquakes are observed. This variation likely reflects spatial variations in frictional properties along the seismogenic portion of plate-boundary megathrusts (e.g., Bilek and Lay, 1998). The frictional properties of materials entering subduction zones are probably different among various materials. Hence, the frictional properties of main oceanic sediments should be revealed.

A number of studies revealed frictional properties of clay sediments collected from the Nankai Trough (e.g., Brown, 2003). However, studies on the frictional properties of biogenic sediments are limited (e.g., Ikari et al., 2013; Namiki et al., 2014). In this study, we investigated the frictional properties of the biogenic sediments, and performed a series of friction experiments on silicic to calcareous ooze. To understand what controls the mechanism, we observed the shear structure in the samples by SEM. The samples tested in this study were collected offshore Costa Rica (Site U1381) during IODP expedition 334 and 344.

Frictional properties of the silicic to calcareous ooze were different from those of the clay sediments (Namiki et al. 2014). The friction coefficient of the ooze at a constant slip velocity of 0.28 mm/s showed an initial peak at 0.4 to 0.6 and subsequent minor decrease, followed by a gradual increase to attain a constant friction value at 0.6 to 0.8.

For friction experiments a rotary-shear friction-testing machine was used with various slip rates according to the radius of the shear area. The slip rate at the center is zero, and the slip rate on the outside is the fastest. In cross-sections near the outside of shear areas, two types of shear structures were observed: (1) shear localized zone (about 50 to 100 μm thick) mainly composed of fine rounded particles which forms parallel to the shear zone and (2) shear distributed zone, in which the silicic and calcareous shells show preferred orientation inclined to the shear zone at an angle within a range of about 30 degrees. Both of the structures were observed in samples, which have slipped until 0.4 rotations or more. A shear distributed zone could only be observed in samples slipped within 0.02 rotations. The particles in the shear localized zone decreased in grain size with larger displacement.

In cross-sections through the center of shear areas, a preferred orientation of particles in the shear distributed could not be observed as the analyzed cross-sections are vertical to the slip direction. The shear localized zone was observed only in the outer region of samples, which have slipped until 0.4 rotations. For samples slipped until 3.3 rotations, the shear localized zone could also be observed in the inner region.

From these results, displacement is a significant factor to develop shear localization. The observation of cross-sections through the center of shear areas suggests that duration of slip and slip rate seldom affect shear localization. The shear localized zone has formed while the friction coefficient attained a steady-state value after strengthening. The shear localized zone and preferred orientation in the shear distributed zone might correspond to Y-shear and P-shear of Riedel shear, respectively. Thus, Y-shear

likely develops with frictional strengthening, and continues to develop during a period while the friction coefficient maintains steady-state value.

キーワード：摩擦実験、剪断組織、珪質・石灰質軟泥、CRISP
Keywords: frictional experiment, shear structure, silicic to calcareous ooze, CRISP

Investigation of friction velocity dependence under the change of pore fluid pressure

*比嘉 咲希[1]、並木 由香[1]、堤 昭人[1]

*Saki Higa[1], Yuka Namiki[1], Akito Tsutsumi[1]

1. 京都大学大学院理学研究科
1. Graduate School of Science, Kyoto University

Pore fluid pressure plays an important role in controlling the mode of fault slip, and friction parameter and fault stability change with pore fluid pressure (Scuderi and Collettini 2016). But, there have been only a few experimental studies focused on role of pore fluid pressure. Scuderi and Collettini (2016) conducted experiments on marble gouge and limestone gouge under pore fluid pressure condition. These experiments revealed significant effect of pore pressure on critical slip distance Dc and the friction velocity parameter (a-b). In this study, we conducted friction experiment on silicic to calcareous ooze under the change of pore fluid pressure continuously, and investigated rate-dependence of steady-state friction.

We conducted friction experiment using a rotary-shear intermediate- to high-velocity friction-testing machine. Samples were sediment on the Cocos plate offshore Peninsula, at U1381, during IODP Exp.334. The samples were dried at 60 ˚C and disaggregated gently using pestle. Sample was placed between a simple gabbro cylinder and cylindrical sandstone mounted on a gabbro cylinder. Pore pressure was controlled by a syringe pump. At the start of experiment, normal stress was 6 MPa, pore fluid pressure was 1 MPa. We raised pore fluid pressure from 1 MPa to 5 MPa continuously after friction coefficient attained a roughly steady-state. The additional shear stresses from PTFE O-rings in experiments were calibrated. In this experiment, slip rate was 0.003-0.028 mm/s, displacement was 0.6 m.

As a result, the frictional velocity dependence was negative when pore pressure was from 1 MPa to 2 MPa. But when pore pressure was from 4 MPa to 5 MPa, the frictional velocity dependence was positive. Namiki et al 2014 conducted friction experiment under the drain condition using same sample, and show that friction velocity dependence was negative through experiment. Our results may suggest that friction velocity dependence change with pore fluid pressure.

キーワード：間隙水圧、摩擦、沈み込み帯
Keywords: Pore fluid pressure, friction, subduction zone

水和した粘土鉱物の摩擦特性の解析と津波地震への応用
Frictional properties of hydrated clay minerals and its application to tsunami earthquakes

*野田 雄太[1]、片山 郁夫[1]
*Yuta Noda[1], Ikuo Katayama[1]

1. 広島大学大学院理学研究科地球惑星システム学専攻
1. Department of Earth and Planetary Systems Science, Hiroshima University

　　［はじめに］
　津波地震とは、地震動から予測される津波に比べ大きな津波を発生させる地震であり、その発生原因には、ゆっくりとした断層のすべりが関係していると考えられている。津波地震は沈み込み帯の浅い領域で発生しており、そのプレート境界には粘土鉱物が多く存在していることから、津波地震の発生メカニズムを考える上では粘土鉱物の摩擦が重要となる。Seno (2002) は、間隙水圧によって沈み込み帯浅部の有効垂直応力が減少することで粘土鉱物が不安定なすべり挙動を示すため地震のすべりが浅部まで伝播すると考えた。しかし、Saffer and Marone (2003) などの先行研究では、水のない状態での粘土鉱物の摩擦特性を報告しており、水和した粘土鉱物の摩擦特性についてはよくわかっていない。そこで、本研究では、水に飽和した環境で粘土鉱物の速度急変による摩擦試験を行い、粘土鉱物の摩擦特性が水和状態によってどのように変化するか調べた。また、そのデータを基に津波地震が発生するために必要な沈み込み帯の条件について考察した。

　　［実験手法］
　本研究では、断層ガウジ試料として異なる陽イオンをもつスメクタイト（NaモンモリロナイトとCaベントナイト、サポナイト）を用いて摩擦実験を行った。乾燥条件の試料は、24時間真空炉で乾燥させたものを用いて実験を行い、水和条件では水槽内で摩擦実験を行った。垂直応力は10, 20, 40, 60MPa、すべり速度は0.3, 3, 33μm/sに設定し速度急変による摩擦試験を行い、摩擦の速度依存性を解析した。速度依存性は、速度の増加に伴い摩擦係数が上昇するものを速度強化、反対に速度の増加に伴い摩擦係数が低下するものを速度弱化とし、速度ごとの定常摩擦の違いから決定した。

　　［結果と考察］
　実験結果から粘土鉱物の摩擦係数は、乾燥条件と水和条件とで大きな差があり、摩擦特性にも大きな影響を与えることが分かった。乾燥条件では、Naモンモリロナイトとサポナイトは常に速度強化を示すのに対し、Caベントナイトは低垂直応力下（≦40MPa）で速度弱化、高垂直応力になるにつれ速度強化を示す傾向がみられた。水和条件では、いずれの試料においても低垂直応力下（≦20MPa）では速度依存性が小さく、ほぼニュートラルな摩擦特性を示し、高垂直応力では速度強化を示した。

　沈み込み帯において、間隙水圧の下で粘土鉱物が存在すると、摩擦の速度依存性はニュートラルに近い性質をもつことが期待される。そのように、沈み込み帯の浅い領域がニュートラルな摩擦特性であれば、深部でのアスペリティ破壊によって浅部でのすべりが誘発されるため津波を伴う地震が発生すると予想される。また、速度弱化の挙動ほどすべりが加速されないため、ゆっくりとした断層のすべりとなると考えられる。このように、水が存在する環境下での粘土鉱物の摩擦特性は津波地震の特徴と調和的である。

キーワード：津波地震、沈み込み帯、粘土鉱物
Keywords: tsunami earthquakes, subduction zone, clay minerals

スロー地震の移動速度と摩擦特性との関係
Characteristics of frictional properties' relationship with slow earthquake migration speed

*有吉 慶介[1]、松澤 暢[2]、ローランド バーグマン[3]、長谷川 昭[2]、日野 亮太[2]、堀 高峰[1]
*Keisuke Ariyoshi[1], Toru Matsuzawa[2], Roland Burgmann[3], Akira Hasegawa[2], Ryota Hino[2], Takane Hori[1]

1. 国立研究開発法人海洋研究開発機構、2. 東北大学大学院理学研究科附属 地震・噴火予知研究観測センター、3. カリフォルニア大学バークレー校
1. Japan Agency for Marine-Earth Science and Technology, 2. Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, 3. 3Department of Earth and Planetary Science and Berkeley Seismological Laboratory, University of California, Berkeley

　大規模なプレート境界型地震が発生すると，それに伴って周囲に伝播する余効すべりによって，余震を誘発することが知られている．そのため，伝播速度をはじめとする余効すべりの物理現象を理解することは，災害リスクを事前評価する上でも重要な課題となっている．

　プレート境界面で発生する余効すべりの伝播速度について，室内岩石実験から推定された速度・状態依存摩擦構成則に基づいたパラメターを使って数値シミュレーションから再現できることが知られている．そこで，観測と合うように数値モデルのパラメターチューニングをすることにより，実際の場の摩擦特性を推定する研究が行われてきた．本研究ではこれをさらに発展させ，余効すべりの伝播速度について摩擦パラメター値と有効法線応力などから構成される関数として表現できるよう，理論的な解析解を導出した．この際，余効すべり伝播に伴う応力擾乱の時間変化については，ramp, linear, step 関数の３つの場合を想定した．

　その結果，すべり速度が8桁も変わる範囲の中で，解析解と数値シミュレーション結果で伝播速度を比べたところ，応力擾乱関数によらず，オーダーレベルで説明できることを確認した．このことは，解析解の妥当性が十分高いことを意味する．本導出においては，余効すべりに限らず，スロー地震の移動現象などにも適用できるため，観測された伝播速度から摩擦特性の条件を絞り込むことが出来る解析手法として期待される．

キーワード：余効すべり、速度状態依存摩擦構成則、応力擾乱
Keywords: afterslip, rate- and state-dependent friction law, stress perturbation

EnKFによる長期的SSE断層面での摩擦特性とすべり発展の推定　-数値実験-

Estimation of frictional properties and slip evolution on the Long-term SSE fault with Ensemble Kalman Filter -numerical experiments-

*錦織 健人[1]、平原 和朗[1]
*Kento Nishikiori[1], Kazuro Hirahara[1]

1. 京都大学大学院理学研究科地球惑星科学専攻地球物理学教室
1. Department of Geophysics, Earth and Planetary Sciences, Graduate School of Sciences, Kyoto University

　長期的スロースリップイベント（LSSE）は、海溝型大地震発生域深部のプレート境界深部に発生しており、プレート境界における応力解放過程であり、海溝型大地震の発生の予測やあるいは直接的なトリガーにも成り得る。したがって、LSSE発生域の摩擦特性を知りそのすべりの発展を予測するのは重要な課題といえる。本研究の最終目標はGNSSで得られたSSE発生時の地表の変位データにデータ同化の一手法であるアンサンブルカルマンフィルタ(EnKF)を適用し、SSE発生域でのすべり発展と摩擦パラメータを推定して海溝型巨大地震の発生予測に役立てることである。本研究では、豊後水道で発生するLSSEを想定し、単純なモデルではあるが、シミュレーション計算で得られたすべり速度、地表の変位速度に観測誤差を加え模擬データとしてEnKFを用いた数値実験を行い、これまで行ってきた八重山地域における場合と比較して、その適用可能性を議論した。

　これまで、八重山地域のSSE(再来間隔: 6ヶ月、継続時間: 1ヶ月)を対象に数値実験を行ってきた。均質半無限弾性体中に設定した平面傾斜断層面での摩擦力は速度状態依存摩擦則に従うとし、状態変数の時間発展にはSlowness則を用いた。断層面に半径30kmの円形速度弱化(A-B<0)パッチを設定し、R/Rc=0.4　（Rc:臨界半径、R:パッチ半径）となるように摩擦パラメータを調整し、八重山地域のSSEを再現するモデルを構成した。このモデルから得たすべり速度、地表の変位速度に観測誤差を加えたものを模擬データとし、断層面での摩擦パラメータA、Lおよびアスペリティ内のB-Aをすべり速度、状態変数とともにEnKFで推定した。同化ステップ幅はSSE発生時は0.5日、それ以外の期間では5日とした。

　この手法では観測値の時間変化が大きくなる際に、イノヴェーション(観測と予報の残差)が大きくなり更新量が大きくなるため、特にSSE発生時に推定値は大きく更新され真値に近づく様子が見られた。しかし、精度の良い推定をするには一回ではなく複数回のSSEを含む観測データが必要であることがわかった。

　一方、SSE時に予報値が大きく更新されるために、計算が停止するという問題がしばしば発生した。これはEnKFの推定能力の有無とは本質的に異なる問題であって、たとえば観測点分布の推定能力への依存性の検証を行う際には厄介である。本問題はSSE時の観測値の時間変化が急であることに起因する問題であり、より時間スケールの大きなSSEの同化においては回避できるのではないかと考えた。

　また、観測点分布が悪い（時間間隔が長い、密度が低い、偏った分布など）ほど、推定値の真値への近づき方は遅くなることが分かった。従って、海域という地理的制約から観測点分布を充実させるのが難しい八重山SSEは、同化の対象として適さないと考えられる。

　以上のことをふまえ本手法が適用可能なSSE発生域の条件は：1)これまでに複数回観測されている、2)SSEの継続時間が長い、3)観測点分布に恵まれている、であると考えた。そこで本研究では、豊後水道を対象とし、LSSE(再来間隔: 7年、継続時間: 1年)を再現するような単純なモデル(パッチ半径は40km、R/Rc=0.9)を構成して八重山SSEの場合と同様の数値実験を行った。同化ステップ幅はSSE発生時は1日、それ以外の期間では5日とした。

　その結果、期待通り同化ステップに比してイベントの継続時間が十分に長ければ、同化による更新は緩やかに行われ計算が停止しにくいことがわかった。また、本研究でのごく単純なモデルを仮定する限りでは、模擬観測点分布として現実のGNSS観測点分布を用いてもかなり精度よく摩擦パラメータを推定することができた。

　現在はSSEパッチ内では摩擦パラメータは一様としているが、今後は、より複雑なモデルを設定して推定するパラメータを増やしたときの本手法の適用可能性を探る数値実験を行う必要がある。

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 Events

3D fluid migration due to complex slab geometries and its implications for short-term slow slip events

*森重 学[1]、van Keken Peter[2]
*Manabu Morishige[1], Peter van Keken[2]

1. 京都大学大学院理学研究科附属地球熱学研究施設、2. カーネギー研究所
1. Institute for Geothermal Sciences, Graduate School of Science, Kyoto University, 2. Department of Terrestrial Magnetism, Carnegie Institution for Science

In Cascadia and Nankai where relatively dense seismic and geodetic networks are available, short-term slow slip events (SSEs) generally occur at ~30-40 km depth along the subducting plate interface near the continental Moho of the overriding plate. This location roughly corresponds to the down-dip limit of large underthrusting earthquakes where the transition from stick-slip to stable sliding is thought to occur. An important characteristic of short-term SSEs is their spatial variation in activity. The average slip rate tends to be large where the slab geometry is convex (i.e., the slab bends toward the mainland) and it tends to be small where the slab geometry is concave (i.e., the slab bends away from the mainland). Considering that fluids play an important role in generating short-term SSEs, it may reflect the along-arc variation in fluid flux due to complex slab geometries. In this presentation we will demonstrate how fluids migrate in subduction zones by taking into account the effects of 3D slab geometries.

We construct 3D finite element models based on a theory of two-phase flow, which allows us to consider the movement of matrix and fluid phases at the same time. The location of fluid source is determined based on the computed slab surface temperature. Fluids are assumed to migrate in a thin serpentinite layer just above the slab in the direction sub-parallel to the slab surface by the effects of permeability anisotropy in the serpentinite.

We find that fluids migrate in the maximum-dip direction of the slab by the combined effects of permeability anisotropy and 3D slab geometry. It leads to the concentration of fluid paths where the slab geometry is convex and porosity increases there. Fluid paths diverge and porosity decreases where the slab geometry is concave. These results suggest that the along-arc variation in short-term SSEs can be explained by 3D fluid focusing possibly through changing pore-fluid pressure and/or formation of wet clay minerals.

九州南部の非火山地域における2次元熱対流モデリング
2-D thermal modeling along a non-volcanic region in southern Kyushu, Japan

*末永 伸明[1]、吉岡 祥一[1,2]、松本 拓己[3]
*NOBUAKI SUENAGA[1], Shoichi Yoshioka[1,2], Takumi Matsumoto[3]

1. 神戸大学都市安全研究センター、2. 神戸大学大学院理学研究科惑星学科、3. 防災科学技術研究所
1. Research Center for Urban Safety and Security, Kobe University, 2. Department of Planetology, Graduate School of Science, Kobe University, 3. National Research Institute for Earth Science and Disaster Resilience

　九州において阿蘇火山帯と霧島火山帯の間には非火山地域が存在しており、この地域では宮崎県の太平洋沿岸付近の直下で深部低周波微動が発生していることが知られている。また、日向灘では1996年10月19日と12月3日にそれぞれM6.6のプレート境界地震が発生したが、それに伴う余効すべりが見出されている。これらのプレート境界付近での地震イベントと、プレート境界付近及びマントルウェッジでの温度構造やフィリピン海プレートからの脱水過程との間の関連性を調べるため、2次元箱型時間依存熱対流モデルを用いて、九州の非火山地域及びこれらの地震イベントの発生域を通る測線に沿った温度構造シミュレーションを行った。得られた温度構造の妥当性は、地殻熱流量の観測データと計算値を比較することで行った。本研究で用いたモデルではフィリピン海プレートの沈み込み史を考慮し、タイムステップ毎にトラフ軸から沈み込むフィリピン海プレートの海底年代及び沈み込み速度を変更したが、約4.5Ma頃に九州-パラオ海嶺が上記測線を通過しており、海底年代の不連続による温度構造への影響が見られた。また、マントルウェッジ付近で観測された低地殻熱流量を説明するため、フィリピン海プレート上面に低粘性層を設定し、低粘性層の粘性率、厚さ、低粘性層の下限の深さを未知パラメーターとしてグリッドサーチを行い、地殻熱流量の観測値を最もよく説明する温度構造を求めた。これらのパラメーターのうち、低粘性層の厚さが地殻熱流量への影響が最も大きく、粘性率の影響が最も小さかった。その結果、1996年日向灘地震に伴う余効滑りが4.0cm/yr以上となるプレート境界面での温度は約300℃、太平洋沿岸付近の深部低周波微動発生地域直下でのプレート境界面の温度は約400-500℃となった。また、得られた温度構造と海洋地殻のMORBの相図を用いてフィリピン海プレートからの含水量分布を計算した。その結果、余効滑り領域付近ではblueshistからlawsonite blueshistへの相転移がみられ、深部低周波微動発生領域付近ではlawsonite blueshistからlawsonite eclogiteへの相転移がみられた。

三次元数値シミュレーションによるカスかディア沈み込み帯における ファンデフカプレートの温度構造とスラブ脱水について

Thermal regime and slab dehydration in the subducted Juan de Fuca plate beneath the Cascadia subduction zone based on 3D numerical simulation

*季 頴鋒[1]、吉岡 祥一[1]
*Yingfeng Ji[1], Shoichi Yoshioka[1]

1. 神戸大学都市安全研究センター
1. Research Center for Urban Safety and Security, Kobe University

Giant earthquakes are considered to have occurred historically and may take place in a near future in the Cascadia subduction zone. In contrast to the cold and thick Pacific (PAC) plate subducted beneath the northeast Japan characterized by numerous interplate earthquakes and comparatively fewer slow earthquakes, the warm and hot Juan de Fuca (JF) plate subducted beneath the North American plate witnesses much more episodic occurrences of tectonic tremors and slow slip events, accompanying less regular earthquakes. This has enabled us to compare and understand the different generation mechanisms between regular and slow earthquakes. Possible candidates to interpret such differences may attribute to slab brittle failure largely determined by different slab thermal regime, while pore fluid pressure variation in the fractures greatly affected by slab metamorphism. We constructed a 3D time-dependent thermal convection model with a size of 1150×700×400 km along the Cascadia Trench, initiating subduction in the northeast direction with calculation time up to 15 Myr. The geometry of the JF plate has been prescribed, being based on the extrapolated data of Slab1.0. Results show a distinct 3D slab dehydration belt and temperature transition zone along the clustered hypocenters of episodic tremors immediately beneath Vancouver Island in the northern part and almost 100 km east of coast of Washington and Oregon in the southern part with temperatures of 500-700℃. Water content in MORB decreased from 2 wt% to 0 wt%. Interestingly, megathrust earthquakes occurred mostly near the triple plate junctions, such as the JF-NA-Explorer and PAC-NA-Gorda plate junctions, and beneath Washington where slab convex portion exists. Regular earthquakes are fewer observed beneath Oregon. The interplate temperatures of the JF plate are averagely 200-400℃ higher than those of the PAC plate beneath Japan at the same depth range (<100 km) with less amount of calculated slab dehydration ratio.

キーワード：熱構造、脱水、モデル
Keywords: thermal regime, dehydration, model

Target oriented seismic tomography: Toward higher-resolution images of subduction zones

*Ping Tong[1]

1. Nanyang Technological University

From the classic ray-based traveltime tomography to the state-of-the-art full waveform inversion, because of the ill-posedness of the inverse problem, regularization techniques are always used to get stable but approximated solutions. If the data sampling or the starting model is not good enough, regularization schemes can migrate anomalies of our interests partially away from their correct places and also suppress their amplitudes.

In Japan islands, earthquakes mainly occurred in the upper crust and the subduction zone, and seismic stations are all very close to the surface, resulting that the recorded seismic data do not have a full spherical coverage over the interested subsurface structures. Meanwhile, the crust is sampled by much more regional data than the subduction zone is. The regularized algorithm may "ignore" the less sampled subduction zone. Many experiences tell that the expected high-velocity subducting slabs sometimes do not show up if the starting model is not close enough to the "real" model. It is not surprising that subduction zone images are manly obtained by using teleseismic data. However, low frequency teleseismic data have relatively low resolving ability. To get high-resolution images, we still need to rely on regional data. As discussed, the spatial distribution of regional seismic data requires us to carefully design seismic tomography algorithms.

In this study we propose a target oriented seismic tomography algorithm for imaging subduction zones. The new seismic tomography scheme consists of three main steps. We first construct a large-scale average background model of the whole crust and upper mantle structure of the study area. To avoid being trapped by local minimums, a multi-grid model parameterization is used to decompose the scale of the inverse problem. The second step is a localized tomographic inversion. We only use seismic data generated by earthquakes in the subduction zone. Considering that the first step is likely to yield an accurate average velocity model of the crust, we only perturb the upper mantle model at the second step. The third step is to invert the differential traveltime residual of two neighboring subduction zone earthquakes at the same station. This approach can further refine the subduction zone structures.

We will test this target oriented method in the framework of ray-based traveltime inversion using our newly developed eikonal-based traveltime tomography software package tomoQuake. Real application results in the Japan subduction zone will be demonstrated.

Keywords: Seismic tomography, Subduction zone

Point and Line Attractors Emerging in the System Including the Interaction among Heat, Fluid Pressure and Dilatancy

*鈴木 岳人[1]
*Takehito Suzuki[1]

1. 青山学院大学理工学部物理・数理学科
1. Department of Physics and Mathematics, Aoyama Gakuin University

We show two geometrically different attractors, point and line attractors, emerge within the framework including the interaction among heat, fluid pressure and dilatancy associated with dynamic earthquake source process. To show that, we consider qualitative behavior of the solution orbit in the ϕ-v space, where ϕ and v describe the inelastic porosity and the slip velocity, respectively. We first consider nullclines, which are obtained by the conditions $\dot{v}=0$ and $\dot{\phi}=0$. For $\dot{v}=0$, the straight line v=0 and the curve v=1-\beta g(ϕ) are nullclines, where g(ϕ) is the function describing the porosity evolution law and \beta is a positive constant number. The curve v=1-\beta g(ϕ)) on the ϕ-v space will be referred to as C^{crit} henceforth. For $\dot{\phi}=0$, the straight line v=0 and the curve ϕ=1 are found to be nullclines. Clearly, the line v=0 is the common nullcline for both equations.

We simply assume that C^{crit} crosses the ϕ-axis once, and C^{crit} is ascending with increasing ϕ. We consider a solution orbit crossing the v-axis in the region 0<v_0<1, where v_0 is the slip velocity at ϕ=0, since v and ϕ are normalized and take values between zero and unity. It should be noted that the orbit is not horizontal nor vertical at the point crossing the line v=0, even though the line is a nullcline. This occurs because v=0 is a nullcline for both equations; both the relationships $\dot{v}=\dot{\phi}=0$ are satisfied on the line v=0, which enables dv/d ϕ to be nonzero there. Moreover, we can confirm the orbit connects the points (0, v_0) and (1, 1).

The solution orbits and the moving direction of the solution conclude that we have attractor and repeller on the ϕ-axis; {(ϕ_a, 0) | 0 \le \phi_a \le \phi_c} is an attractor, while {(ϕ_r, 0) | \phi_c \le \phi_r \le 1} is a repeller, where ϕ_a and ϕ_r are the real numbers satisfying \phi_a < \phi_c and \phi_r > \phi_c, and ϕ_c is the ϕ value of the point where C^{crit} and ϕ-axis cross. In particular, note that \phi_a and \phi_r take continuous values. These non-isolated fixed points appear because the line v=0 is a nullcline for both equations, and this is characteristic behavior of the present system. In addition, the point (1, 1) is also the attractor because C^{crit} and all orbits are absorbed into the point (1, 1). We can therefore summarize that the attractors are categorized into two geometrically different groups: they are given by the line {(\phi_a, 0) | 0 \le \phi_a \le \phi_c} or the point (1,1). The detail of g(ϕ) does not affect the emergence of the attractors.

キーワード：熱、流体圧、空隙生成、解軌道、アトラクタ、リペラー
Keywords: heat, fluid pressure, dilatancy, solution orbit, attractor, repeller