

Determining slip near trench in the M 9 Tohoku-oki earthquake using bathymetry differences before and after the rupture

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Many studies of the 2011 M 9.0 Tohoku-oki earthquake indicate very large coseismic slip that breached the trench and induced the devastating tsunami. In order to understand the behavior of the shallow fault during the earthquake, it is important to know the amount of coseismic slip near the trench and how the slip varies in the updip direction. However, a compilation of more than 40 published rupture models derived from various datasets, including seismic, tsunami, and geodetic observations, shows large uncertainties in determining the near-trench coseismic slip. While some models show that the slip peaked at the trench, other models show that it peaked at some distance from the trench and then decreased trenchward. The large uncertainties are due mainly to the lack of very-near-field observations. For example, the most near-trench seafloor GPS/Acoustic site operational at the time of the earthquake is ~50 km from the trench. However, high-resolution multi-beam bathymetry surveys conducted by JAMSTEC before and ~10 days after the 2011 earthquake recorded coseismic deformation directly at the trench. In this work, we use differential bathymetry, i.e. bathymetry differences before and after the earthquake, to determine the shallow coseismic slip in the area of the largest moment release. Using a 3D elastic finite element model with actual seafloor and fault geometry of the Japan trench subduction zone, we produce Synthetic Differential Bathymetry (SDB), and compare the SDB with observations. The SDB can well predict short-wavelength features, which correspond mainly to local seafloor slope variations. For longer-wavelength features, our tests using different slip profiles with slip increasing or decreasing to the trench show that the internal elastic deformation of the hanging wall plays an important role in generating bathymetry differences. We use two parameters, the average fault slip over the most near-trench 50 km and a constant gradient of the slip over the same distance, to describe the assigned slip distribution, and search for the slip profile that can best explain the observed differential bathymetry. Bathymetry surveys before the Tohoku earthquake were conducted in 1999 and 2004. Our modeling indicates that a fault slip averaging 65 m over the near-trench 50 km and decreasing by 5 m over the same distance can optimally predict the differential bathymetry from the 1999 and 2011 data. Because the coverage seaward of the trench in the 2004 survey was shorter, causing greater uncertainty in correcting depth bias between surveys, differential bathymetry between 2004 and 2011 is less reliable. Compared to the 1999-2011 data, a smaller average slip (45 m) with a larger trenchward decrease over the most near-trench 50 km is required to explain the 2004-2011 data. Although some uncertainties exist in determining the absolute amount of slip, moderate decrease in fault slip to the trench should be a robust feature, as required by both the 1999-2011 and 2004-2011 data. If some pre-seismic slip and/or short-term afterslip occurred near the trench, the finding of the trenchward decrease of the coseismic slip would be further strengthened. The large coseismic slip but with a small decrease toward the trench suggests that the shallow megathrust may have initially exhibited velocity-strengthening at low slip rates but then changed to dynamic weakening at higher rates. The delay of weakening in the shallow fault may have led to less net coseismic weakening than in the deeper seismogenic zone.

キーワード: 2011 M 9.0 Tohoku-oki earthquake, near-trench coseismic slip, differential bathymetry, elastic finite element model, coseismic weakening

Keywords: 2011 M 9.0 Tohoku-oki earthquake, near-trench coseismic slip, differential bathymetry, elastic finite element model, coseismic weakening

日本海溝付近で発生するスロースリップに伴う低周波微動 Small low-frequency tremor coincident with slow slip events near the Japan Trench

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Understanding the changes in rates of transient deformation prior to large earthquakes in subduction zones is critical for predicting impending earthquakes and tsunamis. In the 2011 Tohoku-Oki earthquake, the shallow plate-boundary thrust at the Japan Trench slipped tens of meters to generate a devastating tsunami. Some slow slip events (SSEs) and intense foreshock triggered by SSEs have been reported prior to the megathrust event. At several subduction zones around the world, SSEs have been commonly observed to be accompanied by tectonic tremors. Here, we investigate low-frequency tremor activity accompanying SSEs prior to the 2011 Tohoku-Oki earthquake using ocean bottom seismometers deployed just above the coseismic slip area of the 2011 Tohoku-Oki earthquake before the mainshock occurred. To identify tectonic tremor activity accompanying the SSEs, we used three-component continuous seismograms in an ocean bottom seismometer (OBS) network. We investigated the ratio of two envelopes in order to remove the effects of regional earthquakes and stormy weather, using one station as a reference site. We identified three excitations with durations exceeding three days on the envelope ratio between January 25 and March 9, 2011, prior to the Tohoku-Oki earthquake. Similar excitations of envelope ratio were identified at the beginning of and during the SSEs detected by ocean bottom geodetic observations in 2008. They showed that low frequencies of 5-8 Hz dominated. These observations suggest that the excitations accompanying the SSEs could have been due to small low-frequency tremors associated with episodic SSEs; thus the shallow plate-boundary thrust near the trench could be characterized as a general location of slow earthquakes.

キーワード: 低周波微動, スロースリップ, 2011年東北地方太平洋沖地震
Keywords: low-frequency tremor, slow slip, the 2011 Tohoku-Oki earthquake

In-Situ Observations of Earthquake-Driven Fluid Pulses within the Japan Trench Plate Boundary Fault Zone

In-Situ Observations of Earthquake-Driven Fluid Pulses within the Japan Trench Plate Boundary Fault Zone

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Transient fluid flow within active faults has long been suspected to be an important process in the earthquake cycle, but has not previously been captured by direct measurements during an episode. Here we report on the signature of fluid pumping events inside the Tohoku Fault associated with individual earthquakes. As part of the Japan Trench Fast Drilling Project (JFAST), a sub-seafloor temperature observatory was installed across the plate boundary fault zone that ruptured during the 2011 Mw 9.0 Tohoku-oki earthquake. In addition to measuring the frictional heat signal from the megathrust earthquake, the high-resolution temperature time series data reveal spatially coherent temperature transients following regional earthquakes. Temperature increases vertically upwards from a fracture zone and decreases downwards, which is consistent with the expected signature of a fluid pulse entering the annulus from the fracture zone. The anomalies are a few hundredths of degree Celsius and occur repeatedly at depths that are independently interpreted to have higher fracture permeability. High-pass filtered data are spatially correlated in areas disturbed by transient fluid advection. Fluid pulses occur in response to over a dozen local earthquakes, including a Mw 5.4 on 14 October 2012, a Mw 5.5 on 11 November 2012, and a Mw 7.3 doublet consisting of two very local intraplate earthquakes on 7 December 2012, and a number of aftershocks of that event. There does not appear to be a response to large far-field earthquakes such as the 28 October 2012 Mw 7.8 Haida Gwaii or 6 February 2013 Mw 8.0 Santa Cruz Islands earthquakes. These measurements provide the first in situ documentation of seismic pumping within the damage zone of an active fault. Near fault measurements such as these may provide insight into drivers of earthquake occurrence. The redistribution of fluid pressures within fault zones, such as observed here in response to earthquakes, is a potential mechanism that may be involved in earthquake triggering.

キーワード: JFAST, Japan Trench, Observatory, temperature, hydrogeology

Keywords: JFAST, Japan Trench, Observatory, temperature, hydrogeology

地震前後におけるアルゴフロートを用いた海洋物理データ収集の研究 Study of the ocean physical data acquisition before and after the earthquake using the Argo float

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2011年3月11日に発生した東北地方太平洋沖地震は、東北から関東に及ぶ広大な地域に甚大な被害をもたらした。しかし、地震発生当時、震源域近海で海洋観測をしていた船舶は確認されておらず、測深などに必要な海中音速データをはじめ、水温や塩分のような海洋物理データは取得できていない。そこで、本研究では、海洋自動プロファイリングシステム（アルゴシステム）に注目した。現在、アルゴフロートは全世界に約3600台展開している。これにより、船舶や係留式ブイによる大掛かりな観測システムを使用することなく、地球的規模の海洋構造を即時的かつ容易に把握できるようになった。

本研究では、地震発生前後に震源域付近に展開していたアルゴデータ（水温、塩分、圧力）から、地震発生前後の海洋物理データの検出を試みた。その結果、巨大津波を伴った今回の地震において、地震発生後の海面付近では急激な水温変化が確認された。

さらに、同様の巨大津波を伴ったスマトラ島沖地震についても解析を行った。2005年に震源海域に展開していた2機のアルゴフロートからデータを取得した。その結果、津波発生後の数日間は、海洋物質的データが通常と異なるプロファイルを示すことが示唆された。これにより、突発的な海洋環境の変動に対して、アルゴシステムが有効的なデータベースの1つであることが示された。

キーワード: 津波, 地震, 海中音波伝搬, アルゴシステム, 海洋物理データ, ビッグデータ

Keywords: Tsunami, Earthquake, Underwater sound wave propagation, ARGO system, Ocean physical data, Big Data

Chemical fingerprints of earthquake event deposits in the Japan Trench Chemical fingerprints of earthquake event deposits in the Japan Trench

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The Japan Trench subduction zone has repeatedly been affected by large earthquakes, as most recently in 2011 by the giant magnitude 9 Tohoku-oki earthquake. The depression of the deep Japan Trench floor (>7500 m water depth) acts as sediment trap, where seismically triggered submarine mass flows are deposited and preserved in the geological record. Sedimentary records, collected east of the Tohoku-oki epicenter in a 60 km north-south transect along the Japan Trench floor axis and from a small basin on the slope, comprise several event deposits, which we test for seismic origin to investigating the earthquake history in this region. Porewater geochemistry and tephrochronological analyses on intercalated ash layers provide an age control and reveal that the records cover the recent 2011 event deposits, historical events, and prehistoric evidence up to ~62ka ago. Detailed analyses of these records, by using their sedimentological and lithological characteristics, their physical properties as well as their elemental composition (X-ray Fluorescence, XRF) allow to characterize and to identify individual turbidite units.

Three prominent seismo-turbidite sequences, related to the 2011 Tohoku-oki, the AD 869 Jogan and an earlier prehistoric earthquake, are widespread and exhibit in all records the same lithology as well as specific, unique elemental characteristics. In combination with reported rupture areas and incorporated calcareous nanno fossils, the deposited turbidity currents seem to originate from slope areas shallower than ~4500 m water depth. Further two chemical correlative seismo-turbidites have been deposited solely in an isolated basin in the deep trench and might be related to an historical earthquakes in AD 1454 (or AD 1611) and a prehistoric event ~2400 years BP. Other turbidite units do not reveal similarities in the elemental characteristics, but may also be the result of seismic triggered slope failures, deposited at locally restricted sites. It is observed that the frequency of turbidite deposition in the deep Japan Trench is higher during the past 1500 years, than during the period from ~15 ka to 2 ka, and might provide hints on the paleoseismic activity along the Japan Trench off Tohoku.

キーワード: Paleoseismology, Japan Trench, event-stratigraphy

Keywords: Paleoseismology, Japan Trench, event-stratigraphy

遠洋性堆積作用とプレート境界断層運動のリンクエージ Linkages between pelagic sedimentation and plate-boundary faulting

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Pelagic sediments may constitute input materials for plate-boundary faults in subduction zones but have been received little attention. Here, we show two examples of the fault localization onto the specific intervals in pelagic sediments. The Japan Trench Fast Drilling Project (JFAST) revealed that the cumulative interplate motion and the large shallow slip during the 2011 Tohoku-Oki earthquake were accommodated by the smectite-rich pelagic clay of less than 5 m thick. Similar ~5 m-thick, smectite-rich pelagic clay layer was recognized in the incoming sediments of the Japan Trench, which is caused by authigenesis and slow sedimentation rate in pelagic environment. Friction experiments revealed that pelagic smectite is weak over a wide range of slip rates, which is consistent with the concentration of interplate motion and coseismic slip. Although coseismic deformations have not been identified, high-velocity friction experiments and permeability measurements on pelagic smectite suggest that thermal pressurization potentially occurred during the shallow coseismic slip. In the coherent chert-clastic sequence of the Jurassic accretionary complex in central Japan, the thrust faults are considered to branch from the plate-boundary fault at temperature of ~220 °C in a region of the prehnite-pumpellyite facies metamorphism. The stratigraphy at the base of the thrust sheet (i.e., carbonaceous claystone and black chert in the base, gray chert, and red chert in ascending order) represents the mid-Triassic recovery from the deep-sea anoxic event that occurred across the Permo-Triassic boundary. The thrust faulting is highly concentrated into ~5 cm-thick black cataclasite defined by fragments of black chert in the carbonaceous clay matrix, where total carbon content increases to 8.5 wt%. The cataclasite is sharply cut by a few millimeters-thick, chert-derived pseudotachylyte, which is marked by fault and injection veins, rounded and embayed vein boundaries, cracked quartz clasts, and the presence of muscovite microlites in amorphous matrix. The localization of deformation onto the black cataclasite may represent that carbonaceous claystone is weaker than surrounding siliceous rocks, thereby facilitating concentration of faulting. However, seismic faulting appears to occur in stronger chert rather than carbonaceous claystone, which could result in frictional melting under higher frictional strength. In summary, concentration of pelagic smectite and deposition of carbonaceous clay during deep-sea anoxia control the localization of plate-boundary fault and subduction earthquakes at shallow and deep depths, respectively.

キーワード: 遠洋性堆積物, プレート境界断層, 日本海溝緊急地震調査掘削, シュードタキライト, チャート-砕屑岩シーケンス

Keywords: pelagic sediments, plate boundary fault, JFAST, pseudotachylyte, chert-clastic sequence

Toward imaging fault zones of outer rise earthquakes succeeding a large megathrust earthquake in the Japan Trench

Toward imaging fault zones of outer rise earthquakes succeeding a large megathrust earthquake in the Japan Trench

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There has been long-standing debate concerning how and where an intra-plate large normal fault earthquake occurred in the oceanic plate seaward of the trench (i.e. outer rise) following a shallow large megathrust earthquake. In the Japan Trench region, the 1933 Showa-Sanriku earthquake are believed to be an outer rise event succeeding the 1896 Meiji-Sanriku megathrust earthquake. Based on those observations, many seismologists have warned a large normal fault earthquake in the Pacific plate seaward of the rupture zone of the 2011 Tohoku-oki earthquake, because no magnitude-8 class outer rise normal fault earthquake has occurred since the 2011 earthquake. Most problematic issue to understand an outer rise earthquake in the Japan Trench region is that there are little information of size and distribution of fault zones of those events. Recent results of active-source seismic studies as well as earthquake monitoring, however, show a possible approach to image fault zone of outer rise normal fault events. We observed, from wide-angle seismic data, P-wave velocity reduction in the uppermost mantle from the outer rise to the trench axis. This may imply mantle serpentinization due to water penetration to the mantle through a bend-related normal fault system (Fujie et al. 2013). Seismic reflection data also show gaps between clearly imaged the Moho reflections (Nakamura et al. 2014). Moreover, aftershock observation of the 2011 Tohoku-oki earthquake in the outer rise shows that normal fault earthquakes are distributed from the crust to ~40 km deep in the mantle. This suggests that the oceanic lithosphere became under extension stress filed down to 40 km deep after the 2011 event (Obana et al., 2012). Comparing the seismic reflection image and the aftershocks distribution likely indicates that a cluster of the normal fault aftershocks seem to be located in the area where we observe gaps of the Moho reflection. This suggest that the gaps of the Moho reflection can be a structural factor to identify the fault zones of the outer rise normal fault event. In this presentation, we summarize the results of our previous studies and introduce a future plan of the integrated seismic study in the outer rise region.

キーワード: Outer rise earthquake, Japan Trench, Fault, Seismic image, Earthquake monitoring, Megathrust
Keywords: Outer rise earthquake, Japan Trench, Fault, Seismic image, Earthquake monitoring, Megathrust

Proper selection of least squares parameters in tsunami waveform inversion through computational intelligence

Proper selection of least squares parameters in tsunami waveform inversion through computational intelligence

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Nature-inspired computational methodologies have been successfully applied to many geophysical optimization problems. One of the advantages of such methods is the ability to avoid local optimum solutions, which is something classical methods fail to do. This is because the methods require no derivative information and thus the search is not restricted by the local gradient of the objective function. This feature is of importance in real world applications, where the optimization problems are often characterized by irregular error surfaces that are sometimes non-differentiable. In the standard tsunami waveform inversion based on the Green's function superposition, the linear assumption allows model parameters to be determined straightforwardly using least squares. Therefore, the use of a more advanced method is unnecessary, unless a different design parameter is introduced leading towards a better solution. To that end, we proposed a utilization of computational intelligence in the tsunami waveform inversion using distinct design parameters.

In this study, a tsunami waveform inversion without the fault model assumption is used to test our proposed method. We develop an optimization method based on a genetic algorithm that further enhanced by a pattern search method to find optimal model parameters for the least squares inversion, which mainly dependent on the spatial distribution. Here, we do not use the method for directly estimating the unknown parameters formulated in the least squares inversion. In addition, we apply the same algorithm to determine the water movement initiation time at specified locations inside the inverse region or tsunami source-influenced area. This is applicable to cases where the transient deformation is not negligible. The results suggest that the method not only leads to better accuracy, but also increases the ability to reveal the underlying physics associated with the tsunami generation process. The method has been applied to both artificial and real event of the 2011 Tohoku-Oki tsunami.

キーワード: Tsunami waveform inversion, Computational intelligence, 2011 Tohoku-Oki tsunami
Keywords: Tsunami waveform inversion, Computational intelligence, 2011 Tohoku-Oki tsunami

2011年東北沖地震の初期破壊過程のダイナミクス Rupture dynamics inferred from early stage of the 2011 great Tohoku-oki earthquake

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The occurrence of the 2011 M 9.0, Japan, Tohoku-oki earthquake gives us a unique opportunity to investigate the detailed process of the initiation and propagation of a rupture during a gigantic earthquake. It is observed that the mainshock of the Tohoku-oki earthquake was triggered by the M7 foreshock with time delay of two days occurred near the hypocenter of the mainshock. Therefore, it is expected that the early stage of the mainshock rupture reflects perturbations caused by the foreshock. In order to test this hypothesis, we examine the stress changes during the dynamic rupture propagation of this event. We used the kinematically inverted slip profile obtained by Uchide (2013), JGR, which conducted the multi-scale seismic slip inversion focusing on the first few ten seconds of the mainshock; he showed that the slip profiles around the hypocenter exhibited high-speed rupture propagations. We calculate the dynamic stress changes on the fault plane given the inverted slip profile by applying the 3-D elasto-dynamic boundary integral equation method (Ando and Okuyama, 2010, GRL). The calculated stress changes shows generally the slip weakening behavior consistent with the occurrence of the high speed rupture. The obtained stress change also shows heterogeneous distribution over the fault area, which might reflect the stress perturbation existed before the mainshock.

キーワード: 東北地方太平洋沖地震, ダイナミクス, 破壊, 摩擦, インバージョン, シミュレーション

Keywords: Tohoku-oki earthquake, dynamics, rupture, friction, inversion, simulation

Characteristics and waveform simulation for dynamic rupture model of the 2011 Tohoku earthquake with deep SMGAs

Characteristics and waveform simulation for dynamic rupture model of the 2011 Tohoku earthquake with deep SMGAs

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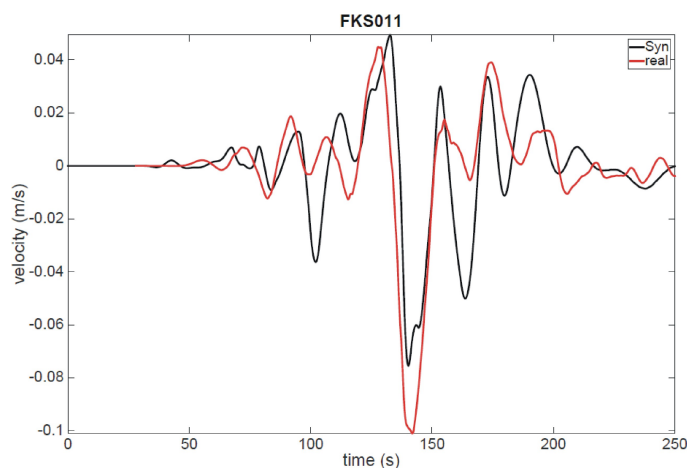
The rupture process of the 2011 Tohoku earthquake is simulated using the spectral element program SPECFEM3D with the recent dynamic rupture module implemented by Galvez et al. (2014). The state-of-the-art unstructured mesh software CUBIT provides a powerful tool to deal with geometrical complexities. We use this capabilities to perform dynamic rupture simulation for the Tohoku earthquake including the non-planar slab interface and tiny angles ($<5^\circ$) found in the trench wedge. Based on this geometry we allocate asperities and SMGAs inspiring by the source inversion results and gradually modify the asperity distribution. To create more slip in the shallow regions, the main asperity has been moved close to the trench. In the deep region we place asperities on the strong-motion generation areas (SMGAs) detected by Kurahashi & Irikura (2013). By a systematic adjustment of stress drops, slip critical distance (D_c), the rupture reproduces final slip recorded by kinematic models (e.g. Suzuki et al.(2011); Lee et al. (2011)).

Moreover, this model also reproduces qualitatively the multi-seismic wave front observed from the strong ground motion and GPS data along the Japanese coast. We take the seismic station (FKS011) and compare the recorded velocity waveform and our 1D synthetic between 20 to 100 seconds period (see Figure). The fitting is remarkable but there are other stations less accurate. For a set of coastal hard rock sites we perform 3D FDM simulations for the JIVSM velocity model and periods 5 to 20sec, and confirm that developed dynamic model reproduce observed wave-packets as amplitude, spectral content and arrival time. Overall, we could resemble the rupture process of the Tohoku earthquake and reproduce qualitatively the recorded multi-seismic wave front detected by the KNET and Kik-net networks.

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キーワード: 2011 Tohoku earthquake, dynamic simulation, slip reactivation

Keywords: 2011 Tohoku earthquake, dynamic simulation, slip reactivation



2011年東北地方太平洋沖地震時の茨城県沖の領域の破壊シナリオ Possible Rupture Scenario for the Area Off-Ibaragi Prefecture in the 2011 Off the Pacific Coast of Tohoku Earthquake

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The 2011 Off the Pacific Coast of Tohoku Earthquake (Tohoku Earthquake, Mw 9.0) was one of the most devastating earthquakes in Japanese history. It ruptured a very broad area of the plate boundary along the Japan Trench, from the northern end of offshore Aomori prefecture to the southern end of offshore Ibaragi prefecture. The largest aftershock (Mw 7.7) occurred 30 minutes after the main shock offshore Ibaragi Prefecture (Off-Ibaragi area). The rupture of this aftershock was not involved in the rupture of the main shock. It might be useful for the assessment of future seismic hazards to understand what physical mechanism stopped the main shock rupture at the edge of the rupture area of this largest aftershock, and if this area can rupture simultaneously with a future huge earthquake. Some studies have addressed these questions based on structural heterogeneities imaged by tomography in the Tohoku region (Liu et al., 2014) or on compilations of observations of subduction zones around the world. However, more investigations based on numerical simulation studies might be necessary to elucidate the physical mechanisms.

In this study, we have carried out dynamic rupture simulations to understand the mechanisms of rupture arrest of the Tohoku earthquake. The simulations assume a slip-dependent friction law (Ida, 1972) and use the 3D Spectral Element Method (Galvez et al., 2013), which is numerically stable and accurate even for subduction earthquake models with low dipping angle. To set the initial stress conditions for the simulation, we use constraints based on a slip-deficit map inferred from the analysis of GPS data (Ikuta et al., 2012) and the estimates of inter-seismic recurrence time along the Japan Trench by the Headquarter of Earthquake Research Promotion in Japan (2011).

In contrast with the real Tohoku Earthquake, the main shock rupture resulting from our simulation propagated to the Off Ibaragi area, indicating that the initial part of the rupture had enough energy to break through the Off Ibaragi area. Factors that we did not include in this simulation, such as attenuation and smaller-scale features of the megathrust geometry due for instance to subducted seamounts, might have played an important role in the rupture arrest in the southern end of the Tohoku earthquake in 2011.

Keywords: Rupture Simulation, Dynamic Model, The 2011 Off the Pacific Coast of Tohoku Earthquake, Slip Deficit

西南日本前弧域のトモグラフィーと巨大地震の発生機構 Structural control on the nucleation of Nankai megathrust earthquakes

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Many large interplate earthquakes ($M > 7$) occurred on the megathrust fault of the Nankai subduction zone, where the young Philippine Sea plate is subducting beneath the Eurasian plate along the Nankai Trough. The landward downdip limit of the Nankai megathrust seismogenic zone is located at a depth of ~30-40 km, marked by the occurrence of episodic tremors and slips. The seaward updip limit is not very distinct, being generally at a depth of ~10 km and correlated with a suite of diagenetic to low-grade metamorphic processes.

To clarify the causal mechanisms of the Nankai megathrust earthquakes, we studied the detailed three-dimensional P and S wave velocities (V), attenuation (Q), and Poisson's ratio (PR) structures of the southwest Japan forearc, using a large number of high-quality arrival time and t^* data measured precisely from seismograms of local earthquakes. The suboceanic earthquakes used are relocated precisely using sP depth phase and ocean bottom seismometer data. Our results show the existence of two prominent high-V, high-Q, and low-PR patches separated by low-V, low-Q, and high-PR anomalies in the Nankai megathrust zone. Megathrust earthquakes during 1900 to 2013 nucleated in or around the high-V, high-Q, and low-PR patches, which may represent strongly coupled areas (i.e., asperities) in the megathrust zone. Our results indicate that structural heterogeneities in the megathrust zone, such as the subducting seafloor topography and compositional variations, control the nucleation of the Nankai megathrust earthquakes.

キーワード: 南海, 沈み込み帯, 巨大地震, スラブ, 流体

Keywords: Nankai arc, Subduction zone, Megathrust earthquake, slab, fluids

海陸統合観測網を用いたレシーバ関数解析に基づくフィリピン海プレートの流体分布
Hydrous state of the Philippine Sea plate inferred from receiver function analysis using onshore and offshore data

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Exploring fluid distribution in subduction zones is an intriguing topic because it is considered that the fluids affect the occurrence of non-volcanic tremors, slow slip events, microearthquakes, and even the rupture area of the megathrust earthquakes. The fluid generating strong contrast in seismic velocity, many studies have utilized scattered teleseismic body waves, or receiver functions (RFs), to infer the hydrous state in worldwide subduction zones [e.g., *Kawakatsu and Watada, 2007; Audet et al., 2009*]. General consensus among these studies is that subducting oceanic crust hosts abundant fluids, which is supported by overlying positive and underlying negative RF amplitudes. Most of the studies, however, conducted analysis by limiting their study area into two-dimensional vertical sections beneath inland area. Lateral variety and seaward extension of the fluid distribution remains uninvestigated. In this study, we conducted RF analysis using ocean-bottom seismometers (OBSs) and on-land permanent stations deployed around the Kii Peninsula in the southwestern Japan.

OBS vertical component records contain dominant water reverberations, so conventional method fails to estimate correct RFs. We hence developed a method to remove the reverberations using a linear filter, which were constructed from the deconvolution of OBS vertical records by source wavelets. We estimated the source wavelets from stacked traces of on-land station records. Resultant RFs by removing water reverberations with the filter show an improvement on later phase identification, compared with those from conventional method. Using these RFs, we constrained the geometry of the subducting Philippine Sea plate and inferred the hydrous state of the oceanic crust.

Our RF image shows negative RF amplitudes on the plate interface and positive RF amplitudes on the oceanic Moho, which we inferred as hydrous oceanic crust. The hydrous oceanic crust seems to extend seaward to ~5 km depth from our results. We found the RF amplitude reduction on both sides of the oceanic crust at the belt-like region of non-volcanic tremors, while the long-term slow slip patch [*Kobayashi, 2014*] is located at the adjacent place with strong RF amplitudes. This contrasting features suggest that difference in pore fluid pressure or permeability of the plate interface controls the slip behavior of the plate interface. The comparison between microseismicity [*Akuhara et al., 2013*] and the configuration of the subducting plate modeled in this study reveals that the oceanic crust becomes aseismic as slab subducts deeper, and that the transition depth varies laterally. This may provide some constraints on the process of slab dehydration although detailed simulation of thermal structure is necessary in the future.

Keywords: Subduction zone, fluid distribution, ocean-bottom seismometer, receiver function

Results from IODP Expedition 348: Deep Drilling Above the Plate Interface, Nankai Trough Subduction Zone

Results from IODP Expedition 348: Deep Drilling Above the Plate Interface, Nankai Trough Subduction Zone

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During IODP Expedition 348 from October 2013 to January 2014, Site C0002 was drilled to more than 3000 meters depth into the inner accretionary wedge at the Nankai Trough, setting a new depth record for scientific ocean drilling. It is the first hole to access the deep interior of an active convergent margin. Site C0002 is part of the NanTroSEIZE transect off the Kii Kumano region of Japan, imaged with 3D seismic reflection and drilled on a series of Chikyu expeditions to shed light on the processes around the up-dip edge of seismogenic locking and slip. At Site C0002, riser drilling has passed through the approximately 900 m thick Kumano forearc basin and pierced the underlying Miocene age accretionary wedge. The zone from 865 to 3056 meters below the sea floor was sampled via limited coring, extensive LWD logging, and continuous observations on drill cuttings that all reveal the materials and processes in the deep interior of the inner wedge. Predominantly fine-grained mudstones with common turbiditic sands were encountered, complexly deformed and exhibiting well-developed scaly clay fabrics, variable bedding dip with very steep dips prevailing, and veins that become more abundant with depth. The biostratigraphic age of the sediments in the lowermost part of the hole is thought to be about 9 to 11 Ma, with an assumed age of accretion of 3 to 5 Ma.

Physical properties suggest that the inner wedge from 1600 to 3000 mbsf has quite homogeneous properties. P wave speeds from sonic logs increase with depth to approximately 1600 meters, but are constant to slightly decreasing with depth from 1600 to 3050 meters. We hypothesize that this change in trend indicates the onset of elevated pore fluid pressure, but structural and lithologic factors may also play a role. A borehole leak-off test (LOT) and a series of borehole pressurization and injection tests were also performed, which we synthesize to estimate the least principal stress, S_{hmin} . Furthermore, downhole pressure while drilling (PWD) measurements recorded during borehole packoff events provide information on the maximum principal stress, S_{Hmax} . Taken together, the LOT and PWD observations suggest that the inner wedge at about 2000 meters depth is currently in a strike-slip stress regime, despite its position as the hanging wall of a main plate boundary thrust.

キーワード: accretionary wedge, seismogenic zone, subduction, Nankai Trough, physical properties, in situ stress

Keywords: accretionary wedge, seismogenic zone, subduction, Nankai Trough, physical properties, in situ stress

南海トラフプレート境界域のダイナミクスと応力状態の海底観測・監視を目指して Seafloor monitoring for dynamics and stress state of the seismogenic plate interface in the Nankai Trough

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Stress and pore-fluid pressure are considered to be key parameters governing behavior of seismogenic plate interface. Direct observation of these parameters is difficult, but we are trying to establish seafloor observation techniques that let us infer these parameters at the seismogenic plate interface in the Nankai Trough, south of Japan.

In the Nankai Trough, we started development of real-time seafloor observation network (called DONET) since 2010. The network aims monitoring of seismic activity in the seismogenic subducting plate boundary in the Nankai Trough where repeated occurrence of large earthquakes in the history. The DONET will distribute more than 50 observatories in the rupture area of Tonankai and Nankai earthquakes. Currently, the network is continuously monitoring micro earthquakes and very low frequency earthquakes in the vicinity of them with 20+ sites. This enables us to look into stress state and its temporal change in the crust through their mechanisms. Very low frequency events were observed below the DONET network after off Tohoku events in March, 11, 2011 (Toh et al, 2011). We consider monitoring of such events is very important to know current status of the interface in preparation for the next earthquake.

The DONET observatories are also monitoring seafloor water pressure using Quartz pressure gauges, which are able to detect seafloor level change as small as 1 cm. We plan to use the networked seafloor pressure observation to detect crustal deformation due to slip in the plate interface. As the pressure gauge has instrumental offset drift in long-term, it is currently difficult to evaluate small ground deformation using pressure data over month period, but we are developing techniques to calibrate seafloor pressure gauge to compensate effects of the instrumental drift so that we can identify long-term change of the seafloor level as small as 1 cm also in such long-term. When such techniques are developed, we expect to identify where in the subducting seismogenic plate interface accumulate slip deficit for the next large earthquake.

We consider pore-fluid pressure near the plate interface may control slip in the plate interface. Observation of pore-fluid pressure in the crust is already in practice using seafloor boreholes drilled in scientific drilling programs (ODP Leg 196, and IODP expeditions 332) here in the Nankai Trough. Existing borehole pore-fluid pressure observations in the Nankai Trough, are reaching up to 1 km below the seafloor. Therefore, it is very effective way to observe pore-fluid pressure in seaward end of the plate interface, but in deeper interface where seismogenic slip occurred in the last large earthquake in the Nankai Trough, existing technology is still out of reach to the interface itself and we need to develop deep borehole observatory penetrating it in the future.

Monitoring characteristics of seismic waves traveling near the target seismogenic plate interface may provide another way to estimate stress state and pore-fluid pressure. Brenguier et al., (2014) suggested that the crustal seismic wave velocity would have strong relationship with status of pore-fluid in crust. Seismic anisotropy is also known to indicate background stress state. We were encouraged from these facts to conduct a series of experiments to observe characteristics of seismic wave velocity in the Nankai Trough seismogenic plate boundary and its temporal change using the DONET and borehole observatory. Using airgun seismic source and the network of seismometers, seismic velocity of the crust is measured precisely. By repeating, we expect to identify its change. To begin with, we conducted an airgun shooting cruise in March, 2013 to survey anisotropic structure of the area, confirming observed seismic anisotropy around IODP site C0002 in accordance with known stress from borehole breakout. Next experiment is planned in March, 2014 to evaluate our ability to identify change in seismic velocity.

Keywords: seafloor observation, seismogenic zone, stress, seismic anisotropy, temporal change, borehole

Estimation of in-situ stress and strength along the Nankai Trough subduction megathrust Estimation of in-situ stress and strength along the Nankai Trough subduction megathrust

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Understanding the mechanics that underlie the spectrum of fault slip behaviors observed along subduction megathrusts requires a sound investigation of depth-varying in-situ stress conditions, absolute fault strength, and fault rheology. The porosity reduction of sediments with progressive burial plays an important role in deformation style in the shallow portion of subduction zones because the deformation mode and strength of porous rocks are largely dependent on both porosity and pressure. Here, we report on results of triaxial deformation experiments on (1) modern sediments currently subducting at the Nankai Trough; and (2) tectonic melange near the Nobeoka thrust in the exhumed Shimanto complex, which is an ancient out-of-sequence-thrust or plate boundary, to provide constraints on the stress state and strength along the plate boundary.

For the mudstone core samples (porosity of 43%) recovered from the Nankai Trough in the IODP NanTroSEIZE project, we conducted triaxial compression and extension tests under a range of loading paths at room temperature, and measured sonic velocity and porosity during the tests. We then used these data to develop empirical relations between sonic velocity, porosity, and stress, in order to estimate in situ stress along the megathrust plate boundary from P-wave velocities defined by seismic survey data. Different loading paths do not affect the relationship between P-wave velocity and porosity, but they do affect the relationship between porosity and effective mean stress: at the same effective mean stress, sediments are more compacted with increasing differential stress. Based on expected in situ stresses and pore pressures for a range of possible scenarios under different loading paths, we suggest that the Kumano basin is loaded in a uniaxial stress condition, whereas the prism and underthrust section are most likely loaded along a near critical stress condition with lateral compression. We find that the Kumano Basin is likely to be hydrostatically pressured, whereas the prism and underthrust section in the vicinity of the plate boundary are moderately overpressured ($\lambda^* \sim 0.5$ in average) and significantly overpressured ($\lambda^* \sim 0.85$ in average).

For the tectonic melange samples (porosity of 2%) from the footwall of the Nobeoka thrust fault in the NOBELL project, we conducted triaxial compression tests along a conventional tri-axial loading path, where confining pressure is kept constant and axial stress is progressively increased. The cylindrical specimens were deformed at an axial displacement rate of $0.5 \mu\text{m/s}$, corresponding to strain rates of $1.6 \times 10^{-5} \text{ s}^{-1}$, and at a temperature of 250°C and an effective pressure (P_e) of 120 MPa (confining pressure of 200 MPa and pore pressure of 80 MPa) or 20 MPa (confining pressure of 200 MPa and pore pressure of 180 MPa). The temperature was chosen based on the estimated temperature ($250\text{-}300^\circ\text{C}$) at which the melange were formed [Kondo et al., 2005]. The two different effective pressures of 120 MPa and 20 MPa correspond to estimated stress conditions at ~ 8 km (geothermal gradient of $\sim 30^\circ\text{C/km}$), for hydrostatic and 90% of lithostatic pore pressures, respectively. The experimental results show that the melange samples deform in a brittle manner at $P_e = 20$ MPa. The strengths reach a peak at 80-90 MPa, followed by strain weakening to residual strengths of 40-60 MPa. At $P_e = 120$ MPa, on the other hand, the foliated cataclasite deforms in a hybrid brittle-ductile mode, with a steady-state strength of ~ 300 MPa. Because the brittle-ductile transition of the melange samples lies on the extrapolation of critical loading on the Nankai mudstone samples, the melange samples in the ancient prism may provide a good analog for the mechanical behavior of underthrust rocks at seismogenic depth in the modern Nankai Trough. The strength of these clay-rich sediments increases as they compact with depth, but is not as high as that of sandstones or carbonates.

キーワード: Nankai Trough, subduction zone, IODP, NanTroSEIZE, Nobeoka thrust, melange

Keywords: Nankai Trough, subduction zone, IODP, NanTroSEIZE, Nobeoka thrust, melange

ピストンコアラ貫入時の摩擦発熱から地層の摩擦係数を推定する試み — NanTroSEIZE 掘削の APC-T データの例 —
Estimation of sediment friction coefficient from heating upon APC penetration during the IODP NanTroSEIZE

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海洋科学掘削では、浅部泥質堆積層の採取に用いる水圧ピストンコアラ（APC）の先端に温度計（APCT）を取り付け、地層温度が測定されている。IODP 南海トラフ地震発生帯（NanTroSEIZE）掘削では、「ちきゅう」により APCT データが取得された。APCT では、APC が水圧により瞬間的に地層に「突き刺さる」時の温度上昇を含めた温度データが毎秒記録されている。その際に得られた全温度データをコンパイルし、貫入直後の最大温度を抽出したところ、温度上昇は 10K ないしそれ以上に達するが、全体的に深度とともに増大していること、深度ゼロでの温度上昇（切片）がゼロでないように見えることが新たに見出された。

温度上昇の原因は、地層物質とパイプの相対運動による摩擦発熱である。摩擦発熱エネルギー Q は、パイプと地層の間に働くせん断応力 τ と滑り量 D の積に等しい。 D はピストンコアラは水圧により押し出される長さ（9.5m）で、深度によらず一定である。一方せん断応力 τ は、クーロン則を適用すると、 $\tau = \tau_0 + \mu (S_v - P_p)$ で表される（ τ_0 は粘着力、 μ は地層とパイプの間の動摩擦係数、 S_v はパイプを押す地層の圧力、 P_p は間隙水圧）。すなわち、 Q の値は、粘着力に起因する（深度に依存しない）部分と、深度とともに増加する部分に分けられることから、摩擦係数が一定であれば、観測された温度上昇を説明できそうである。

最大温度と Q の関係は、有限要素法（COMSOL）による推定から、互いに比例することが示され、得られた比例係数を利用して、APCT による測定値ごとに摩擦係数を推定した（ S_v として静水圧を仮定し、有効応力を与えた）。また同じサイトで得られたコア試料について、船上で計測されたベーンせん断計測データも選び出し、同様にして摩擦係数を求めた。

その結果、ベーンせん断地から推定した粘着力・摩擦係数はそれぞれ 20-80kPa、0.05-0.2 に、温度上昇から推定した粘着力は 10-20kPa、摩擦係数は 0.01-0.06 という低い値になった。また、どちらの推定でも、サイト C0012（沈み込む前の四国海盆海丘上）において、付加体斜面における他よりも摩擦係数が有意に大きいことが分かった。半遠洋性地層が卓越することが原因の一つと推定される。

摩擦発熱から推定した摩擦係数が、ベーンせん断からの推定値の数分の一になった理由として、パイプと泥の間に水が浸入したことにより、その間の摩擦が泥の内部摩擦よりも低いこと、あるいは温度上昇を発熱エネルギーに変換する比例係数が実際の APCT での値とは異なること、などが考えられる。いずれにせよ、静水圧を仮定して計算した摩擦係数が、0.06 とか 0.2 とか、表層堆積物の内部摩擦と比べて有意に小さいように見えるのは、測定・推定された値が現場条件と異なるための誤差であろうとも推定される。今後さらに精度を上げる工夫を行いたい。

キーワード: IODP, NanTroSEIZE, APC-T, Friction coefficient
Keywords: IODP, NanTroSEIZE, APC-T, Friction coefficient

巨大分岐断層の起源、順序外断層か沈み込み史転換か Origin of mega-splay fault in subduction zone - out-of-sequence thrust or evolution gap in subduction

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Mega-splay fault in subduction zone is a major seismogenic fault in subduction zone and separates outer and inner wedges of the forearc in many places. Origin of the mega-splay fault, however, is not so clear and is ambiguously considered to be out-of-sequence thrust in accretionary prism or accidental result of thrust branching from the plate boundary mega-thrust.

The out-of-sequence thrust model assumes that terrigenous sediments supply and relative plate convergence are constant, and the prism grows constantly. The prism grows by in-sequence thrusting at the deformation front, with out-of-sequence thrusting occurring in the inboard of the prism and maintaining the critical taper. The resulting accretionary prism can thus thicken until it obtains the thickness of continental crust of ~30 km and more with association of exhumation of high grade metamorphic rocks to keep the critical taper.

If we attempt to apply this out-of-sequence thrust model to the mega-splay fault in the Nankai margin and tectonic boundary faults in ancient accretionary prisms of southwest Japan, the model implies that the northern Shimanto Belt was continuously followed by the growth of the southern Shimanto Belt and modern Nankai accretionary prism without any serious break since Late Cretaceous time to present.

The tectonic history of southwest Japan, however, presents several complications of the events, such as global change in relative convergence with subduction of several different oceanic plates such as Farallon, Kula, Philippine Sea, Pacific and other anonymous plates, intermittent sediment supply to the trench in Late Cretaceous and Palaeogene times as suggested by many researchers.

Given that one or some combination of these tectonic scenarios may have controlled the onset and evolution of the main tectonic boundaries and setting of the mega-splay fault in the forearc. Present mega-splay fault in the Nankai Trough may be related to the onset of new tectonic framework at ~2Ma and present inner wedge appears to have related to the onset of new subduction in the Nankai Trough at ~6Ma. Thus, out-of-sequence thrust interpretation for the origin of the megasplay fault should be avoided.

Plate geometry, splay fault and tsunamigenic earthquake in the southernmost Ryukyu trench Plate geometry, splay fault and tsunamigenic earthquake in the southernmost Ryukyu trench

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In the last few decades, a series of megathrust earthquakes and their ensuing tsunamis worldwide required us to reassess seismic potentials in subduction zones. A typical example in controversy is the Ryukyu subduction zone, extending 1,200 km from Kyushu, SW Japan, to Taiwan collision zone (e.g., Lin et al., 2014). Along this subduction zone, historical evidence for great interplate earthquakes ($M > 8$) has been poorly documented and ongoing back-arc rifting along the Okinawa trough implies that the plate coupling is weak (Peterson and Seno, 1984). In more recent years, a variety of seismic activities including large earthquakes with $M > 7$ (Engdahl and Villasenor, 2002), repeating slow-slip events (Heki and Kataoka, 2008) and very low frequency earthquakes (Ando et al., 2012) were found indicative of spatial variation in frictional property along the plate boundary and surrounding faults. Historically, the Yaeyama earthquake in 1771 with $M \sim 8$ is thought to have ruptured a shallow portion of the plate interface and generated devastating tsunami with a maximum run-up height of ~ 30 m, causing approximately 12,000 fatalities (Nakamura, 2009). Although these documentations imply that a diversity of seismogenic processes along the Ryukyu subduction zone, fundamental structural features associated with plate subduction are not well understood. Moreover, the slab geometry itself is poorly constrained due to the sparse seismic observation networks.

In order to improve our understanding seismic potentials and structure controlling the seismogenic process in the Ryukyu subduction zone, we started a new 8-year project that consists of four two-dimensional active-source seismic experiments and extensive passive-source seismic observations covering the entire Ryukyu arc. In 2013, active-source seismic data were collected in the southernmost Ryukyu trench that crosses the potential source region of the 1771 Yaeyama earthquake (Nakamura, 2009). For refraction/wide-angle reflection analyses, seismic wave from air-gun shots were recorded at a total of 60 ocean bottom seismographs with approximately 6-km spacing on a ~ 390 -km-long profile. On the same line, multichannel seismic (MCS) reflection profiling using the ~ 6 -km-long, 444-channel streamer cable was also carried out.

Using this data set, we succeeded in imaging the plate boundary down to ~ 30 km depth. The dip angle of the slab increases from ~ 5 degree closer to the seafloor to ~ 20 degree at greater depths. In the fore-arc region, we found a fault branches from the plate boundary to the seafloor and they form a low-velocity accretionary wedge in between. This splay fault and accretionary wedge almost overlap the source region of the 1771 Yaeyama earthquake proposed by Nakamura (2009) and thus may have played a role in tsunami generation. The slab contacts with the overriding wedge mantle at depths greater than ~ 25 km. This region shows greater reflectivity at the plate boundary and is also coincident with repeating slow-slip events (Heki and Kataoka, 2008). These results probably suggest a changing frictional property along the plate interface with increasing depths.

Keywords: Ryukyu subduction zone, Philippine Sea plate, Accretionary wedge, Reflection/refraction analysis

Unlocking the secrets of slow slip at the Hikurangi subduction margin Unlocking the secrets of slow slip at the Hikurangi subduction margin

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The northern Hikurangi subduction margin, New Zealand is the site of the shallowest well-documented slow slip events (SSEs) on Earth. Due to the close proximity of the SSE source area to the seafloor at the offshore Hikurangi margin (<5-15 km), it has become an important international target for a variety of geophysical studies to understand the offshore physical mechanisms that lead to slow slip. The centerpiece of these efforts is a series of IODP proposals to undertake riserless (Joides Resolution) and riser (Chikyu) drilling, and CORK observatory installation on a transect spanning the shallow Hikurangi SSEs. We understand that if scheduling of riserless drilling (and observatory installation) occurs, it is likely for 2017. We will discuss the plans and scientific objectives for both riser and riserless drilling, and borehole observatories. We will discuss other ongoing experiments at the northern Hikurangi margin, including an upcoming heatflow survey, and recent seafloor geodetic (Absolute Pressure Gauges) and OBS deployments to undertake near-source investigations of SSE deformation and related seismicity of the shallow (<10 km depth) subduction thrust (the HOBITSS project). We will also present preliminary analysis of slip distribution and seismicity (using onshore data) from a large SSE that occurred in October 2014 directly beneath the HOBITSS network.

キーワード: subduction, slow slip events, GPS, scientific drilling, seafloor geodesy, New Zealand
Keywords: subduction, slow slip events, GPS, scientific drilling, seafloor geodesy, New Zealand

コスタリカ沖沈み込み帯の上盤に発達する地震波反射断面における岩石物性・微細組織・化学組成のコントラスト
Physical property and Microstructure across the Seismic reflectors in the Upper plate of the Costa Rica Subduction zone

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Costa Rica subduction zone offshore Osa peninsula is known as an erosive margin characterized by active seismicity, subduction of the Cocos Ridge, active fluid seeps, and mud volcanoes. To understand the geologic processes of this margin, Integrated Ocean Drilling Program (IODP) Expedition 334 and 344 have drilled into the overriding Caribbean plate and the subducting Cocos plate offshore Osa in 2011 and 2012. Velocity structures acquired from previous seismic reflection surveys indicate that the upper plate is composed of a few hundred meters to ~2 km thick slope sediments overlying consolidated high velocity material (~3.5-4.3 km/s), bounded by distinct seismic reflectors (von Huene et al., 2000). The nature of the seismic reflectors and the lithology of the consolidated material beneath the slope sediments had been unknown and were considered to be the uplifted basement or old accreted material (e.g. Vannucchi et al., 2013) before Expedition 344 drilled deeper into the middle slope. The unconformity between the slope sediments (Unit 1) and consolidated materials (Unit 2 and 3) were penetrated at Site 1380, across zones that correlate with seismic reflectors. Unit 2 and 3 consists of lithified, low porosity sediments compared to Unit 1, but the age gap between Unit 1 and 2 is very small (<~0.49 m.y.), indicating rapid sedimentation rate (NN18 zone, ~600 m/m.y.) despite the unconformity (Harris et al., 2013). The process for the formation of the unconformity and the physical property transitions are yet to be clarified. In our study, to understand the tectonic and depositional history and the processes of subduction erosion occurring at the Costa Rica subduction zone, we evaluate the depositional, tectonic, and geochemical factors that account for the consolidation nature and the formation of the seismic reflectors in the upper plate, by conducting microstructural observations, particle size analysis, X-ray fluorescence analysis, X-ray diffraction analysis, and resistivity measurements using the samples from Site 1380.

The microstructures of the samples observed through the microscope tend to develop dense and cohesive textures in the low porosity sediments of Unit 2 and 3, and particle size changes across several unconformities. Particle size decrease with depth in Unit 2 and finer sediments form well-sorted structures that may account for the porosity decrease. The cross correlation between measured particle size and shipboard porosity show negative correlation especially at Unit 2, indicating that larger sized particles form smaller or fewer pores which may be due to finer particles filling pores between larger particles. The microstructures of the sediments occasionally exhibit foliated fabrics that are partially distributed. From the X-ray fluorescence and X-ray diffraction measurements, Al, K, Ti tend to concentrate in the higher porosity sediments of Unit 1, whereas Si, Ca, P, Mg, Na, and Mn concentrate in the lower porosity sediments of Unit 2 and 3, which are consistent with the transition in mineral composition marked by the increase in analcime and chlorite and the decrease in clay abundance in Unit 2 and 3. The crossplots between porosity and element concentration show negative correlations in Mg, Na, and Mn with porosity, suggesting that the minerals rich in these elements may relate with the consolidation and/or form the pore-filling materials or cements in Unit 2 and 3.

The depositional effect of grain size sorting, the tectonic effect of formation of foliated fabrics, and the geochemical effect of mineral precipitation and/or cementation are indicated to be the factors that characterize the unconformity, consolidation state and the seismic reflectors. In our presentation, we further investigate each effect to constrain the geologic processes occurring across the unconformity and seismic reflectors that form the upper plate structure of the Costa Rica subduction zone.

キーワード: コスタリカ沖沈み込み帯, 地震波反射断面, 統合国際深海掘削計画, コスタリカ地震発生帯掘削計画, 岩石物性, 微細組織

Keywords: Costa Rica subduction zone, seismic reflector, IODP, Costa Rica Seismogenesis Project, physical property, microstructure

Rupture process of the 2014 Iquique, Chile earthquake estimated from tsunami waveforms, teleseismic, and GPS data

Rupture process of the 2014 Iquique, Chile earthquake estimated from tsunami waveforms, teleseismic, and GPS data

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We applied a new method to compute tsunami Green's functions for slip inversion of the 1 April 2014 Iquique earthquake using both near-field and far-field tsunami waveforms. Inclusion of the effects of the elastic loading of seafloor, compressibility of seawater, and the geopotential variation in the computed Green's functions reproduced the tsunami travel-time delay relative to long-wave simulation, and allowed us to use far-field records in tsunami waveform inversion. Multiple time window inversion (Satake et al., BSSA, 2013) was applied to tsunami waveforms iteratively until the result resembles the stable moment-rate function from teleseismic inversion. We also used GPS data to perform a joint inversion of tsunami waveforms and co-seismic crustal deformation (Gusman et al., EPSL, 2012). According to results, the major slip region with a size of 100 km × 40 km is located down-dip the epicenter at depth ~28 km, regardless of assumed rupture velocities. The total seismic moment from the slip distribution estimated by the joint inversion is 1.24×10^{21} Nm (Mw 8.0) (Gusman et al., GRL, 2015). This seismic moment is slightly smaller than 1.88×10^{21} Nm (Mw 8.1) from a teleseismic waveform inversion.

The tsunami arrival time and polarity reversal observed at far-field DART stations can be accurately reproduced by solving shallow water equations and applying the phase velocity correction to the simulated waveforms (Watada et al., JGR, 2014). The slip distribution of the 2014 Iquique earthquake from our joint inversion method can accurately explain the tsunami waveform in the near-field as well as in the far-field. We propose the tsunami phase velocity correction to be included as a standard procedure in inversion methods when using far-field tsunami waveforms.

The teleseismic inversion with different rupture velocities (1.5, 2.0, and 2.5 km/s) yielded similar moment rate functions which all peaked at ~35 s, but their spatial slip distributions are different. On the contrary, the joint inversion gives a stable spatial slip distribution for different rupture velocities. Among the slip distributions from the teleseismic inversions with the three different rupture velocities, the one for 1.5 km/s is most similar to the slip distribution from the joint inversion of tsunami waveforms and GPS data in terms of large slip area. Thus, the velocity of 1.5 km/s may better represent the rupture process of the 2014 Iquique earthquake (Gusman et al., GRL, 2015).

キーワード: Rupture process, Tsunami waveforms, GPS data, Teleseismic body waves, Tsunami dispersion, Joint inversion
Keywords: Rupture process, Tsunami waveforms, GPS data, Teleseismic body waves, Tsunami dispersion, Joint inversion

Tsunami Hazards from secondary sources in the Makran Subduction Zone, northwestern Indian Ocean

Tsunami Hazards from secondary sources in the Makran Subduction Zone, northwestern Indian Ocean

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We present evidence for hazards from secondary tsunami sources in the Makran subduction zone (MSZ), NW Indian Ocean, by analyzing two tsunami events of November 1945 and September 2013 in this region. We revisited the source of the 27 November 1945 tsunami in the MSZ by analyzing two observed tsunami waveforms in Karachi and Mumbai and coastal deformation data. However, the source model based on far-field tsunami waveforms (Heidarzadeh and Satake 2014, *Pure Appl. Geophys.*, doi: 10.1007/s00024-014-0948-y) produces a maximum coastal runup height of 5-6 m in the near-field; almost half of the observed runup height of 12-15 m. This finding combined with the reports of failure of the trans-oceanic submarine communication cables during this earthquake and tsunami may indicate possibility for submarine landslides triggered by the main shock. Another possibility can be large slip due to splay faults which branch from the plate boundary during large earthquake since many splay faults are present in the seismic profiles of the MSZ. These secondary tsunami sources cannot be estimated from far-field tsunami data. The recent tsunami on 24 September 2013 in the Makran region was triggered by an inland Mw 7.7 earthquake. While the main shock and all aftershocks were located inland, a tsunami with a dominant period of around 12 min was recorded on nearby tide gauges and a DART station. We examined different possible sources for this tsunami including a mud volcano, a mud/shale diapir, and a landslide/slump through numerical modeling (Heidarzadeh and Satake 2014, *Geophys. J. Int.* 199, 752-766). Only a submarine landslide/slump with a source dimension of 10-15 km and a thickness of around 100 m, located 60-70 km offshore Jiwani (Pakistan) at the water depth of around 2000 m, was able to reasonably reproduce the observed tsunami waveforms. In terms of tsunami hazards, analysis of the two tsunamis shows that the MSZ is posed to potential tsunami hazards from secondary sources such as submarine landslides and splay fault branching from the plate boundary.

キーワード: Northwestern Indian Ocean, Makran subduction zone, Tsunami, Splay faulting, Landslide, Tsunami secondary sources

Keywords: Northwestern Indian Ocean, Makran subduction zone, Tsunami, Splay faulting, Landslide, Tsunami secondary sources

台湾チェルンプー断層における地震サイクルに伴う小断層の分類とラフネス変化 Microfault classification and difference in roughness with seismic cycles exemplified from the Chelung-pu fault, Taiwan

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Change in stress with seismic cycle was strongly related to stress drop. Just after Tohoku-Oki earthquake, the stress orientation was changed from horizontal compressional stress to vertical compressional stress. The change in stress orientation with seismic cycle can be detected also in paleostress using slip data from microfault close to seismic faults in on-land accretionary complex. In addition, after the change in paleostress is detected, we can classify the microfault into two. One is related to the stress state before earthquake and another is related to the stress state after earthquake. Furthermore, we also observed the classified microfault directly. In this study, we examined the paleostress in the Chelung-pu fault, Taiwan, which was a seismogenic fault at the time of the Chi-Chi earthquake, 1999 and then we analyzed roughness of the classified micro-faults.

We have conducted paleostress analysis using multiple inversion method for slip data from microfault in cores drilled in Taiwan Chelung-pu Fault Drilling Project (TCDP). Two stress orientations were classified; one is the horizontal maximum principal stress and another is the others are the horizontal minimum or intermediate principal stresses in the compressional stress orientation at the time of the Chi-Chi earthquake, which is the switch in stress orientation similar to that in Tohoku-Oki earthquake. Combining the estimated stress orientations with stress polygons, the stress magnitude for each stress state was constrained. Stress magnitude for the horizontal compressional stress is larger than that for the horizontal extensional stress, which support the idea that the change in stress state can be related to seismic cycles.

On the basis of the stress inversion results, we classified the microfaults into that related to horizontal compressional stress and that related to horizontal extensional stress. We have collected samples of microfault for each stress state and identified that the roughness of the fault surfaces is different between them. Relief of slicken lines on microfault for horizontal compressional stress is deeper than that for horizontal extensional stress. To examine the topography of microfault surface quantitatively, we have conducted topographical analysis using a confocal microscope. Power Specter Density (PSD) was obtained from topographical data. Higher PSD value was detected in the samples for horizontal compressional stress than that for horizontal extensional stress. The slope angle of trend in PSD vs wavelength is shallower in horizontal compressional stress than that in vertical compressional stress. The differences in roughness of microfault surface can be related to the difference in stress magnitude as identified above.

キーワード: 古応力, 地震サイクル, 小断層, ラフネス

Keywords: paleostress, seismic cycle, microfault, roughness

準高速すべりに伴うスメクタイト質断層の動的強度弱化 Dynamic weakening of smectite-bearing faults at subseismic slip rates

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The hydrous clay mineral smectite, which is pervasive in sediments on subducting oceanic plates, is thought to weaken and stabilize subduction thrust faults. However, these frictional properties of smectite alone cannot explain the large coseismic slip in the vicinity of a trench. Here, we performed friction experiments to demonstrate the rate dependence of friction at slip rates from 30 $\mu\text{m/s}$ to 1.3 m/s for water-saturated smectite-quartz mixtures with various smectite contents, so as to shed light on the frictional response of smectite-bearing faults at intermediate to high slip rates. At slip rates of 30 to 150 $\mu\text{m/s}$, the friction coefficients decreased gradually from 0.5-0.6 to 0.1 with an increase in smectite content from 20 to 50 wt%. In contrast, at slip rates higher than 1.3 mm/s, friction exhibited marked slip weakening, resulting in low friction coefficients of 0.1-0.05, even for low smectite contents (roughly <30 wt%). Drastic slip weakening occurred at smectite contents of 10-30 wt% at slip rates of ~ 10 mm/s, which is one to two orders of magnitude lower than the slip rate at which slip weakening was observed in previous experiments on various rock types. The intermediate-velocity weakening could be attributed to a rise in pore pressure caused by both shear-enhanced compaction and microscopic thermal pressurization of pore fluids. This process could weaken the fault even below seismic slip rates, leading to an acceleration of fault motion and potentially facilitating large coseismic slip and a stress drop in the vicinity of a trench.

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キーワード: 海底堆積物, 摩擦実験, 速度弱化, デコルマ, 巨大分岐断層, 津波地震

Keywords: marine sediments, friction experiment, velocity weakening, decollement, megasplay fault, tsunamigenic earthquakes