

Eastern Gondwana breakup: Rifting and subsidence from the Tasman Basin through Lord Howe Rise

*Brian Boston¹, Yasuyuki Nakamura¹, Shuichi Kodaira¹, Seiichi Miura¹, Flora Gallais¹, Gou Fujie¹, Yuka Kaiho¹, Ron I Hackney², Yasuhiro Yamada¹, Saneatsu Saito¹, Kazuya Shiraishi¹, Scott Nichol², George Bernardel², Cameron Mitchell²

1. Japan Agency for Marine-Earth Science and Technology, 2. Geoscience Australia

During the Late Cretaceous, the eastern Australian margin rifted to form the Lord Howe Rise continental ribbon. To understand the history of this region since rifting we use reflection seismic data collected in 2016 onboard R/V *Kairei*. We focus on processing and interpreting a regional ~900-km-long east-west oriented seismic reflection profile at 27.2°S. The seismic data were processed through pre-stack depth migration and interpretation shows the structure and evolution of this margin. The profile covers the oceanic Tasman Basin through the continental Lord Howe Rise. Sediment-filled depressions are found within the Tasman Basin and likely relate to early transform faulting with later deposition. The Lord Howe Rise is largely made up of syn-rift and post-rift sedimentary sequences in multiple structurally controlled basins. Two additional features are found between these regions, the Dampier Ridge and the Middleton Basin. The Dampier Ridge has a sharp, probably transform, boundary against the eastern edge of the Tasman Basin. Within the ridge are multiple rift basins up to 3 km deep that are comparable in size and structure to those found on the Lord Howe Rise. Between the Dampier Ridge and the Tasman Basin is the Middleton Basin which contains well-stratified sediments that are up to ~3.5 km thick. Stratal relationships indicate that the Middleton Basin formed during a post-rift event with large amounts of subsidence. Deep reflections beneath this basin reveal mantle at a shallow depth. The results have important implications for the evolution of the margin from initial rifting, opening of the Tasman Basin, and subsequent deformational processes.

オントンジャワ海台は分厚い海洋性地殻か？ Is the Ontong Java Plateau thick oceanic crust?

*三浦 誠一¹、藤江 剛¹、白井 太郎¹、野口 直人¹、小平 秀一¹、ミラード コフィン²、カワグル サイモン³、ヴェラヴ ロナルド⁴

*Seiichi Miura¹, Gou Fujie¹, Taro Shirai¹, Naoto Noguchi¹, Shuichi Kodaira¹, Millard F Coffin², Simon A Kawagle³, Ronald T Verave⁴

1. 海洋研究開発機構、2. タスマニア大学、3. パプアニューギニア大学、4. パプアニューギニア鉱物資源庁

1. Japan Agency for Marine-Earth Science and Technology, 2. University of Tasmania, 3. University of Papua New Guinea, 4. Mineral Resource Authority, PNG

オントンジャワ海台 (OJP) は大規模火成岩区域 (LIP) の中でも最大級であり代表例のひとつである (Coffin and Eldholm, 1994)。周囲の海洋底から水深が浅くなっている部分は日本列島の5倍にも匹敵する面積 ($1.6 \times 10^6 \text{ km}^2$; Mahoney et al., 2001) である。OJPにおけるこれまでの深海掘削結果から、基盤岩は概ね120Maの玄武岩となっており (Shipboard Scientific Party, 2001)、広大なOJPが地質学的に短時間に形成されたことが推定されている。このようなOJPおよびLIPの形成メカニズムについて、プリューム説 (e.g. Richards et al., 1989)、隕石衝突説 (e.g. Ingle and Coffin, 2004)、デラミネーション (e.g. Elkins-Tanton, 2005)、など様々なモデルが提唱されているが、既存の観測事実をすべて説明するには至っていない。形成メカニズム解明のためには構造情報が重要であるが、これまでモホ面深度についても観測手法によって諸説ありははっきりしていなかった。例えば地震学的手法による結果では最大42km (Furumoto et al., 1976) だが、重力モデリングによる結果では25kmと大きく異なっていた (Sandwell and Renkin, 1988)。そのため信頼性の高いモホ面深度を求めることが必要であった。海洋研究開発機構では2010年にOJPの中央部High Plateauにおいて大容量エアガンアレイと100台の海底地震計 (OBS) を用いた大規模地震学的構造探査を実施した (Miura et al., 2011)。得られたデータは高品質で、OBSデータではオフセット距離300km以上からの初動走時が確認できる。初動走時とモホ面反射波を用いたインバージョン解析によるP波速度構造からモホ面の最大深度は約43kmとなる。その速度構造は海洋性地殻を大規模にしたもののように見える。速度勾配の比較的大きな地殻上部と、速度勾配の比較的小さい地殻下部が分布しており、海洋性地殻第2層と第3層に相当すると考えられる。P波速度だけでなく、S波速度および V_p/V_s 比からも海洋性地殻とほぼ同等である。速度構造から密度を仮定した簡易計算によるとアイソスタシーがなりたち、高密度層は必要としない。そのため現在のOJPが陸化していないのは構造的に説明できることとなる。またOJPの速度構造は地殻の厚さは異なるもののアイスランドの構造と似ている (Foulger et al., 2003)。アイスランドは大西洋中央海嶺にホットスポットが影響して陸化しているが、OJPでは陸化していないと考えられている。形成メカニズムが全く同じというわけにはいかないが、重要な示唆を与える。本発表では形成メカニズムについて検討したい。

キーワード：大規模火成岩区域、オントンジャワ海台、MCS、OBS、地殻、モホ面

Keywords: Large Igneous Province, Ontong Java Plateau, MCS, OBS, crust, Moho

Plate Boundary Reorganization of the Pacific Plate during Cretaceous

*中西 正男¹

*Masao Nakanishi¹

1. 千葉大学大学院理学研究科 地球生命圏科学専攻

1. Geosystem and Biosystem Sciences Division Graduate School of Science Chiba University

Several major tectonic events occurred in the Pacific plate during the mid-Cretaceous. A gigantic oceanic plateau was formed around 125 Ma and immediately separated into three plateaus, Ontong Java, Manihiki, and Hikurangi plateaus (Taylor 2006). At approximately the same time, Shatsky Rise ceased to be formed and then Hess Rise started to be formed (e.g. Sager, 2006). These events were accompanied by plate boundary reorganization of the Pacific plate. There are two large troughs in the western Pacific Ocean that are scars of the plate boundary reorganizations of the Cretaceous Pacific plate. One is the Nova-Canton Trough in the western equatorial Pacific Ocean. Taylor (2006) showed that the trough was formed during the separation of Ontong Java and Manihiki plateaus around 125 Ma. The other one is the Hokkaido Trough north of Shatsky Rise. Mammerickx and Sharman (1988) concluded that the trough was the initiation site of a failed oceanic rift which rifting propagated westward along the trough. Norton (2007) proposed another model that the trough is the abandoned Pacific-Izanagi Ridge. The origin of the Hokkaido Trough is still controversial.

The Hokkaido Trough is situated between Kuril Trench and Shatsky Rise. Most of the seafloor around the Hokkaido Trough were formed during the Cretaceous Normal Polarity Superchron (125.93-83.64 Ma), implying little magnetic anomaly lineations are available to reconstruct plate boundaries. Seafloor spreading fabric as abyssal hills and topographic features can give us the information of the reorganization of the mid-Cretaceous Pacific plate. We examined the topographic features around the Hokkaido Trough using multibeam bathymetric data. Most of the multibeam bathymetric data were obtained by the research cruises by R/V *Mirai*, JAMSTEC. The multibeam bathymetric data exposed the detailed topographic expression of the trough and seafloor spreading fabric around the trough. The topographic expression indicates that the Hokkaido Trough is not an abandoned spreading ridge proposed by Norton (2007). We found several curved troughs, which topographic feature is similar to those around the propagating ridges. Our study suggests that the reorganization of the Pacific-Izanagi ridge during Cretaceous was accompanied by propagation of the Pacific-Izanagi ridge and fragmentation of the Pacific plate.

キーワード：アビスサルヒル、断裂帯、北海道トラフ、太平洋プレート、白亜紀

Keywords: abyssal hill fabric, fracture zone, Hokkaido Trough, Pacific Plate, Cretaceous

Direct-ascended petit-spot magma from asthenosphere with little or no assimilation

*佐藤 勇輝¹、平野 直人²

*Yuki Sato¹, Naoto Hirano²

1. 東北大学大学院理学研究科、2. 東北大学東北アジア研究センター

1. Graduate School of Science, Tohoku University, 2. Center for Northeast Asian Studies, Tohoku University

Petit-spot is alkaline monogenetic volcano distributed at the localities of plate-flexure such as the concavely flexed zone of the outer rise prior to plate subduction and rebounding lithosphere after glacial unloading. Petit-spot volcanism is unlikely related to mantle plumes or hotspots because they are randomly distributed without making seamount tracks. Alkaline melt erupted at petit-spot volcanoes originate from asthenosphere which move upward through the oceanic lithosphere by tectonic forces associated with plate flexure. Therefore, sampling the petit-spot lavas may be the only way for us to gain the materials directly from the asthenosphere below oceanic plate.

In the case of petit-spots at the concavely flexed lithosphere, the base of the lithosphere is extended so that the least compressive principal stress (σ_3) is perpendicular to the flexural axis. Otherwise, the σ_3 changes to be parallel to the flexure axis below the upper lithosphere, where the stagnation of ascending melt is speculated at the mid-depth of lithosphere. During the stagnation, melt could experience various degrees of fractionation and/or assimilation with lithospheric mantle materials (Valentine and Hirano, 2010). Pilet et al. (2006) showed the chemical similarity between clinopyroxene observed in petit-spot mantle xenoliths and clinopyroxene from melt-metasomatized continental mantle peridotites. They argued the petit-spot melt experienced metasomatic interaction with lithospheric peridotite. Thus, it is indispensable to ignore consider the lithospheric interactions when we estimate the asthenospheric composition from petit-spot lava. We present the geochemical variation of petit-spot lavas in relation to the tectonic regime of subducting Pacific Plate.

Submersible investigation of petit-spot lava field off the Pacific coast of northeastern Japan, called Site C, was conducted in 2014 (YK14-05). In this cruise, we found a young petit-spot volcano (~ 0.1 Ma) on outer rise and collected fresh lavas. The lavas are low-SiO₂ and strongly alkaline relative to previously reported petit-spot basalts. In contrast to aphyric petit-spot basalts previously reported, strongly alkaline lavas in this study contain much olivine phenocryst, indicating more rapid magma ascending than other petit-spots caused by unique tectonic regime below the young volcanoes on the outer rise. We found that such tectonic forces of both upper and lower lithosphere below their eruptions sites are clearly correspond to geochemical variations.

キーワード：プチスポット、アセノスフェア、プレート屈曲、アルカリ玄武岩

Keywords: Petit-spot, Asthenosphere, Plate flexure, Alkali basalt

Ocean Bottom Gravity Measurement Using a Landing AUV

*押田 淳¹、巻 俊宏²、松田 匠未²、大熊 茂雄³、駒澤 正夫³、立花 冬威¹、久保田 隆二¹

*Atsushi Oshida¹, Toshihiro Maki², Takumi Matsuda², Shigeo Okuma³, Masao Komazawa³, Toi Tachibana¹, Ryuji Kubota¹

1. 川崎地質株式会社、2. 東京大学生産技術研究所、3. 産業技術総合研究所

1. Kawasaki Geological Engineering Co., Ltd., 2. Institute of Industrial Science, The University of Tokyo, 3. Geological Survey of Japan, AIST

Gravity measurement at sea is usually conducted by using a research vessel. The accuracy of this sea surface gravity data is around 1 mgal at most. Recently, gravity measurement using the cruising type AUV URASHIMA of JAMSTEC has been conducted. The accuracy of this subsea moving gravity measurement is about 0.1 mgal (Shinohara et al., 2015). On the other hand, gravity measurement at the ocean bottom was also carried out by using a ROV or using a hanging wire rope from a ship (Joshima et al., 2006, etc). The accuracy of this method is higher than those of the two moving methods mentioned above and is comparable with that of on land. The ocean bottom gravity measurement is generally conducted near the targets for exploration. Therefore, relatively large gravity anomalies can be observed. If the ocean bottom gravity measurement by using a seafloor landing AUV is implemented, it is possible to get more accurate gravity data in deep sea at low cost.

Preliminary experiments for ocean bottom gravity measurement using a hovering type AUV Tri-TON of IIS/UTokyo and an ocean bottom gravity meter OBG manufactured by KGE were successfully carried out in August 2015 and December 2016 at Numazu, Shizuoka Prefecture. To avoid use of vertical thrusters while the gravity measurement on seafloor and obtain an efficient grounding force, the buoyancy of Tri-TON attached with OBG was adjusted slightly negative in advance. Although tilt correction bias due to an ambiguity of the passive gimbal leveling system still remains, the gravity data obtained on seafloor have low SD values and its accuracy is almost comparable with those of on land.

キーワード：海底重力測定、着底型AUV、Tri-TON、OBG

Keywords: Ocean Bottom Gravity Measurement, Landing AUV, Tri-TON, OBG

自律動作の高性能広帯域海底地震計(NX-2G)の開発:動作試験報告

Development of the autonomous BBOBS-NX (NX-2G) : preliminary test report

*塩原 肇¹、伊藤 亜妃²、杉岡 裕子³、篠原 雅尚¹

*Hajime Shiobara¹, Aki Ito², Hiroko Sugioka³, Masanao Shinohara¹

1. 東京大学 地震研究所、2. 海洋研究開発機構 地球深部ダイナミクス研究分野、3. 神戸大学大学院 理学研究科

1. Earthquake Research Institute, University of Tokyo, 2. D-EARTH, Japan Agency for Marine-Earth Science and Technology, 3. Graduate School of Science, Kobe University

We have developed the broadband ocean bottom seismometer (BBOBS) and its new generation system (BBOBS-NX), and, with them, several practical observations have been performed to create and establish a new category of the ocean floor broadband seismology, since 1999. Now, our BBOBS and BBOBS-NX data is proved to be at acceptable level for broadband seismic analyses. Especially, the BBOBS-NX is able to obtain the low noise horizontal data comparable to the land station in periods longer than 10 s, which is adequate for modern analyses of the mantle structure. Moreover, the BBOBS(T)-NX is under practical evaluation for the mobile tilt observation at the seafloor, which will enable dense geodetic monitoring by its mobility and low cost.

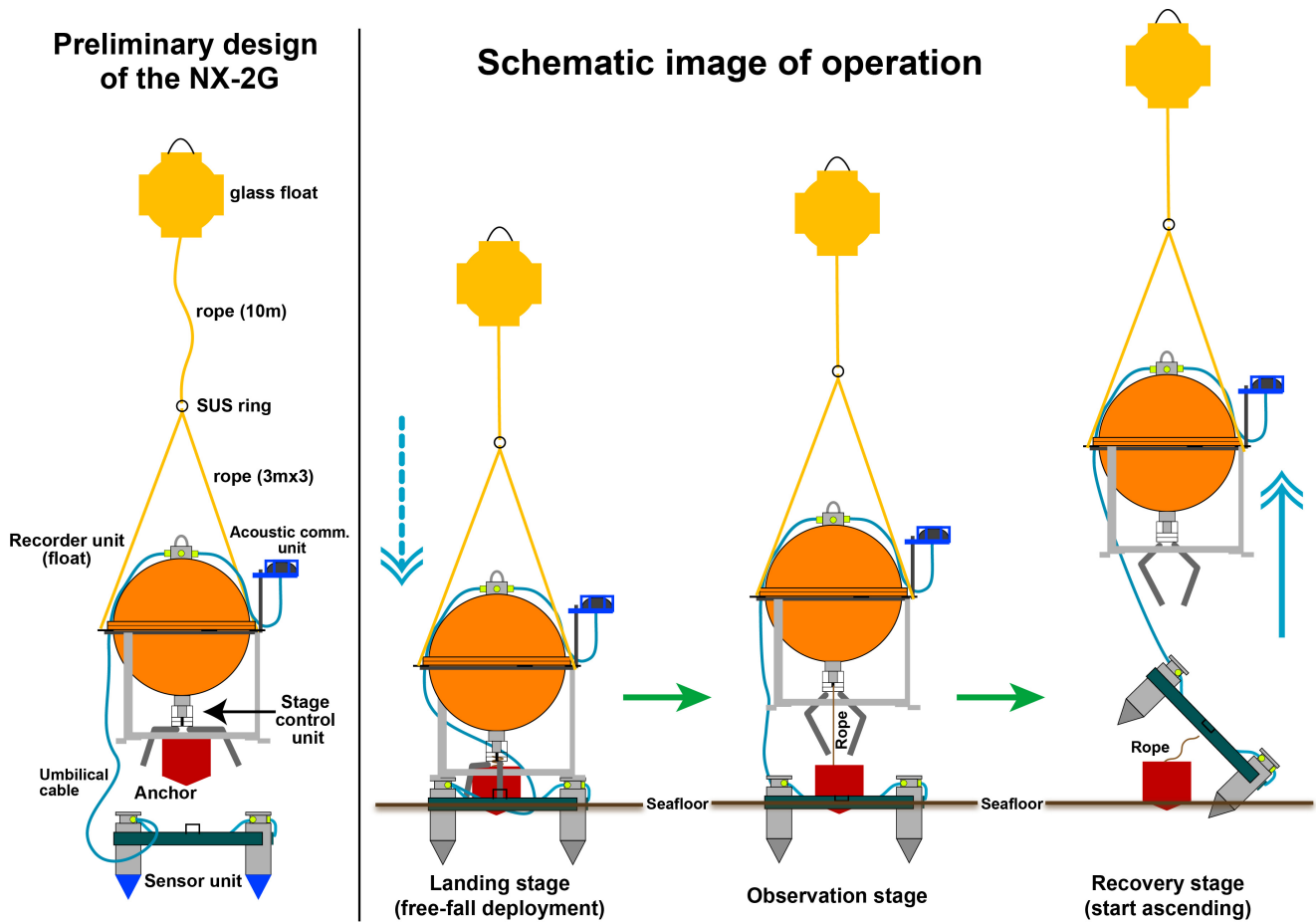
The BBOBS-NX system is a powerful tool for ocean bottom seismic studies, although, the current system has intrinsic limitation in opportunity of observations due to the necessary use of the submersible vehicle for the deployment and recovery. If we can use this system at almost any kind of vessels, like as the BBOBS (self pop-up system), it should lead us a true breakthrough of ocean bottom observations in geodynamics. Hereafter, we call the new autonomous BBOBS-NX as NX-2G in short. There are two main problems to be cleared to realize the NX-2G system. The first one is a tilt of the sensor unit on landing, which is larger than the acceptable limit of the sensor ($\pm 8^\circ$) in about 50% after our 16 free-fall landings of the BBOBS-NX. As we had no evidence at which moment the tilt occurred, we tried to observe it during the BBOBS-NX landing in 2015 by attaching a video camera and an acceleration logger. This result shows that the tilt on landing would be determined by the final posture of the BBOBS-NX system just before the penetration into the sediment. The second problem is a required force to extract the sensor unit from the sticky sediment, which was about 80 kgf in maximum from several in-situ measurements. This value is not so large to realize the self pop-up recovery system. The function of the NX-2G system is based on 3 stage operations like as the current BBOBS-NX system as shown in the figure. The core mechanism to perform these operations has been developed for the ultra-deep OBS system in 2012, already. It was also examined that we can place any object close to the sensor unit as far as they were mechanically decoupled, in the sense of the seismic band noise induced by the bottom current in 2012, too. Additional glass floats are aimed not only for obtaining large buoyancy to extract of the sensor unit, but also for suppressing the rotation (oscillating tilt) of the main part of the NX-2G system in descending.

In Oct. 2016, we made the first in-situ test of the NX-2G system near the observation node (YOB3) of the new off Kamaishi ocean floor cable system by using a ROV, where the water depth is 1570 m. Same as the deployment of the BBOBS-NX in 2015, the video camera and the acceleration logger were equipped with the NX-2G system, and then, it was dropped from the sea surface. The ROV was used to watch the operation of the NX-2G system at the seafloor. The landing looked well with small tilt, and it was examined from the acceleration data in descending. The maximum tilts measured this time was about $\pm 2.5^\circ$, whereas that of the BBOBS-NX in 2015 was more than $\pm 12^\circ$. So that, the additional glass float effectively worked to suppress the rotation of the main part of this system, which is almost same design as

the BBOBS-NX. The extraction of the sensor unit, which had been penetrated well, was also succeeded with the total buoyancy of about 75 kgf, although it took more than 2 minutes to finish the extraction completely. As the final experiment, we will start one-year-long observation of this NX-2G system in this April, with the BBOBS-NX and the BBOBS, to obtain simultaneous data for comparison of the noise level.

キーワード：海底地震計、広帯域地震学、機器開発

Keywords: ocean bottom seismometer, broadband seismology, instrument development



Structural interpretation of the hydrothermal activity area by the Multi-source ACS survey method

*多良 賢二¹、浅川 栄一¹、村上文俊¹、塚原 均¹、齊藤 秀太郎¹、李 相均¹、加藤 政史¹、Jamali Hondori Ehsan¹、角 知則³、山川 正²、古瀬 雅己⁴

*Kenji Tara¹, Eiichi Asakawa¹, Fumitoshi Murakami¹, Hitoshi Tsukahara¹, Shutaro Saito¹, Sangkyun Lee¹, Masashi Kato¹, Ehsan Jamali Hondori¹, Tomonori Sumi³, Tadashi Yamakawa², Masami Kose⁴

1. J-MARES/JGI, 2. J-MARES/MMTEC, 3. J-MARES/NSENGI, 4. J-MARES/JAPEX

1. J-MARES/JGI, 2. J-MARES/MMTEC, 3. J-MARES/NSENGI, 4. J-MARES/JAPEX

Seafloor Massive Sulfide (SMS) deposits have been recognized to be formed at the hydrothermal vent site in the submarine volcano. They typically show abundant chimney structures, massive sulfide mounds and highly hydrothermal altered host rock. Active seafloor hydrothermal systems, related to forming the SMS deposits, are good natural laboratories for understanding the genesis of ancient Volcanogenic Massive Sulfide (VMS) deposits. While studies on these active hydrothermal sites have been progressing, the inactive hydrothermal sites are not well studied because of few efficient methods to detect and characterize them.

Therefore, we proposed a multi-source Autonomous Cable Seismic (ACS) survey system using a deep-towed autonomous cable and multiple sound sources with different acoustic characteristics. With this high-resolution acoustic survey system, we focused on the detection of physical (e.g., density) anomaly in volcanic sediments caused by hydrothermal alteration. The main objective of this study is to identify the variations in the acoustical characteristics of volcanic sediments with respect to SMS deposits and hydrothermal alteration.

Izena Hole is one of the most studied fields of SMS deposits around Japan. We conducted the multi-source ACS survey in the Izena Hole, using the Koyo-maru, in November 2016. We used three different sound sources of air gun, sparker and Sub-Bottom Profiler (SBP) in order to demonstrate the resolution and efficiency of our technique and describe the hydrothermal alteration of different stages and their acoustic characteristics. We obtained seven profiles running through the hydrothermal active/inactive area, caldera floor and outside of caldera wall. As a result of the survey, we obtained a cross-section of the internal caldera that enabled us to study the area from the viewpoint of seismic stratigraphy, and the resulting classifications of sedimentary features on the section suggested the possibility of restricting fluid circulation. In addition, penetration of high frequency components of sound sources suggested the potential existence of low-porosity layers in the shallow part of the sub-seafloor. From these results and discussion, it was suggested that the hydrothermal alteration zone in the volcanic caldera could be identified by the seismic data.

キーワード：海底熱水鉱床、マルチソースACS探査、熱水変質帯

Keywords: Seafloor Massive Sulfide (SMS) deposits, multi-source Autonomous Cable Seismic (ACS) survey, hydrothermal alteration zone

スミスカルデラ北部外輪山における熱水活動の可能性

Potential of Hydrothermal activity around the northern part of Sumisu Submarine Caldera, Izu-Ogasawara Arc

*松下 小春¹、坂本 泉¹、上原 太樹¹、四宮 裕太¹、堤 康祐¹、中尾 凪佐¹、三浦 眞綸¹、八木 雅俊¹、岡村 聡²、棚橋 道郎³

*Matsushita Koharu¹, Izumi Sakamoto¹, Taiki Uehara¹, Yuta Shinomiya¹, Kosuke Tutumi¹, Nagisa Nakao¹, Marin Miura¹, Masatoshi Yagi¹, Satoshi Okamura², Michio Tanahashi³

1. 東海大学、2. 北教大札幌、3. 海洋先端研

1. Tokai University, 2. Hokkaido Univ.Edu, 3. OHTI

日本は陸海問わず多くの活発な火山活動が存在し、噴火やそれに伴う自然災害が多い。一方で温泉・地熱開発や熱水資源など火山活動による恩恵を得てきた。近年海洋における鉱物資源の利用が注目され、特に海底熱水鉱床は伊豆・小笠原弧や沖縄列島沖といった海域にて、積極的に海底資源分布や資源保有量の推定などの調査が行われている。

東海大学では新たな熱水活動域の発見を目標に2014年度より、東京から南に約470kmに位置している伊豆・小笠原弧のスミスカルデラにおいて、東海大学が所有する調査船望星丸を用いて地形的・地質的調査を行ってきた。本研究は、2016年度の調査から実施した水中音響調査の結果と同地域の採泥結果を併用し、スミスカルデラ北部外輪山における熱水活動の可能性を推定することを目的とした。

調査によりスミスカルデラ北部は、外輪山のカルデラ側斜面に放射状を呈したリッジの発達を確認された。さらに同地域の外輪山山頂部において東西約4kmにわたって連続する水中音響異常を複数検出し、それらの分布域を「望星site」と仮称した。望星site東西端での採泥から、火成岩とともに多量の赤褐色砕屑岩が採取された。採取された赤褐色砕屑岩の礫間充填物の蛍光X線分析から、充填物中には高いカルサイト(方解石)と酸化鉄量が検出された。さらに薄片観察では充填物部分から、結晶質なカルサイトと赤褐色に変質した粒状のカルサイトの結晶、酸化鉄の濃集帯と思われる赤褐色の脈、さらにクリストバライトの結晶が認められた。X線回折では、含鉄結晶は認められなかったが、カルサイトおよびクリストバライトは検出された。一般に方解石はアルカリ寄りの中性変質帯にて産出し、クリストバライトは比較的低温(100℃前後)な酸性変質帯に産出する。以上のことから、スミスカルデラ北部の望星siteでは、カルサイトを形成するアルカリ寄りの中性変質帯を形成する熱水が活動していたが、なんらかの環境変化が発生したことにより、現在は酸性変質帯を形成する比較的低温であり、非晶質な鉄を含む熱水が小規模ではあるが活動していると推定した。また、マルチビームで広範囲に水中音響異常が検出されたことから、現在の熱水活動によって、音響散乱を生じるような現象が海底付近で起きていると考えられる。

キーワード：スミスカルデラ、水中音響異常、赤褐色砕屑岩、熱水

Keywords: Sumisu Submarine Caldera, Acoustic water column anomaly, Reddish brown clastic rock, Hydrothermal activity

Three-dimensional seismic structure of the Rainbow area, Mid-Atlantic Ridge, at 36°14' N: Fault development, crust-mantle transition, core complex formation, and mantle alteration at slow spreading ridges

*新井 隆太¹、Dunn Robert²、Eason Deborah²、Canales Pablo³、Sohn Robert³

*Ryuta Arai¹, Robert Dunn², Deborah Eason², Pablo Canales³, Robert Sohn³

1. 国立研究開発法人海洋研究開発機構、2. University of Hawaii at Manoa、3. Woods Hole Oceanographic Institution
1. Japan Agency for Marine-Earth Science and Technology, 2. University of Hawaii at Manoa, 3. Woods Hole Oceanographic Institution

Oceanic lithosphere formed along slow-spreading mid-ocean ridges is structurally and compositionally heterogeneous due to spatial and temporal variations in tectonic extension and magmatic accretion. While mid-ocean ridges with greater magma supply host a greater abundance of hydrothermal systems, the relative roles of magmatic input, heat advection and faulting in controlling ridge structures are still poorly understood. The MARINER (Mid-Atlantic Ridge INtegrated Experiments at Rainbow) seismic and geophysical mapping experiment was designed to examine the relationship between tectonic rifting, heat/melt supply, and oceanic core complex formation at a non-transform offset of the Mid-Atlantic Ridge, 36°14' N, the site of the Rainbow core complex and its associated hydrothermal vent field. Using the seismic refraction data from this experiment, we constructed three-dimensional tomographic images of the crust and upper mantle around the Rainbow area. The seismic velocity images reveal clear stripe-like structures with alternating high- and low-velocity patterns aligned in the ridge-parallel direction which correlate with the locations of large normal faults and the variation in lower crustal thickness. This structure suggests that the entire crust has been rotated by semi-vertical faulting during tectonic stretching. Throughout the experiment area, there is little evidence in the wide-angle data for persistent reflected arrivals from the Moho discontinuity (PmP). This implies that the crust-mantle transition occurs gradationally in the vertical direction rather than forming a sharp seismic boundary. At the Rainbow massif, where mantle rocks have been recovered by direct sampling, seismic velocities near the seafloor (the upper 2 km of the lithosphere) are lower than expected for mantle rocks and have a sharp contact with higher-velocities below. The velocity boundaries are consistent with reflectors within the Rainbow massif revealed by MCS reflection data [Canales et al., Geology, in press] and probably represent alteration and cracking fronts of the mantle lithosphere. These results suggest that fluid circulation channeled by dense faults alter the whole massif efficiently and enhances the active hydrothermal system.

キーワード : Mid-Atlantic Ridge、 Seismic refraction、 Normal faults、 Hydrothermal vents、 Mantle alteration

Keywords: Mid-Atlantic Ridge, Seismic refraction, Normal faults, Hydrothermal vents, Mantle alteration

インド洋ロドリゲス三重会合点かきれい熱水域における地震活動と3次元速度構造

Seismicity and 3D seismic velocity structure at the Kairei hydrothermal vent field near the Rodriguez Triple Junction in the Indian Ocean

森 大湧¹、*佐藤 利典¹、高田 裕能¹、今井 裕輝²、野口 ゆい¹、河野 昭博¹、山田 知朗³、篠原 雅尚³
Taiyu Mori¹, *Toshinori Sato¹, Hiroyoshi Takata¹, Yuki Imai², Yui Noguchi¹, Akihiro Kono¹,
Tomoaki Yamada³, Masanao Shinohara³

1. 千葉大学大学院理学研究科、2. 千葉大学理学部、3. 東京大学地震研究所

1. Graduate School of Science, Chiba University, 2. Faculty of Science, Chiba University, 3. Earthquake Research Institute, the University of Tokyo

1. はじめに

インド洋ロドリゲス三重会合点の北側、中央インド洋海嶺の第1セグメント北部の東側には、かきれい熱水域があり、水素を多量に含む熱水が噴出している。この熱水域周辺の海底面で、蛇紋岩や斑レイ岩、かんらん岩などの岩石が採取されている。本来深部にあるはずのこれらの岩石が浅いところにあるので、熱水に水素が豊富に含まれると考えられている。また、この熱水域には、水素を活動源にする生物が生息している。「海底下の大河」プロジェクト（海底下での熱水循環に関わる生物・地学的現象の解明研究）では、この地域を「水素の大河」と呼んでいる。この地域は、第2セグメントとの境界のnon-transform offset (NTO)に近く、NTO massifであると言われている。かきれい熱水域において、深部岩石がどう分布しているのか、また、熱水循環がどうなっているのかを調べるために、海底地震計の用いた地震活動と地殻構造の調査を行った。

2016年連合大会では、かきれい熱水域の北西 3-5km のところに群発地震があり、深さ約4-7kmまでのところに集中していて、そのメカニズムは正断層型であることや、海嶺軸部の群発地震は、深さ約6-8kmのところに集中し、その分布は上下に2つに分かれていて、両者ともに西に60°-70°傾斜していることなどを報告した。

今回は、より正確な震源分布と構造を求めるため、TomoDD(Zhang and Thurber, 2003)を用いて人工震源と自然地震の両方を用いて3次元地震波速度構造を求め、同時に震源の再決定を行った。

2. 観測・解析概要

2013年1月27日から3月19日にかけて海洋研究開発機構、観測調査船「よこすか」を用いて人工震源構造調査および自然地震観測を行った(YK13-01航海、YK13-03航海)。使用した海底地震計は全部で21台である。解析は、震源分布と速度構造の同時決定が行えるTomoDD(Zhang and Thurber, 2003)を用いた。自然地震を用いることにより深部（海面下8kmくらいまで）の解像度がよくなった。

3. 結果

かきれい熱水域がある白鳳海丘とYokoniwa Riseの地下1-2 km付近で速度6.0 km/sを超える高速度領域が確認された。Yokoniwa Rise直下の高速度領域はYokoniwa Rise全体に広がっている。海嶺軸下は周辺より速度がやや遅くマグマの存在を示唆している。震源分布は第1セグメント北部の海嶺下や熱水域付近に集中していて、西に60°-70°傾斜の分布が複数存在している。このことは複数の断層が活動していてNTO massifの形成に関与しているように見える。かきれい熱水域の北西 3-5km のところの群発地震は、熱水域から遠いところに浅い地震が分布していて、海水の取り込み口のようにも見える。

謝辞

観測に関して、海洋研究開発機構の観測調査船「よこすか」の船長と乗組員の方々の協力を頂きました。本研究は科研費新学術領域20109002の助成を受けて行われました。

キーワード：海底下の大河、熱水地域、地震活動、地殻構造、NTOマッシフ

Keywords: TAIGA Project, hydrothermal field, seismicity, crustal structure, NTO massif

Mantle heterogeneity across segment at southern segment of Central Indian Ridge

*佐藤 暢¹、町田 嗣樹²、仙田 量子²

*Hiroshi Sato¹, Shiki Machida², Ryoko Senda²

1. 専修大学経営学部、2. 国立研究開発法人 海洋研究開発機構

1. School of Business Administration, Senshu University, 2. JAMSTEC

Recent petrological and geochemical investigations of MORB at the southern segments of Central Indian Ridge (CIR) reveal the heterogeneous distributions of MORB-source mantle (Sato et al., 2015). Sato et al. (2015) concluded that MORB from off-ridge area at the CIR-S1 segment are depleted trace element compositions than typical MORB. Furthermore, depletions of trace element geochemistry of off-ridge MORB from CIR-S1 segment decrease toward present spreading ridge. Because off-ridge MORB was recovered from several dredge sites parallel to the flow line, these distributions might indicate spatial distributions of mantle heterogeneity beneath CIR-S1 segment. Newly analyzed isotope compositions suggest that MORB depleted in trace element is enriched in radiogenic Sr and Nd. Machida et al. (2014) proposed that "Radiogenic Depleted component (RD)" contributes to the genesis of basalts from CIR-15 segment at 20 degree south and CIR-18 segment at 16 degree south. We suggest that RD component widely spreads along CIR.

キーワード：中央海嶺玄武岩、中央インド洋海嶺、マントル不均質

Keywords: Mid-ocean ridge basalt, Central Indian Ridge, Mantle heterogeneity

Unraveling the oceanic serpentinization reaction from aluminum-zoning in mesh textures

*大柳 良介¹、岡本 敦¹、針金 由美子²、土屋 範芳¹

*Ryosuke Oyanagi¹, Atsushi Okamoto¹, Yumiko Harigane², Noriyoshi Tsuchiya¹

1. 東北大学大学院環境科学研究科、2. 産業技術総合研究所

1. Graduate School of Environmental Studies, Tohoku University, 2. Geological Survey of Japan National Institute of Advanced Industrial Science and Technology (AIST)

Serpentinization (hydration of mantle peridotite) gives significant changes to both chemical and physical properties of lithosphere. Mesh texture was usually observed in serpentinized peridotite, and is a key to understand the dynamics of oceanic lithosphere. Serpentine minerals in mesh texture commonly contain subtle amounts of aluminum, but the influences of Al on kinetics of serpentinization is poorly understood.

In this study, we conducted hydrothermal experiments in olivine (Ol)–plagioclase (Pl)–H₂O system at 230 °C and a vapor-saturated pressure of 2.80 MPa for understanding the effect of Al on the mechanism of olivine replacement. By using unique tube-in-tube type hydrothermal experiments vessel (e.g., Oyanagi et al., 2015), spatial and temporal data were obtained.

We found the systematic difference in olivine replacement textures between Al–metasomatic zone near the Ol–Pl contact and isochemical zone far from the contact. In the isochemical zone, lizardite + brucite + magnetite was formed and original olivine outline was not clear. In contrast, in the metasomatic zone, Al-rich serpentine + Ca-Saponite aggregate replaced olivine with forming a characteristic zoning of core, mantle, and rim parts. Microstructural observations revealed that this zoning was produced by initial formation of mantle part at Al-free solution, subsequent to simultaneous progress of pseudomorphic replacement at olivine front (core part) and overgrowth (rim part) with migration of Al metasomatic front. Similar Al zonings of olivine mesh texture were observed in partly serpentinized harzburgite and Pl-bearing wehrite, suggesting that local mass transfer plays an essential role on replacement progress and texture development with volume expansions during serpentinization of oceanic lithosphere by onset of break down of Al-bearing minerals.

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キーワード：蛇紋岩化反応、メッシュ組織、水熱実験、蛇紋岩

Keywords: Serpentinization, Mesh texture, Hydrothermal experiment, Serpentine

CK16-05航海速報：伊是名海穴および伊平屋小海嶺における科学掘削－ コア採取、地熱ツール検層とモニタリング装置の設置

Preliminary results of the CK16-05 Cruise: Scientific drilling in Okinawa Trough of coring, logging using geothermal tool and refit of Long-term monitoring apparatus

*熊谷 英憲¹、石橋 純一郎²、野崎 達生¹、前田 玲奈¹、山田 泰広¹、猿橋 具和¹、許 正憲¹、CK16-05
乗船者一同

*Hidenori Kumagai¹, Jun-ichiro Ishibashi², Tatsuo Nozaki¹, Lena Maeda¹, Yasuhiro Yamada¹,
Tomokazu Saruhashi¹, Masanori Kyo¹, CK16-05 On-board Member

1. 国立研究開発法人海洋研究開発機構、2. 九州大学

1. Japan Agency for Marine-Earth Science and Technology, 2. Kyushu Univ.

The CK16-05 Cruise by D/V Chikyu was performed at the Izena Hole and Iheya Minor Ridge, in the middle Okinawa Trough from November 16th to December 15th, 2016. Aiming to construct the genetic model of seafloor hydrothermal deposits, the subseafloor polymetallic sulfide ore body and relevant geology were investigated under an umbrella of Cross-ministerial Strategic Innovation Promotion Program (SIP). Throughout the cruise, systematic coring partly coupled with logging using a geothermal tool were conducted at the Hakurei Site, Izena Hole. Within the five of the eight sites, massive sulfide ore-bodies were successfully drilled and sampled. Owing to an improved sampling tool, a hydraulic piston-coring system modified to adjustable (short) penetration, the transition zones from sediments to ore bodies were continuously sampled without significant disturbances. The continuous profiles of natural gamma-ray together with borehole temperature and pressure were also obtained at the half of the holes. In the middle of the cruise, installation of a revised long-term monitoring apparatus equipped with sensors to monitor the secular variation of pressure, temperature, flow rate and precipitation weight within the apparatus on hydrothermal vents artificially made as Hole C9017A at the very vicinity of the last installation at the Hole C9017B, at Noho site, in the south of Iheya-Minor Ridge.

In this presentation, we report the preliminary results of operations conducted in the CK16-05 Cruise.

キーワード：伊是名海穴、硫化鉱物の系統的採取、自然ガンマ線、長期モニタリング

Keywords: Izena Hole, Systematic sampling of sulfide minerals, Natural gamma ray, Long term monitoring

Estimation of seafloor environment at active hydrothermal fields in Okinawa Trough based on mineralogical and geochemical analysis

*戸塚 修平¹、石橋 純一郎²、野崎 達生³、島田 和彦²、木村 純一⁴

*Shuhei Totsuka¹, Jun-ichiro Ishibashi², Tatsuo Nozaki³, Kazuhiko Shimada², Jun-Ichi Kimura⁴

1. 九州大学大学院理学府地球惑星科学専攻、2. 九州大学大学院理学研究院地球惑星科学部門、3. 海洋研究開発機構海底資源研究開発センター、4. 海洋研究開発機構地球内部物質循環研究分野

1. Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University, 2. Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, 3. Research and Development Center for Submarine Resources, JAMSTEC, 4. Department of Solid Earth Geochemistry, JAMSTEC

A series of drilling campaign was conducted in Okinawa Trough under the framework of the Next-generation Technology for Ocean Resources Exploration Project. I investigated hydrothermal alteration, sulfide and sulfate minerals in drill core samples. The study fields of this investigation are the Iheya-North hydrothermal field and Noho Site in mid-Okinawa Trough. Deep sea drilling was conducted in 2014 (CK14-04 Cruise) and 2016 (CK16-01 Cruise) using the drilling vessel *Chikyu*. In total, 7 holes in the Iheya-North hydrothermal field and 3 holes in Noho Site were drilled. The deepest hole reached 208.5 mbsf (meters below seafloor). X-Ray Diffraction analysis of the core samples was performed onboard for 199 samples to identify mineral species in the cores. 67 polished sections were prepared to determine rock texture and mineral assemblage. Electron Probe Micro Analysis was applied to determine chemical composition of the sulfide minerals. Pb isotope ratios were analyzed for 26 representative sulfide samples using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry.

Site C9021 is located midway between Natsu Site and Aki Site in the Iheya-North hydrothermal field. The core sample consisted of a 70 m thick layer of fresh pumice. Sites C9016 and C9023 were drilled in the vicinity of two active hydrothermal vents. The core samples consisted of abundant anhydrite with clay minerals associated with minor sulfides (pyrite, sphalerite, galena, and chalcopyrite). K-bearing minerals such as illite and K-feldspar were also observed. The abundant anhydrite indicates rigorous mixing between the seawater and hydrothermal fluids beneath the seafloor. Sphalerite was relatively low in Fe suggesting deposition under an oxidative condition. Pb isotope composition of the sulfide minerals shows a narrow range indicating deposition from a common hydrothermal fluid. Site C9017 is located in the Noho Site. The 120 m-long core sample consisted of alternations between basaltic lava and clay-rich layers. Hydrothermal alteration was not intense but observed over the entire core sample. Ca-bearing minerals, anorthite, wairakite, and dolomite occur in ascending order of core depth. Minor pyrite, pyrrhotite, cubanite, sphalerite, and anhydrite were identified. Sphalerite was relatively high in Fe indicating deposition under a reduced condition.

In the Iheya-North hydrothermal field, hydrothermal alteration and sulfide minerals occur under oxidative condition beneath the seafloor, in the vicinity of the active hydrothermal vents. Indicative of a high seawater flux entrained through the permeable pumice layer. In contrast, the Noho Site is under a reduced condition. This may have been generated by the lava layers which act as cap rocks and prevent seawater penetration. In both fields, a high temperature condition is estimated in the deeper portions, based on occurrence of alteration minerals. Alteration minerals in the Iheya-North hydrothermal field are rich in K, whereas those in the Noho Site are Ca-rich. This difference reflects different host rock, dacite pumice for the former and basaltic lava for the latter. In summary, degree of seawater entrainment, temperature of the hydrothermal fluid, and chemical composition of the host rock are important controlling factors that determine environment beneath the active hydrothermal fields in Okinawa Trough.

キーワード：海底熱水鉱床、伊平屋北海丘、野甫サイト、CK14-04航海、CK16-01航海、熱水変質

Keywords: Seafloor hydrothermal deposit, Iheya-North hydrothermal field, Noho Site, CK14-04 Cruise, CK16-01 Cruise, Hydrothermal alteration

沖縄トラフ伊平屋北海丘熱水活動域における間隙水化学組成 Geochemistry of pore fluids collected from active hydrothermal fields in Iheya North Knoll, Okinawa Trough

*石橋 純一郎¹、堤 彩紀¹、蝦名 直也¹、土岐 知弘²

*Jun-ichiro Ishibashi¹, Saki Tsutsumi¹, Naoya Ebina¹, Tomohiro Toki²

1. 九州大学大学院理学研究院地球惑星科学部門、2. 琉球大学理学部海洋自然科学科

1. Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, 2. Department of Chemistry, Biology and Marine Science, Faculty of Science, University of the Ryukyus

We investigated chemical composition of pore fluids extracted from sediment samples collected by scientific drilling from Iheya North Knoll hydrothermal field in mid-Okinawa Trough. Two drilling campaigns CK14-04 and CK16-01 were conducted employing Drilling Vessel Chikyu under the framework of the Next-generation Technology for Ocean Resources Exploration Project. Sediment cores were drilled from Site C9016 within the hydrothermal field of Aki Site, from Site C9021 about 1 km apart from Aki Site, and from Site C9023 drilled on an active hydrothermal mound of Aki Site (27°46.1' N, 126°54.1' E; water depth = 1070 m). Prior to these campaigns, another scientific drilling in Iheya North field was conducted as IODP (Integrated Ocean Drilling Program) Expedition 331, which targeted at Original Site (27°47.5' N, 126°53.8' E; water depth = 1000 m). After the pore fluid study reported as the result of Expedition 331, we document geochemical signature of pore fluids, to discuss fluid interactions and migrations within the sediment layer.

Pore fluid from Site C9021 away from the active field showed approximately same chemical composition as seawater for whole range of the sampled depth, from 0 to 66 mbsf (=meters below the seafloor). The exception was recognized in slight decrease of SO₄ and increase of alkalinity at the depth from 45 to 58 mbsf. Together with detection of H₂S in the same layer, this change is attributed to sulfate reduction within the sediment. Similar seawater entrainment was recognized in shallow layer (< 11 mbsf) at Site C9016 located within the active field. Whereas pore fluid in deep layer (>30 mbsf) showed distinctive chemical composition which showed similarity in several species rather to the vent fluid emanating from the hydrothermal mound. Pore fluid at Site C9023 collected directly from the active hydrothermal mound showed complicated profiles, but likely to converge to the vent fluid composition in deep layer (> 40 mbsf).

Occupation of pore fluid in deep sediment layer by the hydrothermal component of vent fluid composition was already recognized in the Original Site by the previous study. As well as seawater entrainment into a certain depth, extensive fluid migration would be attributed to distribution of porous pumiceous sediment piled on Iheya North Knoll. Combination of the lateral migration of the ascending hydrothermal component and seawater entrainment is responsible for the drastic change in pore fluid chemistry profiles in subseafloor region of the active hydrothermal field. Given that mixing between these two components is not obvious in the chemical profiles, separation by an impermeable layer would be inevitable. Pore fluid chemistry beneath active hydrothermal field in Iheya North Knoll would be controlled by geologic structure of a stratovolcano as well as hydrothermal structure.

キーワード：海底熱水系、熱水変質反応、火山性堆積物、流体移動

Keywords: submarine hydrothermal system, hydrothermal alteration, volcanic sediment, fluid migration

海底熱水活動域岩石サンプルの比抵抗特性と鉱物種の関係性

Relationship between Resistivity Characteristics and Mineral Species of Rock Samples in the Seafloor Hydrothermal Area

*大田 優介¹、後藤 忠徳¹、柏谷 公希¹、小池 克明¹、林 為人¹、多田井 修³、笠谷 貴史²、金松 敏也²、町山 栄章²

*Yusuke Ota¹, Tada-nori Goto¹, Koki Kashiwaya¹, Katsuaki Koike¹, Weiren Lin¹, Osamu Tadaï³, Takafumi Kasaya², Toshiya Kanamatsu², Hideaki Machiyama²

1. 京都大学大学院工学研究科、2. 海洋研究開発機構、3. マリンワークジャパン

1. Graduate School of Engineering, Kyoto University, 2. Japan Agency for Marine-Earth Science and Technology, 3. Marine Works Japan

現在、金属資源量調査を目的として、海底熱水活動域に対して物理探査が行われている。しかしながら、物理探査で得られる情報には限りがあり、鉱床の品位および空間分布の定量的解釈には新たな技術開発が必要である。このような問題を解決する手段のひとつとして、対象地域の物性・化学組成の相関関係を組み込んだ適切な岩石物理学モデルを構築するという手法が挙げられる。これは岩石物理学に基づく複合解析の概念として知られ（例えば鈴木,2013）、複数の物性情報を元に、間隙率や岩石組成などの情報を推定する手法である。本研究では物理探査の複合解析によって資源量評価を行うことを最終的な目的として、海底熱水活動域において採取された岩石の物性および化学組成の測定・分析を行い、それらを基に基礎的なモデルの構築を行った。

本研究で構築した岩石物理学モデルは、間隙率およびその他複数のパラメータに基づいて岩石の比抵抗を与えるものである。このような比抵抗に重点を置いたモデルを構築した理由としては、海底熱水活動域においては電気探査などによる比抵抗構造の推定が金属資源量調査に有用であるということが先行研究でも確認されており（例えばKowalczyk, 2008）、また海底熱水活動域において豊富に見られるpyriteなどの硫化鉱物が極めて高い導電性を持つことが知られていることが挙げられる。

適切なモデル構築のためには、岩石サンプルが持つ物理的・化学的特性を明らかにすることが必要である。そこでまず我々は、海底熱水活動域として知られる野甫サイト、伊是名海穴および伊平屋北海丘といった、沖縄トラフ内の3地域から採取した岩石サンプルに対して、複数の物性の測定、および化学組成の分析を行った。測定項目としては、比抵抗、間隙率、粒子密度、自然残留磁化、金属元素含有率である。特に比抵抗測定においては、間隙水の導電性に対する比抵抗の依存特性を明らかにするため、鈴木（2003）を参考に、間隙水を満たすNaCl溶液の濃度を変更した複数の測定を行った。これらの測定・分析によって得られたデータに対し、我々の新たなモデルを適用することで、モデルの各パラメータを決定するとともに他の物性および化学組成との比較に用いた。

結果として、構築したモデルの各パラメータと特定の元素含有率との間に相関性が確認された。これは本研究において構築したモデルが、比抵抗という物性情報から鉱物種という化学組成情報を抽出し得るものであるという可能性を示唆している。今後はこの比抵抗モデルを発展させ、他の物性および化学組成を定量的に組み込むとともに、整合性についてのさらなる検討を行っていく予定である。

キーワード：海底熱水鉱床、アーチーの式、電気伝導度、岩石物理学モデル

Keywords: seafloor massive sulfides, Archie's law, electrical conductivity, rock physics model

掘削試料の比抵抗・IP特性から見る沖縄県伊平屋北海丘および野甫サイト熱水域 (ちきゅうCK16-01航海)

Electrical features of the submarine hydrothermal system around the Iheya-North Knoll area and the Noho Site, Okinawa, Japan, inferred from resistivity and IP properties of drilling samples from the Chikyu CK16-01 cruise

*小森 省吾¹、正木 裕香²、谷川 亘²、鳥本 淳司²、大田 優介³、榎尾 雅人⁴、前田 玲奈²、石橋 純一郎⁴、野崎 達生²、多田井 修⁵、熊谷 英憲²、CK16-01 乗船者一同

*Shogo Komori¹, Yuka Masaki², Wataru Tanikawa², Junji Torimoto², Yusuke Ota³, Masato Makio⁴, Lena Maeda², Jun-ichiro Ishibashi⁴, Tatsuo Nozaki², Osamu Tadai⁵, Hidenori Kumagai², CK16-01 on board member

1. 国立研究開発法人産業技術総合研究所、2. 国立研究開発法人海洋研究開発機構、3. 京都大学、4. 九州大学、5. マリン・ワーク・ジャパン

1. National Institute of Advanced Industrial Science and Technology, 2. Japan Agency for Marine-Earth Science and Technology, 3. Kyoto University, 4. Kyushu University, 5. Marine Works Japan

The exploration and exploitation of submarine hydrothermal deposits are becoming increasingly important for the steady supply of metal resources to Japanese industry. Valuable metal elements are commonly included as sulfide minerals in these deposits. Most of the sulfide minerals generally exhibit a high electrical conductivity, and an anomalous signature of the Induced Polarization (IP) effect. Therefore, electromagnetic investigations have been considered to be effective in finding unidentified sub-seafloor deposits. Understanding the resistivity and IP properties of rock samples taken from the deposits is important for the improvement of exploration techniques and the reduction of risks during exploitation. The present study involved measurements of resistivity and IP properties of drilling samples from the research program entitled “the Chikyu CK16-01 cruise” from February to March 2016.

The drilling research was conducted in the Iheya-North Knoll and the Noho Site adjacent to the Iheya-Minor Ridge (Kumagai et al., in prep.), where an extensive high-temperature hydrothermal system was expected based on previous surveys (e.g., Takai et al., 2015). The present study included complex resistivity measurements with a wide frequency range between 0.01 Hz and 100 kHz, using non-polarizable electrodes in a four-electrode configuration. Most of the measured sulfide samples are of hydrothermal origin, including fine-grained pyrite. Some samples consist of other sulfide minerals such as chalcopyrite, galena, pyrrhotite, and sphalerite. Massive sulfide rocks were rarely sampled, and disseminated sulfide rocks dominated.

The measurements showed the following results. There is a negative correlation between resistivity and porosity. However, no significant correlation was found between resistivity and sulfide mineral fractions, and the measured resistivity values (greater than 1 Ω m) are higher than those of typical massive sulfides (less than 0.1 Ω m), suggesting that the resistivity is controlled by the connectivity of the interstitial sea water filling the pores. Regarding the IP signature, the sulfidic sediments bearing fine-grained pyrite have low phases at low frequencies, and the values increase with frequency. This feature is consistent with experiments by Revil et al (2015), which demonstrated that fine-grained sulfide causes anomalous high phases at high frequencies. According to further data analyses based on the Cole-Cole model, the

estimated chargeability exhibits a positive correlation with the sulfide content.

In this study area, it was shown that the presence or absence of sulfide minerals is reflected in the IP properties, rather than in the resistivity values. In general, pore water resistivity decreases with an increase of temperature, resulting in a reduction of bulk resistivity. Therefore, not only massive sulfides but also high-temperature hydrothermal fluids maintained in porous sediments could be identified as a low-resistivity body by seafloor electromagnetic surveys, meaning that more care should be taken in the interpretation of the resistivity structure.

Acknowledgements:

This study was conducted under the program “Next-generation technology for ocean resources exploration, Cross-ministerial Strategic Innovation Promotion Program (SIP)” by the Council for Science, Technology and Innovation (managed by JAMSTEC). We would like to thank the laboratory technicians for supporting our measurements.

キーワード：海底熱水鉱床、伊平屋北海丘、野甫サイト、比抵抗、誘導分極、硫化鉱物

Keywords: submarine hydrothermal deposit, Iheya-North Knoll, Noho Site, resistivity, induced polarization, sulfide minerals

沖縄トラフ野甫熱水サイトにおける掘削孔近傍での海底温度・圧力計測の試み

Challenge to monitor the nearby hydrological response to the drilling into hydrothermal venting area: A case for mid-Okinawa Trough Noho hydrothermal site

*木下 正高^{1,2}、正木 裕香²、谷川 亘²、濱田 洋平²、野崎 達生²、熊谷 英憲²、山本 啓之²

*Masataka Kinoshita^{1,2}, Yuka Masaki², Wataru Tanikawa², Yohei Hamada², Tatsuo Nozaki², Hidenori Kumagai², Hiroyuki Yamamoto²

1. 東京大学地震研究所、2. 海洋研究開発機構

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

海底熱水鉱床がどのように成長するかは、地下のマグマによる熱の供給量に加えて、いかに効率よく海水を循環させ、岩石中の金属などを溶融させて海水中に運ぶという、水理学的特性が重要である。これまで海底熱水域での熱水噴出・湧出の観測、あるいは掘削孔内観測により、地下の熱水たまりの規模や浸透率が推定されている。特に熱水噴出域掘削（ファンデフカ海嶺や中部沖縄トラフなど）では、掘削直後に孔から黒い熱水が噴き出す様子が観察されている。このような「現場実験」の結果、地下の圧力は減少し、その結果、特に孔の周囲から海水の吸い込みが増大するなど、熱水循環系の変化が起きることは容易に想像できる。掘削に先立ち孔の近傍で必要な観測を行ってれば、そのような吸い込みなど、掘削に起因する時間変化が捉えることができ、その様子から地下の水理特性が推定できる貴重なチャンスとなる。

中部沖縄トラフにある伊平屋小海嶺（野甫サイト）において、2016年2月~3月に「ちきゅう」による熱水噴出域掘削が実施された。我々は、掘削の直前(半日前)に、掘削孔（C9017）の100m東南東の堆積物で覆われた海底に、熱流量プローブおよび海底温度・圧力計測装置を設置した。熱流量プローブは温度計5本が1mのプローブ内部に装填され、地中の温度を1分間隔で計測する。海底温度圧力装置は2台の精密水圧計と2台の温度計からなり、海底に10cm程度突き刺して、1秒間隔で計測を行う。両装置は掘削後、2016年11月に無事回収された。

C9017孔での掘削は、2/16から3/4まで、3孔で実施された。掘削後に熱水が噴出しているのが確認されたが、100m離れた海底観測装置には特段の変化が見られなかった。BAYTAPによる理論潮汐との比較では、圧力値はほぼ海面高変動（高低差約1m）をそのまま記録しているようである。一方温度にも半日周期等の変動が明瞭に観測されるが、さらに約6時間周期で+0.1K程度の正の温度異常(海水温度)も生じている。海底付近の海水の流れ場が分からないので確定的なことは言えないが、おそらくは海洋潮汐に伴う底層流があり、M2周期で行ったりきたりする（つまり6時間ごとに反対向きの流れが装置の上を通過する）と考え、その上流側（両側）に熱源があると考えたと説明がつくかもしれない。

熱流量プローブの温度記録は、深くなるに従い変動の振幅が減衰し、位相が遅延している。これは上述のような海水温度変動地下に熱拡散で浸透しているためと考え、適当な熱拡散率 ($2.4e-7 \text{ m}^2/\text{s}$)を与えるとすべての観測温度がよく説明できることが分かった。すなわちプローブの温度変化の要因は、海水の温度変化が拡散のみで地中に伝搬したことであると考えられる。なお得られた温度から計算された温度勾配は $6.84(+/-0.04) \text{ K/m}$ とかなり高い値であったが、温度プロファイルは直線的であり、その点からも地中の間隙水流動の兆候は見られない。

今後は、掘削孔自体に取り付けられた流速計データなどとの相関についても検討する予定であるが、このような実験のためには、おそらくさらに掘削孔に近い場所での観測が必要であろうと推測する。

キーワード：熱流量、沖縄トラフ、熱水循環

Keywords: heat flow, Okinawa Trough, hydrothermal circulation

伊豆・小笠原・マリアナ弧の背弧海盆で見られる2種類の上層海洋地殻地震波速度構造

Two types of upper crust seismic velocity structure in the Izu-Bonin-Mariana back-arc basin

*古川 優和¹、島 伸和¹、高橋 成実²、海宝 由佳³、小平 秀一³

*Yuka Furukawa¹, Nobukazu Seama¹, Narumi Takahashi², Yuka Kaiho³, Shuichi Kodaira³

1. 神戸大学、2. 防災科学技術研究所、3. 国立研究開発法人海洋研究開発機構

1. Kobe University, 2. National Research Institute for Earth Science and Disaster Resilience, 3. Japan Agency for Marine-Earth Science and Technology

本研究は伊豆・小笠原・マリアナ弧(IBM弧)の背弧海盆の地殻構造に注目し、上層海洋地殻のP波速度構造の空間的变化を明らかにする。一般的な海洋地殻の速度構造には、速度勾配が大きくP波速度 V_p が遅い(約3~6 km/s)層layer2と、速度勾配が小さく V_p が約6~7 km/sの層layer3がある。中央海嶺で形成された海洋地殻のlayer2の厚さは約1~2 kmである(e.g., Kearey *et al.*, 2009)。背弧海盆の上層地殻のP波速度構造はlayer2の厚さと速度勾配によって次の2グループに分けられる(Sato *et al.*, 2015) ; 1)中央海嶺で形成された地殻と同じ標準的な構造のグループ(以下、“標準的構造”と呼ぶ)、2)約3 kmの厚いlayer2をもち、速度勾配が小さいために同じ深さでより低速度な構造のグループ(以下、“低速度構造”と呼ぶ)。“低速度構造”は岩石サンプルや重力異常の対比を根拠とする地殻の高空隙率に起因すると考えられる。高空隙率の原因は、背弧地殻が形成された時に近くに沈み込み帯が存在し、沈み込むスラブから供給された水を含んだマグマが地殻を形成したためだと推測されている(Dunn and Martinez, 2011)。南マリアナトラフやラウ海盆の沈み込み帯に近い拡大軸付近では“低速度構造”が見られ、水を含んだマグマの影響が現れていると推測される(Jacobs *et al.*, 2007 ; Dunn and Martinez, 2011 ; Sato *et al.*, 2015)。

本研究では、2次元の地震波速度構造を用いてIBMの背弧海盆の各地点直下の地震波速度とlayer2の深さの関係を表すグラフを作成し、速度構造をグループ分けして構造の空間的变化を見る。使用した2次元の地震波速度構造は、伊豆・小笠原弧を横切る8本の測線とマリアナ弧を横切る1本の測線に沿ったものであり、地震波速度構造探査の解析により得られた(Takahashi *et al.*, 2015)。これらの測線は東西方向に走り、南北方向のIBM弧の古い拡大軸付近まで及んでいる。使用された海底地震計(OBS)の設置間隔が最短で5 kmであるため、グラフは5 kmおきに作成する。layer2の最も浅い所を深さ0 kmとするため、海水および堆積層と考えられる地震波速度が2 km/s以下のデータを除く。Sato *et al.* (2015)において構造の差が大きく現れている、深さ1.5 km、地震波速度5 km/sでのP波速度の値を元にグループ分けを行う。グラフが境界点付近を通っており、はっきりと区別できないものは“中間構造”に分類する。

地震波速度構造の空間的变化は9本すべての測線において、海盆の火山弧に近い東端から西へ向かって“低速度構造”、“中間構造”、“標準的構造”の順に表れる。各構造が見られる幅は測線によって異なる。各測線名を北から順に測線1から測線9とすると、測線1・2・8では、海盆の東端から15~40 kmの“低速度構造”、30~80 kmの“中間構造”、それ以西は拡大軸付近まで“標準的構造”が見られる。測線3は“標準的構造”のみである。測線4・5・6・9は海盆の東端から30~70 kmの“低速度構造”、それ以西は“中間構造”を示し、背弧拡大軸付近まで“標準的構造”は見られない。測線7は東端から約30 kmの“中間構造”とそれ以西の“標準的構造”を示し、“低速度構造”は見られない。測線9のみマリアナトラフを横切っており、トラフの東端40 kmと西端55 kmは“中間構造”を、それ以外の拡大軸付近約100 kmは“標準的構造”を示す。

研究地域の測線に低速度構造・中間構造が含まれることから、IBM弧の背弧海盆においても沈み込み帯の影響を受けた地殻が形成されたと推測される。“低速度構造”や“中間構造”が見られる範囲はいずれも形成された年代が古い地殻である。このことは、沈み込み帯の影響を受けた地殻は拡大軸がスラブに近い背弧拡大初期に形成されたことを示す。“低速度構造”“中間構造”を示す幅が測線によって異なることから、沈み込み帯の影響の受け方は拡大軸に沿って変化している。特に四国海盆の中部とパレスベラ海盆には“標準的構

造”が見られず、沈み込み帯の影響が大きいことを示唆する。

地震学的構造から推定される沖縄トラフ北部および中部域におけるリフティングの特徴

Rifting structure in the northern and middle Okinawa Trough deduced from seismic reflection and refraction data

*西澤 あずさ¹、金田 謙太郎¹、及川 光弘¹、堀内 大嗣¹、藤岡 ゆかり¹、岡田 千明¹

*Azusa Nishizawa¹, Kentaro Kaneda¹, Mitsuhiro Oikawa¹, Daishi Horiuchi¹, Yukari Fujioka¹, Chiaki Okada¹

1. 海上保安庁海洋情報部

1. Hydrographic and Oceanographic Department, Japan Coast Guard

The Okinawa Trough is an active backarc basin as the Ryukyu (Nansei-Shoto) arc-trench system, to southwest of Kyusyu, Japan. The length and width of the trough are around 1,000 km and 100-200 km, respectively, and its rifting stage varies from north to south. Previous seismic surveys demonstrated that the crust beneath the trough has continental characteristics and the Moho depth shallows southward from about 25 km at the north to around 15 km at the south. However, the number of the seismic explorations in the Okinawa Trough was not so many to obtain detailed rifting structure considering the large dimension of the trough. We, Japan Coast Guard, have conducted extensive seismic reflection and refraction surveys in the Nansei-Shoto region since 2008 and we compiled the seismic structure in the northern and middle Okinawa Trough. We will show the results from seven seismic lines in this presentation: we carried out two lines along the trough strike and five lines perpendicular to the trough. The two of the five across-trough lines are positioned to the north of the Tokara Gap, the distinctive topographic depression between the north and middle trough. The other three lines are designed in the middle trough from the Tokara Gap to the Kerama Gap. These across-trough seismic lines intersect the along-trough lines at around the center of the trough.

The seafloor topography and multi-channel seismic (MCS) reflection records largely vary in the direction of the across-trough, in spite of a common feature that many normal faults were observed beneath all the MCS lines in the Okinawa Trough. The western part of the trough shows a flat topography and the several intrusions recorded in the MCS profiles do not reach to the seafloor. In contrast, the seafloor in the eastern part of the trough is characterized by many small-scale lineament structures. The strike of most of the lineaments is almost parallel to the volcanic front especially in the northern trough. The MCS records reveal many volcanic intrusions penetrate the seafloor.

The P-wave velocity models beneath the northern and middle Okinawa Trough generally show an extended arc crust of the Ryukyu Islands which consists of upper, middle, and lower crusts. We estimated crustal thicknesses below the trough mainly from Moho reflection (PmP) travel times. The along-trough seismic line in the middle trough demonstrates that the crustal thickness becomes thinner from north to south due to the decrease in thickness of the lower crust. However, such systematic decrease is not observed in the northern trough because of very inhomogeneous distribution of the middle and lower crusts along the seismic line. The across-trough seismic lines show that the crust below the trough is significantly thinner than the crusts beneath the Ryukyu Islands and the continental shelf of the East China Sea. The position of the shallowest Moho along the line is not necessary corresponding to the areas with the deepest water depth.

キーワード：沖縄トラフ、リフティング、地震学的構造

Keywords: Okinawa Trough, rifting, marine seismics

沖縄トラフ西端における海底地殻変動観測 GNSS/Acoustic geodetic measurement at the west end of spreading Okinawa trough back arc basin.

*香味 建¹、生田 領野¹、Chen Horng-Yue³、Lin Cheng-Horng³、Hsu Ya-Ju³、安藤 雅孝²

*Takeru Koumi¹, Ryoya Ikuta¹, Horng-Yue Chen³, Cheng-Horng Lin³, Ya-Ju Hsu³, Masataka Ando²

1. 静岡大学理学部、2. 静岡大学防災総合センター、3. 中央研究院地球科学研究所

1. Faculty of Science, Shizuoka University, 2. Center for Integrated Research and Education of Natural Hazards, Shizuoka University, 3. Institute of Earth Sciences, Academia Sinica

本発表では、2012年7月から2016年5月にかけて行われた、台湾の宜蘭沖でのGNSS/音響測距結合方式による海底地殻変動観測の結果を示す。

沖縄トラフは南西諸島の北西側に位置する背弧海盆である。与那国島の北沖の領域は、沖縄トラフの中でも特に背弧拡大が活発である(Nakamura(2004))。与那国島にあるGEONETの電子基準点の2010年~2013年の変位速度は、ユーラシアプレートを基準にして、ほぼ南方向に6~7cm/yrである。台湾の中央研究院地球科学研究所が海底の地殻変動を捉えるための4つの海底局を、与那国島北沖の拡大軸の西側延長上、深さ約1200mの場所に設置した。この海底局の位置の移動から、トラフ軸付近での背弧拡大の様子を観察することができる。2012年7月、2013年4月、7月、9月、2014年9月、2015年6月、2015年9月、2016年5月、以上全部で8回の海底地殻変動観測が行われた。本研究では、その海底地殻変動観測データを用い、海底局の位置決定を行い、2012年7月~2016年5月までの海底局の移動を推定した。

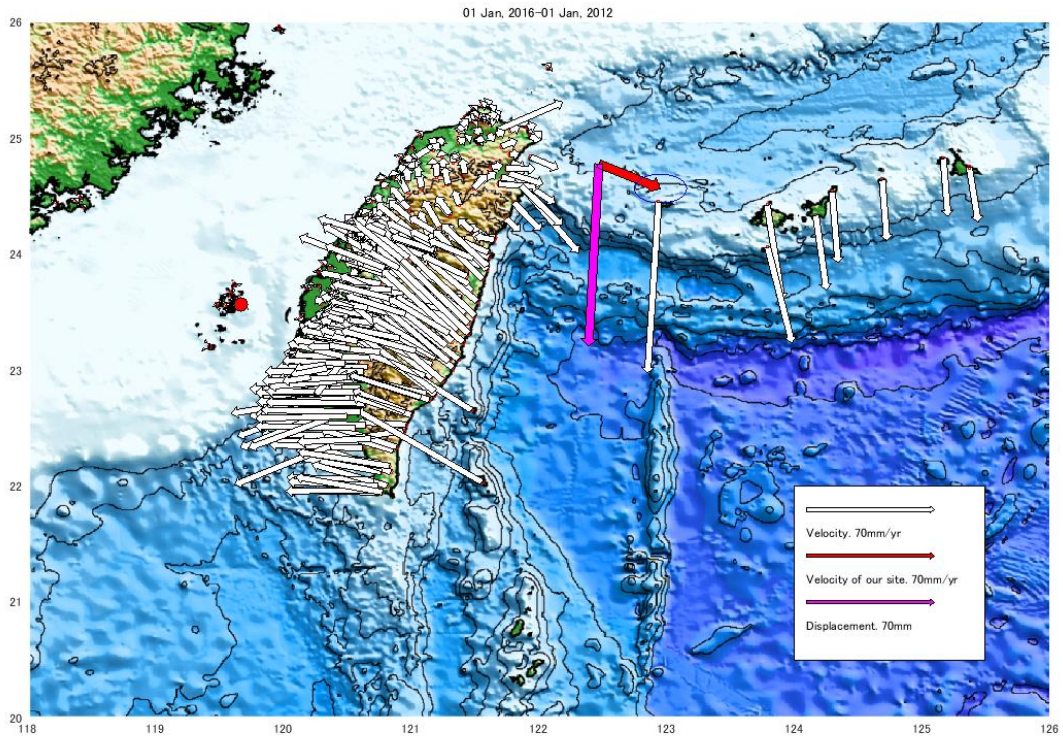
海底局の位置決定は、キネマティックGPSデータ、船の姿勢データ、音波の走時データ、CTDデータを使用して、Ikuta et al(2008)の手法を用いて行った。キネマティックGPSデータの解析には、NASA/GSFCで開発された長基線解析ソフトウェアIT(Interferometry Trajectory)を導入した。今回は、全観測期間において4つの海底局の相対位置が変化しないと仮定して、4つの海底局の重心の位置の移動を推定した。

その結果、海底局の重心の変位速度は南東方向におよそ5.7cm/yr(ユーラシアプレート基準)であることが推定された。重心の水平方向の時系列は、1本の直線でフィッティングした場合、残差が最大でも7cm程度と、ばらつきの小さい時系列となった。しかし、2013年9月頃にステップがあるように見えるため、複数の直線でのフィッティングを試みた。AIC(赤池情報量規準)を用いて結果を評価したところ、最もAICの値が小さくなったのは、2012年7月~2013年7月と2013年9月~2016年5月の2つに分けて2本でフィッティングした場合であった。

2本でフィッティングした場合、2013年7月から9月にかけて約11cm程南方向に移動していると捉えることができる。Ando et al(2015)によると、2013年4月に与那国島の北沖で、拡大軸で群発地震を伴うダイクの貫入が発生したと推定されている。宜蘭沖の南方向の移動は、2013年4月に起きたこの背弧拡大イベントが3~5ヶ月かけて西方向に伝播したことを表しているのかもしれない。南西諸島の陸上のGNSSに基づく観測ではほぼ一定速度に見えている沖縄トラフの拡大が、沖縄トラフ軸直近では地震活動を伴わずに断続的に生じている可能性が示唆される。重心の時系列を一本の直線で近似した傾向は、宜蘭平野と与那国島の間断的な速度を示し、長期的に見た背弧拡大の動きが、南西諸島と台湾の間で不連続でないことを示している。

キーワード：沖縄トラフ、背弧拡大、海底地殻変動、GNSS/音響測距

Keywords: Okinawa trough, back arc spreading, seafloor crustal deformation, GNSS/Acoustic measurement



琉球海溝南西域および台湾東海岸の巨大地震発生のメカニズム

Mechanism of large earthquakes along the southwestern Ryukyu subduction zone and the east coast of Taiwan

*安藤 雅孝¹、生田 領野¹

*Masataka Ando¹, Ryoya Ikuta¹

1. 静岡大学防災総合センター

1. Center for Integrated Research and Education of Natural Hazards, Shizuoka University

フィリピン海プレートの北西域端では、琉球海溝に沿って沈み込み、台湾東海岸では衝突する。この地域で、我々が最近実施した津波堆積物の調査、海底地殻変動観測に基づき、琉球海溝南西部の巨大地震のテクトニクスについて議論する。

1. 宮古島・石垣島沖での巨大津波

本地域では、過去数千年にわたり、巨大な津波が繰り返し発生したことが知られている。我々が行った石垣島での津波堆積物の調査から、過去2000年にわたり、ほぼ600年に一回の割合で巨大津波が発生したことを明らかになった(Ando et al. 2017)。これらの地震のうち、最新の1771年八重山地震の際には、石垣島沿岸では地割れが生じ、揺れは震度V弱(またはそれ以上)に達したことも判明した。この地震による、400km離れた沖縄本島での震度は、IVと推定されおり(宇佐美 2010)、1771年地震は“津波地震”ではなく、通常の地震である可能性が高い。1771年地震の東側でも、別の巨大津波がそれ以前に発生したことが知られている。下島(宮古島市)には、日本で最大の津波石(帯石)が打ち上げられており、珊瑚のC14年代測定から、11世紀以降、1771年以前に、巨大津波によるものと推定される。このような結果を総合すると、琉球海溝南西域沿いには、長さ250kmを超える巨大地震発生域があると考えられる。Nakamura(2009)のプレート境界面上の逆断層地震モデルを採用すると、プレートの地震性カップリング率は20%程度と低くなる。

2. 琉球海溝の後退と伸張歪み場

GPS観測によると、沖縄諸島は4-6cm/yの速度で南～南東に向かって移動する。この変動は琉球海溝が南東に後退するために生じるもので、先島諸島は $1-3 \times 10^{-8}$ /yの伸張歪み場にある。この伸びに応じて、背弧の沖縄トラフでは、マグマの貫入が起きるものと考えられる。2013年4月には与那国島の北50kmの沖縄トラフ内で、2日間にわたりマグマが貫入したと推定された(Ando et al., 2015)。2013年7月から9月の間に、その地点から西100kmで、マグマ貫入が生じたと、海底地殻変動観測から推定されている(香味・他、2017)。琉球海溝南西域では、海溝が後退しつつ、プレート沈み込みに伴う歪み応力を蓄積し、巨大地震を発生させるものと考えられる。カップリング率の低い伸張応力場でも、巨大地震が繰り返し発生しうるとは注目される。

3. 海底地殻変動観測結果

2014年に、波照間島(西表島の南)の南60kmに、海底地殻変動観測点が設置され、観測が継続されている。この結果から、観測点が西表島に対し南に移動していることが明らかになった。ただし、観測期間は2年間と短く、結果の信頼性はまだ低い。海溝付近でも伸張場であることを確かめるには、さらに3年間の観測が必要である。一方、台湾東海岸には、琉球海溝から沈み込むプレート間カップリングの検証を目的として、3カ所に海底地殻変動観測点が設置された。その内の一つの宜蘭沖の観測点の2012年～2016年の地殻変動観測結果が明らかにされた(香味・他、2017)。それによると、速度ベクトルは、南向きに4cm/y、東向きに8cm/yで、60km西の陸域の変動と調和的である。ただし、観測点が海溝から離れ過ぎているため、プレート間カップリングの有無を検証するに至っていない。さらに、海溝に近い他の2地点での観測を継続する必要がある。今後、波照間沖、台湾沖での海底地殻変動から、この地域の巨大地震の準備過程が、解明されよう。

4. まとめ

琉球海溝南西域の巨大地震発生のメカニズム解明には、波照間島沖の地殻変動観測を継続し、かつ台湾東海岸に海溝に近い海底地殻変動観測を継続して行う必要がある。

キーワード：琉球海溝、津波、プレートカップリング率、地震間隔、巨大地震、伸張歪み場

Keywords: Ryukyu trench, Tsunami, Plate coupling rate, Recurrence interval, Large earthquake, Extensional strain field

Detection of offshore vertical displacements after the 2011 Tohoku-oki Earthquake from GPS-A observations

*富田 史章¹、本莊 千枝²、木戸 元之²

*Fumiaki Tomita¹, Chie Honsho², Motoyuki Kido²

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 and Faculty of Science, Tohoku University, 2. International Research Institute for Disaster Science, Tohoku University

Postseismic displacements following the 2011 Tohoku-oki Earthquake (Tohoku Eq.) have been detected by on- and off-shore geodetic observations. Especially offshore GPS/Acoustic (GPS/A) observations showing an extensive postseismic displacement pattern [Watanabe et al., 2014, GRL; Tomita et al., 2016, AGU], which have strong constraints on modeling postseismic deformation processes [e.g., Sun et al., 2014, Nature]. However, these GPS/A studies have basically detected only in horizontal components. Postseismic vertical motions are sensitive to the postseismic processes because they show different spatial pattern from horizontal motions; therefore, detecting vertical motions is quite important. Although Watanabe et al. [2014] detected vertical motions after the Tohoku Eq., an extensive pattern of the postseismic vertical motions has not still been obtained.

It has been a difficult work to detect vertical motions by GPS/A observations because a parameter of calculating vertical motions has the trade-off nature with a parameter of the sound speed in the seawater (SSS). Sato et al. [2013, J. Geod.] showed acoustic ranging data obtained from numerous and extensive sea-surface ranging points could constrain the parameters; Watanabe et al. [2014] similarly estimated the postseismic vertical motions. In contrast to their data collections, we have collected acoustic ranging data from a fixed ranging point just above the center of a seafloor transponder array (point survey data) based on the strategy of Kido et al. [2006, EPS]. In this strategy, we can obtain a horizontal seafloor motion precisely by each ping, but it is difficult to constrain vertical motions. However, we have also collected less but extensive acoustic ranging data (moving survey data) occasionally to initially configure the seafloor transponder array. In this study, we challenge to calculate extensive vertical motions after the Tohoku Eq. using moving survey data obtained from Sep. 2012 to Nov. 2016 at the 20 GPS/A sites in the Tohoku-oki region.

In our strategy, we initially calculated relative positions of seafloor transponders at each site; then we simultaneously calculated positions of arrayed transponders (array positions) in both horizontal and vertical components for each cruise and temporal changes of SSS. In order to accurately calculate vertical motions, we also have to estimate an offset between a GPS antenna and an acoustic transducer mounted on each research vessel. Since we have employed a different vessel for each cruise, the transducer offset values may cause critical biases in the calculated vertical motions. Thus, we iteratively estimated the transducer offset values and the initial relative positions of seafloor transponders and the array positions. Then, postseismic displacement rates were calculated from the obtained vertical motions.

The obtained vertical displacement rates show spatially characterized pattern: subsidence above the coseismic rupture area and uplift near the trench, but they have 3-15 cm/yr errors in 1σ that are much larger than the errors in the horizontal components. The worse errors in the vertical component are probably caused by the trade-off nature with SSS and the shortage of the moving survey data. Some sites show small errors with ~ 3 cm/yr, but we cannot figure that the accurate results are actually obtained because the larger errors are obtained in the other sites by the same method. Due to the errors, it is difficult to quantitatively discuss the postseismic deformation processes at the moment. However, this study successfully showed the potential capability of our data for detecting vertical motions. In order to

quantitatively discuss the vertical motions, further moving survey data in the future and detailed evaluation of the errors are required.

キーワード：海底測地、2011年東北地方太平洋沖地震、GPS音響結合方式、余効変動、上下変動

Keywords: Seafloor geodesy, The 2011 Tohoku-oki Earthquake, GPS/Acoustic observation, Postseismic deformation, Vertical motions

An estimation of undersea sound speed structure: a more accurate strategy of GPS-A seafloor geodesy

*石川 直史¹、横田 裕輔¹、渡邊 俊一¹

*Tadashi Ishikawa¹, Yusuke Yokota¹, Shun-ichi Watanabe¹

1. 海上保安庁海洋情報部

1. Hydrographic and Oceanographic Department, Japan Coast Guard

The Hydrographic and Oceanographic Department of Japan Coast Guard has been developing a system for precise seafloor geodetic positioning with the GPS-Acoustic combination technique and deploying seafloor observation sites on the landward slope of the major trenches around Japan, such as the Japan Trench and the Nankai Trough.

The primary purpose of this observation is to detect and monitor the crustal deformation caused by the subduction of the oceanic plate near the plate boundary.

For the precise GPS-Acoustic seafloor positioning, we are developing analysis software, which combines a GPS positioning result and undersea acoustic travel times to get a precise position of an array of seafloor stations.

In this analysis, undersea sound speed structure must be given to convert travel times of acoustic wave into travel ranges. In order to estimate the seafloor positions accurately, it is necessary to have a sufficiently accurate sound speed structure. However the sound speed varies with time and space. Therefore it is practically impossible to cover all these variations in detail.

For positioning at the centimeter level, we are trying to estimate the sound speed variation from the travel time residuals in the positioning analysis. The travel time residuals include the information of the temporal variation, spatial variation and systematic difference of sound speed. By taking a proper strategy, the correction of sound speed based on this estimation improves the final positioning result significantly.

We investigate the behavior of the travel time residuals using spectrum analysis to extract the various frequency of sound speed variation. Based on the result, we will examine a more accurate analysis strategy.

キーワード：GPS-音響結合方式、海底地殻変動観測、海中音速度構造

Keywords: GPS-Acoustic ranging combination technique, seafloor geodetic observation, undersea sound speed structure