

## Insights on Structure and Deformation in the Input Section of the Sumatra Seismogenic Zone: Preliminary Results from International Ocean Discovery Program (IODP) Expedition 362

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The Sunda Trench where the Indo-Australian Plate subducts beneath the Sunda and Burma Plate, is an active seismogenic zone which generated the 2004 Mw 9.2 mega-earthquake and devastating tsunami offshore Northern Sumatra, characterized by a large shallow slip near the trench and an extremely thick (>4 km) incoming section at the deformation front. To investigate the nature and impact of the incoming section on seismogenic processes, the International Ocean Discovery Program (IODP) Expedition 362

drilled into the Indo-Australian Plate ~225 km distance from the trench at 2 primary sites offshore Northern Sumatra during August to October 2016. Here, we report preliminary results from shipboard structural observation on the recovered cores.

The lithostratigraphic sequence of the oceanic plate acquired from Site 1480 consists of Unit I: subsurface calcareous and silty clay (~26.4 m), Unit II: silty clay and sand of the Nicobar Fan sequence (~26.4-1250 m), Unit III: pelagic gray-green to reddish-brown tuffaceous claystone and chalk (~1250-1327 m), Unit IV: basaltic lava flows and volcanoclastic/tuffaceous sandstone (~1327-1350 m), Unit V: chalk and calcareous claystone with magmatic intrusion/extrusion with abundant mineral veins (~1350-1420 m), and Unit VI: basaltic basement cut by veins (1420 m~). Units I and II exhibit little deformation as observed from the continuously near-horizontal bedding dips ( $<10^\circ$ ), except for several localized horizons of syn-sedimentary normal faults in Unit II and intervals of slumping and folds. The bottom of Unit II (~460 m interval) was particularly undeformed, possibly reflecting the most distal portion of the fan deposit. A distinct concentration of normal faults was observed in Unit III, characterized by primarily two sets of thin anastomosing normal faults which randomly cross-cut each other. Sand injections and lighter-colored diagenetic spots also occur in the sediments, and the normal faults generally cut through the sand injections but generally leave the diagenetic spots uncut. The flattened geometry of the diagenetic spots overprinting the normal faults and the high conjugate angle ( $>90^\circ$ ) and curvy geometry of the faults may imply that the normal faulting occurred before significant compaction. Concentrated deformation in the pelagic section may have occurred in an active ridge environment at that time and thermal subsidence followed by rapid sedimentation of the Nicobar Fan, but the actual mechanism is yet to be revealed.

Ongoing post-cruise research will further examine the internal structure, paleo-stress state, and material properties at these horizons of localized deformation in the input section, and ultimately investigate how they would evolve upon entering the subduction zone through comparison with current stress states and active fault systems.

キーワード：国際深海科学掘削計画、スマトラ沖地震発生帯、インド・オーストラリアプレート

Keywords: International Ocean Discovery Program, Sumatra Seismogenic Zone, Indo-Australian Plate

## Measurements of thermal conductivity of a basalt core sample retrieved from subducting oceanic crust in Nankai subduction zone under high temperature

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Knowledge of rock thermal conductivity is a key to understand thermal structure in active seismogenic zones such as the Nankai Trough subduction zone, SW Japan. To estimate thermal conductivity at the oceanic crust surface in the seismogenic zone, we measured the thermal conductivity of a basalt core sample retrieved from subducting oceanic basement at a depth of ~573 mbsf in input site C0012 of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) under high temperature (maximum 160°C). The high temperature condition corresponds to that at the oceanic crust surface in the updip limit of the Nankai seismogenic zone (~7 km below the seafloor). Thus, we set our high temperature condition of the thermal property measurements up to 160°C at atmospheric pressure for a dry basalt core sample, and up to 100°C for a wet basalt core sample at the same pressure condition.

As results of the experiments, thermal conductivity of the dry basalt core sample under high temperature and atmospheric pressure gradually increased with increasing ambient temperature. The thermal conductivity of the wet sample also showed an increasing trend, but the value measured at 100°C might be strongly influenced by the evaporation of pore water, and consequently revealed a sharp increase between 80 and 100°C. The thermal conductivity of the wet basalt was ~1.62 W/mK at room temperature. Under atmospheric pressure condition we could not measure the thermal conductivity of the wet basalt at 160°C, but we estimated the value to be ~1.77 W/mK based on both measured thermal conductivity of the dry basalt sample and literature thermal conductivity data of pore water at the same temperature 160°C. Generally, for other rock types such as sandstone and granite, however, their thermal conductivity decreases with increasing temperature, in contrast to the thermal conductivity of the oceanic basalt increased with increasing ambient temperature.

The thermal conductivity at ~7km also depends on the in situ pressure condition. We will also show our estimation of the thermal conductivity at ~7km in Nankai subduction zone not only for high temperature but also for high pressure effects.

キーワード：熱伝導率、高温条件、玄武岩

Keywords: thermal conductivity, high temperature, basalt

## Heat flow distribution along the Nankai Trough floor: Correlation with the structure of the incoming oceanic crust

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Surface heat flow observed on the floor of the Nankai Trough should reflect the thermal structure of the incoming Philippine Sea plate (Shikoku Basin). Detailed measurements along the trough axis revealed that heat flow on the trough floor in the central part (between 135°E and 136°E) is extremely high and variable, much higher than the value corresponding to the seafloor age. On the east of 136°E, heat flow steeply decreases eastward to the value consistent with the age with no appreciable scatter. In the area west of 134.5°E, the observed heat flow is more or less normal for the age and shows low scatter. This peculiar heat flow distribution is well correlated with the structure of the Shikoku Basin oceanic crust. The high and variable heat flow area in the central part corresponds to the youngest part of the Shikoku Basin, which was formed by spreading in the NE-SW direction, whereas the neighboring areas with less scattered and lower heat flow were formed by E-W spreading. Other geophysical data, e.g., seismicity, crustal thickness, and basement topography, also show significant variations around the boundaries between the two spreading directions, indicating that the crustal structure changes across the boundaries. The high heat flow in the central part can be attributed to vigorous fluid circulation in a permeable layer (aquifer) in the subducted oceanic crust, which efficiently transports heat upward along the plate interface (Spinelli and Wang, 2008). It is probable that the permeability structure of the oceanic crust changes at the boundaries between the E-W and NE-SW spreading, which yields variations in vigor and/or pattern of fluid circulation, resulting in the observed high to normal heat flow transitions across the boundaries. Another feature of the heat flow distribution in the central part, high variability, appears to arise from the crustal structure as well. The central part is characterized by large basement relief and heat flow values have negative correlation with sediment thickness; heat flow tends to be high on basement highs. Similar correlation cannot be recognized in the areas formed by E-W spreading. It suggests that the high heat flow variability in the central part may also be due to fluid circulation in the permeable layer. These results indicate that the structure of the Shikoku Basin originated from its spreading history has a large influence on physical/chemical conditions along the plate interface (seismogenic zone of large thrust earthquakes and slow earthquakes) through fluid and heat transportation in the oceanic crust.

キーワード：南海トラフ、四国海盆、熱流量、海洋地殻、流体循環、基盤地形

Keywords: Nankai Trough, Shikoku Basin, heat flow, oceanic crust, fluid circulation, basement topography

## Along-trough variation in the seismic structure of the incoming Philippine Sea plate just seaward of the Nankai Trough

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Rupture of large-thrust earthquakes along the Nankai Trough is known by always initiating from off the Kii Peninsula. The segmentation boundary between the 1944 Tonankai (Mw=8.1) and the 1946 Nankai (Mw=8.4) earthquake rupture is located on the Kii channel, off the Kii Peninsula. Activity of the nonvolcanic deep low-frequency tremors and very low-frequency earthquakes observed around the down-dip limit of the coseismic rupture zone of the last Tonankai and Nankai earthquakes is not homogeneous, and the belt-like tremor zone is divided into several segments bounded by gaps [Obara, 2010]. Largest gap is recognized around the Kii channel between the Shikoku Island and Kii Peninsula.

Our recent integrated result of first-arrival tomography based on the 2012 and 2014 wide-angle OBS data shows dramatic along-trough variation in P-wave velocity just beneath the basement of the incoming Philippine Sea plate. Variations in P-wave velocity from ~4km/s to more than 5km/s can be recognized south off the Cape Muroto, Shikoku Island and the Shima Peninsula, about 50-60km and 20km seaward of the deformation front, respectively. Such dramatic velocity change corresponds with the structural boundary observed as variation in the configuration of the basement reflection in the time-migrated section, and the boundary of the plate age of about 20-21.5Ma proposed based on magnetic lineation by Okino [2015]. Similar along-trough structural variation in the incoming Philippine Sea plate can be recognized along two seismic profiles across the central Shikoku Basin far south from the trough axis [Nishizawa et al., 2011]. Furukawa et al. [this meeting] also find out the similar structural change around the eastern margin of the northern Shikoku Basin along several seismic profiles across the Izu-Ogasawara arc [Takahashi et al., 2015]. The low P-wave velocity of the oceanic layer 2 formed at backarc region is concerned to be related to high porosities and arc-related mineralogies [e.g. Dunn and Martinez, 2011]. Seismic velocities decrease in the oceanic crust may also indicate high water contents, which may be one of the causes of the low-frequency seismic phenomena around the down-dip limit of the Nankai Trough subduction seismogenic zone. This structural characteristic is thought to continue northwards to the subducting Philippine Sea plate beneath the southwest Japan, and may cause the segmentation of an earthquake rupture, and heterogeneous activity of the nonvolcanic deep low-frequency tremors and very low-frequency earthquakes.

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# Crustal structure of the eastern Nankai Trough from Full Waveform Inversion of the dense Ocean Bottom Seismometers data

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The Nankai Through region is one of the best sites providing an excellent natural laboratory for studying factors controlling segmentation of the earthquake rupture zones in subduction systems. The area has a ~1300 year historical record of damaging earthquakes and is constantly under intense multidisciplinary scientific investigation. For this purpose enormous number of data are acquired in this region. Among them high quality seismic datasets, including multi-channel reflection seismic (MCS) and wide-angle reflection/refraction seismic (WARR) acquired using Ocean Bottom Seismometers (OBS), provide a great potential for seismic imaging.

Crustal-scale velocity models from 2D marine WARR surveys are usually built using ray-based methods. However their ability to resolve complex structures is limited by factors such as: OBS spacing, width of the Fresnel zone or interpreter's ability to distinguish and associate the picked phases with the model interfaces. From the other hand rapid development of the Full Waveform Inversion (FWI) methodology during last decade allows for automation of the crustal velocity model building in the unprecedented resolution, given that the sufficiently dense acquisitions are used. Additionally, potential of FWI stimulates not only development of the imaging algorithms –but also new acquisition technologies including growing pools of OBS instruments available to the academic community making it possible to acquire dense WARR OBS data in 3D.

Here we present multiscale, layer-stripping strategy for the semi-automatic, high resolution, crustal-scale imaging using FWI. We develop practical workflow including: (i) preprocessing focused on the improvement of the data coherency and boosting low frequencies; (ii) thorough and early stage QC starting from the analysis of the traveltimes error in the initial model; (iii) final model validation procedures using source estimation, evaluation of the data fit with Dynamic Image Warping, correlation with PSDM image and the interpretation of crustal phases by the ray-tracing. We successfully apply this workflow to the 2D OBS dataset from the eastern Nankai Through acquired by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) involving 100 OBS uniformly deployed along a 100-km long profile recording air-gun shots extended along 140-km long profile with a 100 m spacing.

As a result we obtain velocity model of the complex subduction zone with clearly delineated shallow and deep structures. In particular in the backstop we observe large-scale stacked thrust sheets covered by sediments of forearc basin. These structures spatially extend to the area of accretionary prism forming Kodaiba and Tokai thrusts. Further into seaward direction we can point sequence of smaller thrusts delineating active wedge covered by slope basins and the thick layers of sediments in the trench. We observe local thickening of the oceanic crust corresponding to the subducting oceanic ridges as well as a sharp low-velocity zone (LVZ) atop the oceanic crust, which represent a damage fault zone created by one of these ridges colliding with the backstop. The top of the LVZ corresponds to a splay fault along which the co-seismic slip can occur during the next large earthquake in the area.

We show that with FWI one is able to retrieve a detailed information on the subduction zone structure that can be used as an input for other studies (e.g. geodynamical modeling). High resolution velocity models

accompanied by image from MCS data increase interpreter's ability not only in terms of structural interpretation but also help to understand formation processes. Our study presents great potential of the FWI as a semi-automatic method for better imaging of complex crustal targets being beyond the reach of the WARR or towed-streamer surveys. Further tests of FWI with decimated acquisitions reveal that even datasets with 5km OBS-spacing have potential to deliver satisfactory results in terms of imaging overall crustal structure.

Keywords: subduction zone, crustal-scale imaging, full waveform inversion, velocity model building, OBS data, Nankai Trough

# 人工地震探査による日本海溝アウターライズ東麓における海洋性地殻構造 Crustal structure beneath the eastern foot of the Japan Trench outer rise by airgun-OBS survey

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海洋性地殻の地震波速度構造は、比較的均質性が高いと考えられるが、海洋性地殻下部から最上部マントルにかけて複雑な構造をもった反射面が認められることがある。こうした地殻深部やマントルにみられる不均質構造の要因の一つとして、海洋プレートの形成・発達過程が考えられる。たとえば、千島海溝沖の北西太平洋の最上部マントルに認められる反射構造は、プレート運動に伴って形成されたリーデル剪断と解釈されている (Kodaira et al., 2014)。本研究では、日本海溝アウターライズの東麓において実施したエアガン-海底地震計 (OBS) 構造探査の波形記録を解析し、この領域の地殻・マントル内の地震波反射構造を詳細に明らかにすることを通して海洋プレートの形成・発達過程を考察する。

本研究で用いるエアガン-OBS 探査データは、2010年に北西太平洋において取得されたもので、6 km 間隔で23台のOBSを設置した測線沿いに、エアガン発振を0.2 km 間隔で1199 回行った。得られたOBS記録を見ると、初動振幅が顕著に小さくなるシャドウゾーンが認められた。シャドウゾーンが現れ始めるまでの初動は海洋性地殻第3層からの屈折波(Pg)と解釈されることから、海洋性地殻深部のモホ面の直上にシャドウゾーンの原因となる構造が存在すると推察される。こうしたシャドウゾーンは測線南側のOBSの記録でより広く認められ、地殻深部の構造が測線に沿って大きく変化することが示唆される。こうしたOBS記録の特徴を再現するよう、P波速度構造を2次元波線追跡法により構築した結果、海洋性地殻第3層下部に低速度層が存在し、その厚さが測線に沿って変化していると仮定することで、観測記録の特徴をおおむね再現することができた (大友・他, SSJ, 2016)。

一方、OBSによる広角反射法地震探査記録に地震波干渉法を適用して合成した稠密な仮想観測点における地震波形に反射法的処理を施すことで、海洋プレート内反射構造のイメージングを試みたところ、地殻深部からモホ面程度の深度に相当する垂直往復走時9秒付近に連続性の良い反射信号を抽出することに成功した (大友・他, JpGU, 2016)。これを、2次元波線追跡法による屈折波のフォワード解析で得られた構造モデルと対応させると、イメージされた反射面は、モホ面ではなく、地殻最深部に分布する低速度層上面からの反射波である可能性がある。そこで、屈折法解析から得た構造モデルをもとに理論波形計算を行い、理論波形に対して反射法的処理を施すことで、低速度層上面からの反射波がイメージングされるのかを調べてみた。観測波形記録に対して施したのと同様の手順で地震波干渉法および反射法的処理を行って得られた反射断面上には、往復走時で9秒、9.7秒付近に反射面がイメージされ、浅い側の反射面が低速度層上面からの反射波に対応することがわかった。この往復走時が、実際の観測記録から得られた反射断面に認められる反射面の走時が低速度層上面反射のものと整合的であることから、実際の探査によって低速度層上面からの反射波が捉えられている可能性が高い。

実際の反射断面上では、この低速度層上面からの反射波は測線の南側で顕著である一方で、北側では不明瞭になっている。このことを、OBSで観測される初動のシャドウゾーンが測線南側でより広く現れる傾向と対応すると考えると、海洋性地殻深部にある低速度層は、層の厚さが測線に沿って変化しているのではなく、層内の速度が南部側ではより低速度で上面における速度コントラストが大きくなっていることが示唆される。

今後は、走時インバージョンとともに詳細な波形モデリングを行い地殻内部の地震波速度分布を詳しく検討するとともに、OBSデータの反射法的処理におけるデコンボリューションなどの波形処理の微調整を行うことにより、反射断面の品位の向上も進める予定である。





## Seismic structure beneath the petit-spot area and its implications

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The nature of the sedimentary layer on the top of the incoming oceanic plate is one of key controlling factors on the interplate coupling after plate subduction. In the northwestern Pacific margin off NE Japan, the Pacific plate is generally covered with a sedimentary layer consisting of mainly pelagic sediments of a few hundreds meter thick. However, locally thin sediments areas have been found by existing seismic reflection profiles. One of such thin sediments areas is located at the outer rise of the central Japan Trench and the size is roughly 50km square. This area is known as one of petit spot volcano sites; more than 80 petit spot volcanos are expected in this area (Hirano et al., 2006, 2011).

In 2014 and 2015, we conducted OBS-airgun surveys along a 600 km long 2-D seismic survey line crossing the petit spot area. We deployed 88 OBSs at intervals of 6 km and shot a tuned airgun array of R/V Kairei. We applied a traveltimes inversion to model P-wave velocity ( $V_p$ ) structure and found  $V_p$  just beneath the shallowest reflector beneath the seafloor is lower in the petit spot area than that in the other areas. To image the detailed seismic structure of the shallow sedimentary layers, we calculated receiver functions using the active-source seismic data. The receiver function analysis is a technique to image P-to-S conversion interface just beneath each OBSs. At most OBSs, only one P-to-S conversion interface is imaged at the expected time of the basement (top of the oceanic crust). But, in the petit spot area, we observed several P-to-S conversion interfaces. Since the deepest interface at the petit spot area is approximately equal to the basement in other areas, we infer that shallower P-to-S conversion interfaces are located within the sedimentary layer and that these interfaces might be related to the intrusion of sills, because we can expect pervasive sill intrusions beneath the petit spot area based on the observation at the outcrop of a petit spot in the central America (Buchs et al., 2013) and on the petit spot model proposed by Hirano et al. (2006).

The seismic coupling between the overlying plate and the subducting plate is probably affected by the nature of the sedimentary layer of the incoming plate, meaning that the subduction of petit spot area might cause the spatial variation in the interplate coupling after subduction. Although each petit spot volcano itself is very small, existing seismic reflection data suggest that the whole petit spot area, roughly 50 km square, is probably characterized by pervasive sill intrusions. Since the size of this petit spot area corresponds to the coseismic rupture area of M7 ~ M8 interplate earthquakes in the subduction zone of the Japan Trench, the subduction of petit spot areas might be one of the causes for a spatial variations in the distribution of interplate earthquakes in this subduction zone.

キーワード：構造探査、日本海溝、プチスポット火山

Keywords: controlled-source seismic survey, Japan Trench, petit spot volcano

## Towards electrical resistivity imaging around outer-rise bending normal faults off the Japan trench

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Hydration in the oceanic crust and uppermost mantle beneath the outer-rise area is thought to be main source of aqueous fluid in the subduction zone (e.g. Ranero et al., 2003). Thus the mapping of hydrating fluid in outer rise areas is essential to understand dynamics, earthquakes and volcanic activities in subduction zones. Imaging of electrical distribution is useful to detect hydration beneath the outer-rise area because electrical resistivity reflects amount, composition and connectivity of fluid, temperature, and serpentinization. Recent developments of control source electro-magnetic (CSEM) investigation methods allow us to obtain high resolution images of resistivity distribution beneath the outer-rise area (Naif et al., 2015). Thus CSEM experiments is being planned in an outer-rise zone in Tohoku-oki area (incoming Pacific plate near the NE Japan arc). In this study, we introduce a present resistivity model based on natural source EM (magnetotelluric) surveys in this area. The model shows that surface conductive layer is thicker beneath the EM station closer to the Japan trench compared to the farther station (40 and 60 km from Japan trench, respectively). Sensitivity tests indicate that the observed data require the variation of thickness of conductive layer. Thus resistivity imaging is effective to investigate hydration in the outer-rise zone in the Tohoku-oki area. Because CSEM investigations can image more detailed resistivity distribution, high resolution mapping of hydration will be realized in this area. Thus we plan CSEM experiments around the Magnetotelluric survey line in mid 2017. The details of CSEM survey plan will be introduced in the presentation.

## 蛇紋岩の弾性波速度に対する間隙水の影響とアウターライズ領域での蛇紋岩化の再検討

### Effect of pore water on elastic wave velocity of serpentinites and implication for serpentization at outer-rise region

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近年の海底地震波探査からアウターライズ領域において地震波の低速度領域が観測されている (e.g., Fujie et al., 2013; Shillington et al., 2015)。この地震波の低速度はマントル領域まで達するため、アウターライズ断層から海水が供給され蛇紋岩が形成していると解釈されている (e.g., Ranero et al., 2003)。カンラン岩の地震波速度は蛇紋岩化率の増加とともに低下することが実験から報告されており (Christensen, 2004)、観測された速度と比較することでマントルの蛇紋岩化率が見積もられている。しかし、蛇紋岩には反応に伴う体積膨張により多くの空隙が発達しており (Macdonald and Fyfe, 1985)、そのような空隙には水で満たされている可能性が高い。そこで本研究では様々な空隙率をもつ蛇紋岩の弾性波速度に対する間隙水の効果を調べ、アウターライズ領域における蛇紋岩化を再評価した。

実験試料には嶺岡帯に産出する蛇紋岩と、南マリアナ海溝、トンガ海溝の海底からドレッチされた蛇紋岩を用いた。それらは低温型蛇紋石であるリザーダイト・クリソタイルから主に構成される。これらの試料は、画像解析から蛇紋岩化率が86–100%であった。空隙率は気相置換法によって測定し、嶺岡帯試料では0.3–4.4%、海底ドレッチ試料は9.6–26.7%であった。実験には広島大学設置の容器内変形透水試験機を用いて、パルス透過法により弾性波速度を測定した。実験は乾燥条件に加え、含水条件では間隙水圧を10MPa一定に制御した条件で測定を行った。封圧は200MPaまで加圧し、温度は室温で測定した。

弾性波速度は封圧の増加に伴って増加し、乾燥条件での封圧200MPaの速度はChristensen(2004)の密度と速度の関係とほぼ一致した。含水条件ではP波速度は乾燥条件の速度より低封圧下では8%程度、高封圧下では3%程度速い速度を示した。これは空隙が水で満たされることで岩石の体積弾性率が増加し、P波速度が上昇すると考えられる。一方で、S波速度は空隙率が低い試料では水の効果は見られないが、空隙率が高い試料では7%程度低下した。これは剛性率に対しては流体の効果は小さいが、密度が増加するためにS波速度が低下したと考えられる。

これまでの研究では、最上部マントルの速度異常から蛇紋岩化率は20%程度と見積もられているが、蛇紋岩の空隙率を10%とし、その空隙が水で満たされる場合、蛇紋岩化率はこれまでの見積もりより低くなり15%程度となる。このようにマントルでの蛇紋岩の分布ならびに割合を評価するには、岩石中の空隙率を正確に把握する必要がある。

キーワード：蛇紋岩、間隙流体、弾性波速度、アウターライズ領域

Keywords: Serpentinite, Pore fluid, Elastic wave velocity, Outer-rise region