

大陸生成の新仮説と西之島における検証

Advent of Continent: Evidence from the Nishinoshima Volcano in the Ogasawara Arc

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Nishinoshima, one of the submarine volcanoes in the Ogasawara Arc, ~1,000 km south of Tokyo, Japan, suddenly erupted in November 2013, after 40 years of dormancy. The Nishinoshima volcano might represent the missing link between the mantle and the continental crust because (1) Nishinoshima, whose underlying crust is only 21 km thick, is one of the world's closest volcanoes to the mantle, and (2) the lavas have been andesites and were similar in composition to the continental crust. Here we report the scientific results of our endeavours to collect lavas from the currently erupting lava flows on the surface to the submarine lavas of the Nishinoshima volcano. Using olivine-bearing phenocryst-poor andesite samples, we developed a mantle-derived andesite model for the genesis of the Nishinoshima volcano. Shallow and hydrous mantle melting is necessary to produce primary andesite magmas, and thus it is only achieved beneath Nishinoshima and submarine volcanoes in the Ogasawara arc, where the crust is thin. We also show that the primary magma composition change from basalt produced at a considerable depth beneath the old thick lithosphere to andesite produced beneath the present crust corresponds to the thermal evolution of the mantle wedge in the Ogasawara arc.

キーワード：安山岩、大陸地殻、海洋島弧

Keywords: andesite, continental crust, oceanic arc



IODP Exp.351 (奄美三角海盆) で掘削された伊豆小笠原マリアナ島弧基盤
Izu-Bonin-Mariana Arc basement from IODP Exp. 351(Amami Sankaku Basin)

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IODP (International Ocean Discovery Program) Exp.351 targeted, in particular, evidence for the earliest evolution of the Izu-Bonin-Mariana (IBM) arc system following inception. This can be obtained by identification and exploration of regions adjacent to an arc, where unequivocally pre-arc crust (basement) overlain by undisturbed arc-derived materials exists. The drill site (U1438) is located in Amami Sankaku Basin (ASB), west of the Kyushu-Palau Ridge (KPR), i.e., paleo-IBM arc. Exp.351 successfully recovered pre-Izu-Bonin-Mariana arc basement, a volcanic and geologic record spanning pre-Arc, arc initiation to remnant arc stages. In this contribution, age and geochemical characteristics of arc basement and its tectonic significance will be discussed. At U1438, 1611m thick section in total was cored, comprising 1461m of sediment section and 150m of igneous basement. Numerous flow contacts were identified in the basement, several chilled margins could be identified but low recovery in basement rock makes their interpretation in terms of volcanic stratigraphy difficult. Paleomagnetic measurements show consistent shallow plunges of maximum anisotropy axes, and that implies these basalts were emplaced as sheet flows rather than pillow lavas.

Basalts have diverse textures that include aphyric to subophitic/ophitic. Phenocrysts are present in approximately half of the basalts and consist of plagioclase, clinopyroxene, titanomagnetite, spinel and minor olivine.

Age interpretations based on biostratigraphy (Arculus et al., Nat Geosci, 2015) determined that the basement section is between 64 and 51 Ma, and direct age determination of basement basalt by Ar/Ar dating is under way.

Whole rock geochemical analysis of the basement basalt shows that these basalts are low K tholeiitic basalts. They mostly have high-MgO (generally >8 wt%), low-TiO₂ (0.6-1.1 wt%), Ti/V, low-Zr (mostly <50 ppm). On Ti/V plot, the U1438 basalts and forearc basalt (FAB) which is supposed to be associated with subduction initiation from IBM arc are similar to each other and clearly distinct from Philippine Sea backarc basin basalts and normal MORB by having low Ti/V.

One prominent characteristic of the basalts is their depletion of immobile highly incompatible elements compared with MORB, e.g., they are strikingly light REE (LREE) depleted. But La/Nd ratio and Th/LREE increases upcore in the uppermost part of the basement, and these trace element variations with depth is accompanied by variation of major element composition such as Si and Ti. Hf-Nd isotopes for the basement basalts show a significant range of compositions, and relatively radiogenic Hf compared to Nd indicates an Indian Ocean-type MORB source. However, the dominant signature, with $e_{\text{Hf}} > 16.5$, is more radiogenic than most Indian MORB.

Preliminary data suggests that the basement basalts are relatively primitive melts and likely

derived from Indian Ocean-type MORB sources that are more strongly depleted in terms of incompatible trace elements than typical MORB or backarc basin basalt in the Philippine Sea. Geochemical variation in the uppermost part of the core might imply variability of slab-derived enrichment and/or fertility of mantle at the onset of subduction. Geochemical characteristics of arc basement from Exp.351 imply that depleted MORB-like basalt ("FAB") appears to have formed in wider area than previously thought, i.e., including "reararc" side of ancient IBM arc. However, critical assessment of genetic relation between FAB and basement basalt of ASB requires precise age determination to constrain tectonic setting where the ASB basalts formed.

キーワード：島弧基盤、伊豆小笠原マリアナ弧、地球化学的特徴、ArAr年代

Keywords: arc basement, Izu-Bonin-Mariana arc, geochemical characteristics, Ar/Ar age

IODP EXP352で掘削された前弧玄武岩・ボニナイトの物性とその海洋地殻地震波速度構造に対する意義

Physical properties of fore-arc basalt and boninite recovered by IODP EXP352 and its significance for the seismic velocity structure in the oceanic crust

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Physical properties of the cores recovered by IODP EXP352 were characterized through a set of measurements on whole core sections and discrete samples. Gamma ray attenuation density (GRA), magnetic susceptibility (MS) and P-wave velocity (PWL) of the cores were obtained using the Whole-Round Multisensor Logger (WRMSL). Natural gamma radiation (NGR) was measured by the Natural Gamma Radiation Logger (NGRL). Point magnetic susceptibility (PMS), reflectance spectroscopy and colorimetry (RCS) data were acquired using the SHMSL. Thermal conductivity (TCON) and moisture and density (MAD) were obtained on sections and discrete samples, respectively. All raw data were subsequently "filtered" to remove spurious points that correspond to empty intervals in the liner or broken pieces. We have mainly studied the relationships among P-wave velocity, density, porosity and magnetic susceptibility. We show that the physical properties are useful dataset for the interpretation of the layer 2 (i.e. volcanic rocks) in the seismic velocity structure of the oceanic crust.

キーワード：IODP EXP352、物性

Keywords: IODP EXP352, Physical property

Evolution process of volcano-bounded basin revealed by mapping of seismic reflectors associated with geological boundary from drilling results in Izu rear arc
Evolution process of volcano-bounded basin revealed by mapping of seismic reflectors associated with geological boundary from drilling results in Izu rear arc

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International Ocean Discovery Program (IODP) has successfully conducted the first rear-arc drilling in the Izu-Ogasawara (Bonin) intra-oceanic arc at Site U1437 in 2014. The drilling purpose of Site U1437 is to reveal the formation of oceanic arc crust and its evolution into continental crust about the history of "the missing half" of the subduction factory. Site U1437 is located at the volcano-bounded basin between the Manji and Enpo backarc seamount chains in the Izu rear arc and ~90 km west of the arc-front volcanoes Myojinsho and Myojin Knoll, at 2117 m below sea level. Site U1437 had excellent core recovery in Holes U1437B and U1437D, and we succeeded in hanging the longest casing ever in the history of R/V *JOIDES Resolution* scientific drilling (1085.6 m) in Hole U1437E and cored to 1806.5 mbsf.

In order to evaluate the crustal structure of this proposed site before the IODP drilling, Japan Agency for Marine-Earth Science and Technology carried out many seismic reflection and refraction surveys using R/V Kaiyo and Kairei in the Izu rear arc during 2006 to 2008. Five clear seismic reflection profiles consisting of three kinds of survey environments and one seismic velocity image by seismic refraction survey are obtained across the drilling site U1437. Five sedimentary units consisting of volcanoclastics are identified from our interpretations around the drilling site in the seismic reflection profiles over the 5 km/s and 6 km/s iso-contours of P-wave velocity obtained by the velocity image of seismic refraction survey in order to evaluate structure of the drilling location before drilling. However, some unit boundary is not recognized from the drilling core. It means the difficulties for identification the geological target from only seismic images in volcanic regions. According to the drilling results, the acquired geological core is consisted of seven lithological units (I, II, III, IV, V, VI and VII). Units I to V was produced at age of 0-9 Ma. The Unit VI and VII, 1320-1806.5 mbsl, have the ages ranging from 9 to ~14 Ma. P-wave velocity calculated from obtained core samples increases downhole from ~1500 to ~4500 m/s which agree with the range of our velocity analysis. Tops of unit II, V and VII correspond to the strong reflector of seismic profiles. We interpreted and mapped using grid survey data around the drilling site. The top of unit II which corresponds to the volcanoclastics has south dipping trend. The top of unit V which corresponds to the mudstone with volcanoclastics layer has south dipping trend. The top of unit VII which corresponds to volcanoclastics estimated by near-vent deposit has southeast dipping trend. Each reflector is interrupted by igneous basement near seamount chains. We also calculate the thickness from unit VII to V and unit II to seafloor from mapped reflectors. These features suggest the different activity of various directions in the Izu rear arc. We will discuss about the evolution process in Izu rear arc deduced from our mapping results.

キーワード：事前調査、海洋掘削、背弧

Keywords: site survey, volcano-bounded basin, rear arc

超低速拡大海域の下部地殻-モホ掘削 (SloMo)速報

Preliminary reports on the Nature of the Lower Crust and Moho at Slower Spreading Ridges (SloMo)

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国際深海掘削科学計画の調査航海360においてジョイデスレゾリューション号によって超低速拡大海域である南西インド洋のアトランティスIIトランスフォーム断層に沿って産する海洋コアコンプレックス、アトランティスバンク、の海洋底から789.7m深度までのはんれい岩掘削に成功した。この調査航海は、マントル掘削を視野に入れた超深度掘削 (Phase II)のための初期掘削の位置付けでもある (Phase I)。また、この地点近傍では、過去に深海掘削計画による735B孔、1105A孔による掘削に成功しており、本調査海域周辺は海洋深部起源岩石の3次元構造を唯一検討できる貴重な研究対象である。発表では、本調査航海の概要と予察的研究成果を報告し、将来のマントル掘削に向けた展望についても紹介する。

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キーワード：低速拡大海域、海洋コアコンプレックス、海洋下部地殻

Keywords: Ultraslow-spreading ridge, Oceanic Core complex, Oceanic Lower Crust

Lord Howe Rise Drilling: Deep stratigraphic record for the Cretaceous eastern Gondwana margin

Lord Howe Rise Drilling: Deep stratigraphic record for the Cretaceous eastern Gondwana margin

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The Lord Howe Rise (LHR) is an elongate ribbon of submerged and extended continental crust that separated from Australia during the Late Cretaceous. Current knowledge of the LHR is based only on widely-distributed marine and satellite geophysical data, limited dredge samples, and sparse shallow drilling into Cenozoic pelagic sediments. Building more detailed knowledge of LHR geology and the evolution of the eastern Gondwana margin requires drilling into rocks that record the tectonic and climatic history of the region.

Geoscience Australia and JAMSTEC are leading an international effort to promote an IODP project (871-CPP) to drill a deep stratigraphic hole through a LHR rift basin using D/V CHIKYU that will recover Cretaceous and older sediments and basement rocks. The objectives of this proposal are to: 1) define the role and importance of continental crustal ribbons, like the LHR, in plate tectonic cycles and continental evolution; 2) recover new high-latitude data in the southwest Pacific to better constrain Cretaceous paleoclimate and linked changes in ocean biogeochemistry; and 3) test fundamental evolutionary concepts for sub-seafloor microbial life over a 100-million-year timeframe.

キーワード：IODP、ロードハウライズ、地球深部探査船ちきゅう、白亜紀、ゴンドワナ、ジーランディア
Keywords: IODP, Lord Howe Rise, Chikyu, Cretaceous, Gondwana, Zealandia

Po/So波から推定した海洋リソスフェアの地震学的構造

Seismological structure of oceanic lithosphere inferred from Po/So waves

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Oceanic lithosphere, comprising oceanic crust and upper mantle, plays an important role in plate tectonics. Knowledge of the detailed structure of oceanic lithosphere is key to understanding its origin.

The propagation of Po/So waves over large distances across oceanic lithosphere provides information about lithospheric structure. Po/So waves, characterized by a high frequency, large amplitude, and long duration, were identified as early as 1935 [Linehan, 1940]. Many previous studies have attempted to quantitatively explain the generation and propagation mode of Po/So phases. Although it is generally accepted that Po/So phases are guided waves traveling very efficiently throughout the oceanic lithosphere, the generation and propagation processes of Po/So phases remain unclear.

In the past two decades, there have been great technological advances in computer simulations of high-frequency seismic waves in heterogeneous structures and in broadband seismic observations on the seafloor. These gains motivated us to further investigate the processes relating to guided waves in oceanic lithosphere and the generation of Po/So waves, using broadband seismic data and the numerical Finite Difference Method (FDM) to simulate high-frequency seismic waves. In this presentation, we outline recent progress in the study of Po/So waves.

Shito et al. [2013] reported that Po/So waves are generated by multiple forward scattering of P- and S-waves due to small-scale heterogeneities in oceanic lithosphere. The laterally elongated heterogeneities are described by a von Karman distribution function with a correlation length of 10 km in the horizontal and 0.5 km in thickness, with a velocity perturbation of 2%.

Kennett and Furumura [2013; 2014] and Shito et al. [2015] found that the propagation efficiency of Po/So waves depends on the age of oceanic lithosphere, and that this relationship can be qualitatively explained by thickening of oceanic lithosphere that contains small-scale heterogeneities and a reduction in intrinsic attenuation. Recently, Kennett and Furumura [2015] proposed a new model that the amplitude of such heterogeneities increases with depth to the bottom of the lithosphere. These results suggest that small-scale heterogeneities may form continuously in oceanic lithosphere, from the time of its formation at a spreading ridge, via the solidification of melts in the asthenosphere.

The petrological and mineralogical processes that cause the small-scale heterogeneities remain poorly known. Future studies that combine seismological observations with petrological analyses will yield a greater understanding of the origin of oceanic lithosphere.

キーワード：Po/So波、海洋リソスフェア、小規模不均質

Keywords: Po/So waves, oceanic lithosphere, small-scale heterogeneities

中央海嶺玄武岩ガラス中の揮発性元素およびハロゲンから推定されるメルト密度、混染、噴出場の効果：国際深海科学掘削計画1256サイトの例

The effect of melt density, assimilation, and eruption location on volatile and halogen contents in MORB glasses: an example from IODP Site 1256

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A continuous section of ~700 m-thick lava pile at Integrated Ocean Drilling Program Site 1256 provides important depth variation of volatile (H₂O, CO₂, S) and halogen (Cl) contents in fresh glasses to understand style of eruption, condition of magma storage, and degree of hydrothermal assimilation. The lava pile is divided into two groups based on eruption location: off-axis basalts of upper portion (250-534 m beneath seafloor, mbsf) and on-axis basalts of lower portion (534-941 mbsf). Majority of the lava pile is composed of pillow, sheet, and massive lavas, but both groups have short (1-2 m) intervals of hyaloclastite layers (e.g., Wilson et al., 2006, Science).

H₂O contents of hyaloclastite samples are distinctly higher than those of lavas, suggesting that the high H₂O would induce explosive eruption to produce the hyaloclastite materials. CO₂/Nb and S/Dy in most fresh glasses are smaller than degassed ratios (e.g., Saal et al., 2002, Nature), and these facts indicate shallow degassing and CO₂ and S losses during transport to the seafloor. Saturation pressures calculated by dissolved H₂O and CO₂ contents are wide range from pressure of seafloor (~25 MPa) to pressure of magma chamber (~60 MPa). The saturation pressure positively correlates with melt density, but obvious differences between off-axis and on-axis samples are not identified. These observations may imply that the melt density is important factor to estimate degassed pressure. When the melt density is low, the melt can ascent from melt lens (top of magma chamber) to shallow place within oceanic crust and highly degassed before reach to seafloor. Conversely, dense melt would not ascent to the shallow place and less degassed at deep level near the melt lens.

The most distinctive character for the Site 1256 glasses is higher Cl/Nb and Cl/K than any other MORB glasses. The strong Cl enrichment is explained by assimilation of highly hydrothermally influenced crust (e.g., Sano et al., 2008, 2011, G-cubed). Beneath the Site 1256, melt lens was very shallow (<1.5 km) and hydrothermal circulation of high-salinity brines would easily reach to roof crust of the melt lens.

キーワード：国際深海科学掘削計画、揮発性元素、メルト密度

Keywords: IODP, volatile, melt density

A seamount on top of Ontong Java Plateau was created by remelting of plateau lithosphere by plate flexure

A seamount on top of Ontong Java Plateau was created by remelting of plateau lithosphere by plate flexure

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The Ontong Java Plateau (OJP) was formed by a main volcanism occurred at ca. 120 Ma, followed by several pulses of the late-stage volcanism on and along the margins of the plateau. The origin of the late-stage volcanism is poorly understood because of limited rock sampling. We present the age and geochemical composition of basalts dredged from Nuugurigia Atoll that stands on the plateau basement, possibly erupted in the late-stage volcanism. The $^{40}\text{Ar}/^{39}\text{Ar}$ age of dredged basalts is ca. 20 Ma, younger than any other known late-stage volcanism on OJP (down to 34 Ma), and is coincided with the collision of the plateau with the proto-Solomon arc. These basalts have enriched isotopic signatures pointing towards EM1 distinct from any other rocks thus far collected from OJP. Moreover, they show unusual trace element composition with Sr enrichment and Zr-Hf depletion relative to the elements with similar incompatibility. Such isotopic and trace elemental feature are shared with quartz-bearing garnet pyroxenite xenoliths rarely found from Solomon Islands (Ishikawa et al., 2007). Ishikawa et al. inferred that such pyroxenite was derived from delaminated granulitic lower crust and was part of the OJP lithosphere underplated beneath the plateau lithosphere via the mantle upwelling responsible for the main plateau-forming volcanism. We suggest that the basalts in the late-stage volcanism at Nuugurigia were products of rejuvenated melting of such pyroxenite. Melt transport through the lithosphere may have been facilitated by plate flexure occurred just south of the atoll when the plateau collided with the proto-Solomon arc around 20 Ma.

キーワード：海台玄武岩、リソスフェア、リサイクル物質

Keywords: oceanic plateau, lithosphere, recycled material

Understanding continental crust emplacement: A continental scientific drilling perspective

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Scientific drilling is a critical tool for Earth science to understand crustal evolution and processes. In the recent past, the International Continental Scientific Drilling Program, ICDP, supported several drilling operations in hard rock addressing the formation and emplacement of continental crust from Archean volcanism (Peering into the Cradle of Life, Barberton, South Africa), Paleoproterozoic volcanism (FAR-DEEP, Baltic Shield, Russia), rift volcanism (Krafla, Iceland), hot spot volcanism (Hawaii, USA, Snake River Plain, Idaho, USA) and Himalyan-style thrust sheet emplacement (COSC, Sweden). The results of these studies have significantly improved our understanding in past and present formation of continental crust.

ICDP supports scientific drilling operations that facilitate outstanding science at globally important sites. ICDP brings together scientists and stakeholders from 24 nations to work together at the highest scientific and technical level. Since its founding in 1996, more than 40 drilling projects and 75 planning workshops have been supported by ICDP worldwide. The outcomes of scientific drilling operations supported by ICDP cover the full range of the Earth sciences from climate change, natural hazards and earth resources to the origins and evolution of life on Earth, effectively addressing the needs of our growing population for energy, sustenance, and quality of life.

Forthcoming ICDP drilling into the Samail ophiolite complex in Oman will provide key data on melt extraction processes from the mantle, igneous accretion of oceanic crust, and hydrothermal modification of that crust. Drilling will also investigate present day alteration processes of mantle peridotites and their relationship to the deep biosphere.

The Surtsey volcano drilling in fall 2016 aims to investigating processes of rift zone volcanism, hydrothermal alteration and biological colonization of basaltic tephra. It will refine our understanding of seawater- interactions with magma and rock that influence diagenetic and microbial alteration of tephra to produce lithified tuff and shed new light on how rift zone volcanic islands form, lithify, and are ultimately destroyed.

ICDP is also funding drilling for Reservoir Triggered Seismicity near the Koyna dam located close to the west coast of India. The basement rocks of the Koyna-Warna region consists of Precambrian basement overlain by a more than 1 km thick Deccan Trap cover that erupted about 65 Ma ago. Two pilot boreholes will provide critical information on the in-situ stress regime, pore fluid pressure, fluid/gas properties and hydrological parameters of basement rocks, and the geothermal regime. These 3 km deep wells will lay the ground for two deep main boreholes for penetrating into the source of induced seismicity at more than 5 km depth.

Keywords: ICDP, Scientific Drilling, Continental Crust emplacement

オマーンオフィオライトの超高温沈み込み帯の末路：その誕生から死まで

From Birth to Death: Fate of The Extremely High-T Subduction Zone of The Oman Ophiolite

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The Oman Ophiolite preserves the entire geological records of intra-oceanic subduction zone formation and arc evolution, where 98-96 Ma MORB-like basalt magmatism (V1) was followed by 96-94 Ma arc tholeiitic and low-silica boninitic volcanism (V2) [1,2,3,4]. The remnants of the subducted slab are now preserved as the high-grade metamorphic soles beneath the ophiolite sheets [5]. After a quiescence period, alkali basalt flows (V3) were extruded at about 90 Ma, which has an intermediate geochemical characteristics between OIB and EMORB [6]. The V3 trace element compositions can be reproduced by pooled partial melts in the stability field of garnet and spinel lherzolite. Through the V2 magmatism, the source mantle shows progressive depletion by stepwise melt extraction, as shown by the lower Nb/Ta ratios for the younger volcanic rocks (V2 boninite < V2 tholeiite < V1) [2] with identical $\epsilon_{\text{Hf}}(t)$ values. V2 glasses have higher B, Pb, and LILEs with age, indicating an increasing contribution of slab fluids from earlier arc tholeiite to later boninite. Boninite magma was generated with the supply of high-T hydrous fluid and sedimentary melt liberated from the metamorphic sole as demonstrated by the Sr-Nd isotopic compositions of the amphibolite and metachert in the sole and clinopyroxene separates from boninites [1,2,7]. Therefore, the metamorphic sole beneath the ophiolite sheets are responsible for the generation of V2 arc magmas. Melt inclusions in Cr spinel derived from boninite comprise homogeneous glass of mostly low-Si boninitic [3,4] and slightly differentiated composition, with SiO₂ ranging in 52-62 wt% and MgO up to 16 wt%. The primary boninite magma assumed as the most magnesian melt inclusion can coexist with mantle olivine and orthopyroxene [9] at 0.4-0.6 GPa and 1350°C. This T-P conditions indicate a segregation depth of ~17 km from the mantle with a potential T of 1400°C. Meanwhile, the peak metamorphic conditions for the subducted slab that liberated high-T fluids to form boninite and arc tholeiite magmas are 770-900°C and 1.1-1.3 GPa [1,6,7].

The keys of the Oman subduction zone are 1) the preservation of diapiric structures in the mantle [10], 2) short time interval of the V1 and V2 magmatism <2 m.y., 3) T-P conditions for a primary low-Si boninite (Umino et al., 2014); and 4) extremely high T & low-P metamorphic conditions for the sole that liberated the fluids generating the V2 magmas [1,5]. These lines of evidence are most readily explained by intraoceanic thrusting initiated near the ridge axis that developed into a shallow and hot subduction zone [1,2,8,10].

Forced subduction of such an extremely high-T, buoyant slab suppressed convection in the mantle wedge, resulted in the progressive depletion of the source mantle through the V2 arc magmatism. Numerical modeling suggests that melting of the slab and mantle wedge occurs only in the early stage and ceases as the mantle wedge cools because of the absence of convection [10]. Consequently, the Oman arc volcanism terminated in only a few million years. After several million years, parts of the subducted slab delaminated and induced upwelling and adiabatic melting of DMM asthenosphere, resulted in the generation of alkalic magmas of V3 extruded onto thick pelagic sediments before

colliding onto the Arabian Peninsula.

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キーワード：オマーンオフィオライト、無人岩、高温沈み込み帯、メタモルフィックソール、沈み込み帯発
生、オブダクション

Keywords: Oman Ophiolite, boninite, high-T subduction zone, metamorphic sole, subduction
initiation, obduction

オマーンオフィオライト・フィズ岩体マントルセクションの酸化還元状態：マントルウェッジのアナログ研究

The redox state in the Fizh mantle section, the northern Oman ophiolite as an analog of mantle wedge in subduction zone

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岩石の酸化還元状態を知ることは、相平衡状態や元素分配を制約する重要な情報となり得る。マントルかんらん岩については、島弧域でのマントル捕獲岩などと比較して海洋底かんらん岩はより還元的との報告がなされている (Parkinson and Pearce, 1998)。これは海洋リソスフェアが沈み込む過程において脱水作用を被り、水や二酸化炭素といった“酸化的な流体”がマントルウェッジの下部に供給されているためと考えられる。

オマーンオフィオライトのマントルセクションは衝上の過程で沈み込み帯のセッティングを経ており、マントルウェッジの酸化還元状態を探る上で格好のアナログになりうる。そこで本研究は、オマーンオフィオライト北部のFizh岩体を沈み込み帯のマントルウェッジのプロキシとして捉え、酸化還元状態の傾向とその要因について考察する。マントルセクションのかんらん岩を対象に、カンラン石とスピネルの化学組成からBallhaus et al. (1991) の計算式を用いて $\Delta \log f_{O_2}$ (FMQ)を算出した。スピネルの二価鉄と三価鉄の比はストイキオメトリーを仮定した。計算値をFizh岩体の上にプロットした結果、東部のモホ面側でより酸化的に、西部の基底スラスト面側でより還元的となることが分かった。これは沈み込むスラブと接触するマントルセクション最下部が最も還元的になることを示している。

EPMAによる分析値とストイキオメトリーによって計算したスピネルの二価鉄と三価鉄の比をメスバウアー分析による結果と比較したところ両者に有意の差は認められず、 $\Delta \log f_{O_2}$ (FMQ)の計算結果に与える影響は限定的であった。続いて、酸素フガシティーに敏感であるバナジウムとそうでないスカンジウムとの比を酸素フガシティーのプロキシとして捉え、 $\Delta \log f_{O_2}$ (FMQ)との関係を検討した。その結果、V/Sc比が減少する還元的な試料ほど $\Delta \log f_{O_2}$ (FMQ)は低く、反対にV/Sc比が増加する酸化的な試料ほど $\Delta \log f_{O_2}$ (FMQ)は高くなるような負の相関が認められた。この結果からもマントルセクション最下部がマントルセクション上部よりも還元的であることが支持される。

Fizh岩体マントルセクションの最下部が還元的となる要因として、沈み込んだ還元的な堆積物の溶融で生じた還元的なメルトとの反応が考えられる。基底スラスト面付近にあたる $\Delta \log f_{O_2}$ (FMQ)値の低い試料は、全岩および単斜輝石とともに比較的高いTh/Ce比を持つ傾向がある。高いTh/Ce比は海洋性堆積物の寄与を示す特徴の一つであり、それらの影響が示唆される。また、基底スラスト面付近のかんらん岩のかんらん石中の流体包有物のラマンスペクトルからはメタンのピークが検出された。一方、モホ面付近の試料中の流体包有物からはメタンのピークは認められず、流体包有物のメタンは蛇紋岩化作用によるものではなく、沈み込んだ堆積物由来である可能性が示唆される。すなわち、オマーンオフィオライトはその衝上の過程で海洋性堆積物がメルトの供給に関与し、その還元的なメルトがマントルウェッジの下部から浸透し、周囲のかんらん岩をより還元的にさせたと考えられる。

キーワード：オマーンオフィオライト、酸化還元状態、マントルかんらん岩、マントルウェッジ、酸素フガシティー、沈み込み帯

Keywords: Oman ophiolite, Redox state, mantle peridotite, mantle wedge, oxygen fugacity, subduction zone

ハードロック掘削でのマッドガスモニタリングとその意義

Mud gas monitoring for hard rock drilling

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Mud logging in a riser drilling operation has been powerful tool in the scientific drilling. Since fast and safe drilling are minimum requirements in the deep drilling operation, it is generally difficult that continuous coring is carried out to obtain geological sample (rocks and fluid). Therefore, cuttings survey and mud gas monitoring in mud logging are essentially important in the riser drilling for scientific research. Some hard rock drilling operations by using the Chikyu have been planned (e.g., IBM, MoHole). Since continuous coring in the hard rock drilling is technically more difficult as compared with the drilling for sedimentary rocks and slow rate of penetration results in consuming much of operation time, the cuttings survey is a unique approach for lithological characterization in the hard rock drilling. In addition, fluid sampling from hard rock core is also difficult, even if core sample is obtained. Thus, the mud logging is especially important for the hard rock drilling, not only minimizing operation time but also maximizing scientific result. In this presentation, we will introduce current technology of advanced mud gas monitoring and discuss on potential of the mud gas monitoring for the hard rock drilling.

キーワード：泥水検層、ハードロック掘削、ガスモニタリング、地層流体

Keywords: Mud logging, Hard rock drilling, Mud gas monitoring, Formation fluid

IODP Exp. 360インド海嶺下部地殻-モホ掘削速報-物性計測と孔内計測結果

Preliminary result of the physical properties and downhole measurements during IODP Exp. 360 Indian Ridge Lower Crust and Moho

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IODP Expedition 360 Phase I of the Nature of the Lower Crust and Moho at Slower Spreading Ridges (SloMo) project of a Multi-Leg Drilling Project was conducted drilling into the lower crustal gabbroic rocks at Atlantis Bank, and penetrated from the top of ocean floor to 798.7 mbsf. The cored interval is 742.7m and total recovered core length 469.65 m (63.2% recovery). Olivine gabbro is the dominant lithology of the recovered core samples, followed in gabbro, oxide gabbro, and oxide-bearing gabbro. Lithological variation is small in the core samples. In order to understand the petrophysics of the site, we measured physical properties on the whole round and splitted half sections and, discrete samples and also took three runs of wire-line logging; Triple-combo, FMS and UBI.

Phase II of the SloMo has proposed to drill 6 km through MOHO by the CHIKYU. In the meeting, we would like to present the preliminary results, especially of the petrophysical measurements, of IODP Expedition 360 and the future perspective leading to Phase II of the SloMo, a mantle drilling into ultraslow-spreading ridges.

キーワード：国際深海科学掘削計画、モホ、南西インド海嶺、低速拡大海嶺

Keywords: IODP, Moho, SW Indian Ridge, Slow spreading ridge

南部マリアナ海溝で採取された海溝カンラン岩の地質学的研究

Peridotites outcropped in the southern Mariana Trench

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伊豆・小笠原・マリアナ弧(IBM弧)は南北3000kmに及び海洋性島弧系である。海溝内に堆積物の付加体を持たず、海溝陸側斜面には地殻物質やマントル物質が露出している。マリアナ弧はIBM弧の南部約1500kmを占め、その海溝軸は小笠原海台とカロリン海嶺の衝突により湾曲している[1]。そのため、グアム島西方からヤップ海溝に至る南部マリアナ海溝はマリアナ島弧やマリアナトラフ(背弧海盆)を横切る特殊な構造を持つ。

これまで、南部マリアナ海溝陸側斜面の地質学的研究はチャレンジャー海淵北東の海溝陸側斜面を対象に行われてきた。北部マリアナ前弧のカンラン岩に類似した高い部分溶融程度のカンラン岩に加えて、肥沃な組成を持つ背弧的なカンラン岩が得られている[3]。一方で、チャレンジャー海淵より西側の海溝陸側斜面を対象にしたマントルカンラン岩の岩石学的な研究例はなく、Hawkins and Batiza (1977)の岩石記載のみである。そのため、南部マリアナ海溝陸側斜面に露出するマントルカンラン岩の全体像はいまだ明らかになっていない。

そこで本研究の目的は、南部マリアナ前弧全域から得られたカンラン岩の岩石学および微細構造的特徴を比較検討することによって、南部マリアナ海溝陸側斜面のマントル領域の全体像を明らかにすることである。研究試料はチャレンジャー海淵より北東の8海域とチャレンジャー海淵西方の2海域で採取されたカンラン岩を用いた。サンプルは研究船白鳳丸の3航海, KH92-1, KH98-1およびKH03-3, 支援母船よこすかの4航海, YK08-08, YK10-12, YK14-13およびYK15-11, R/VThomas WashingtonのMARIANA Expedition in 1978で採取された。

チャレンジャー海淵西方の2海域から採取されたカンラン岩の岩石学的特徴は海域ごとに異なっていた。ヤップ海溝との接続部の近傍(Site1:11°2'N 139°3'E)から得られたカンラン岩は肥沃な組成を持ち、パレスベラ海盆カンラン岩の組成と一致する特徴を示した[4]。Site1より東方のチャレンジャー海淵に近い海域から採取されたカンラン岩は北部マリアナ前弧のカンラン岩に似た枯渇した組成を示した[5]。ポスターでは、これらのデータを加えて、南部マリアナ海溝全域のカンラン岩の特徴について議論する予定である。

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キーワード：海溝カンラン岩、南部マリアナ海溝、地球化学、かんらん石ファブリック

Keywords: Trench Peridotite, Southern Mariana Trench, Geochemistry, Olivine Fabric

Geochemical characteristics of Izu rear arc magmatism after the cessation of the Shikoku Basin opening: Results from IODP Exp. 350

Geochemical characteristics of Izu rear arc magmatism after the cessation of the Shikoku Basin opening: Results from IODP Exp. 350

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International Ocean Discovery Program Expedition 350 Site U1437 drilled, for the first time, into the rear arc volcanoclastic sediment in the Izu arc. The drilling reached 1806.5 m below seafloor (mbsf) and in-situ lava clasts were recovered in the deepest part of the hole (stratigraphic Unit VII, below ~1460 m) (Tamura et al., 2015).

The U-Pb zircon ages obtained from an intrusive rhyolite sheet of the Unit VI at the depth of ~1390 mbsf showed 13.6±1.6/-1.7 Ma (Tamura et al., 2015) and 13.71±0.25 Ma, thus Unit VII lava clasts suggest magmas erupted after the cessation of the Shikoku Basin opening (~15 Ma) and before onset of the rear arc seamount chain magmatisms (hot fingers).

We have analyzed the major and trace element compositions, and Sr, Nd, Pb and Hf isotope ratios of selected >2 cm lava clasts collected from Unit VII. These show neither rear arc nor Quaternary volcanic front signatures in terms of trace elements and isotopes. The Nd and Hf isotope compositions are similar to those in the Quaternary volcanic front magmas. However, most samples have Sr and Pb isotope compositions similar with those in the rear arc magmas. The isotopes of Unit VII are also similar to samples collected from the active rifts. Most of samples show low Ba/La and La/Sm, and chondritic Sm/Hf ratios, suggesting that the addition of slab derived fluids/melts is small despite the horizontal trend of Nd-Hf isotopes.

Above results show that Izu rear arc magmatism at Site U1437 differed from that in the rear arc seamount chains after cessation of the Shikoku Basin opening. Contribution of the slab flux was small and the source mantle was highly depleted in terms of isotopes.

嶺岡瀬戸川帯深成岩類のジルコンU-Pb年代と地球化学：IBM弧の中部～下部地殻か？

Zircon U-Pb age and geochemistry of plutonic rocks in the Mineoka-Setogawa Belts:

Fragments of middle to lower crust of the IBM Arc?

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The Mineoka-Setogawa Belts are Paleogene accretionary complexes distributed around the Izu Peninsula. These belts contain the various sizes of detrital and tectonic fragments of serpentinized mantle peridotites, plutonic rocks (gabbro, diorite and tonalite), metamorphic rocks and volcanic rocks (e.g., Arai 1994), which likely show ophiolitic constituents. Although Middle Eocene microfossils were reported from sedimentary rocks in these belts (e.g., Saito, 1992; Sugiyama and Shimokawa, 1990), reliable data of the isotopic age have not been obtained yet. In this study, we determined the precise age of the plutonic rocks in the Mineoka-Setogawa Belts using the zircon U-Pb method, and compared with the current age models proposed for the Philippine Sea and IBM Arc.

The U-Pb age was measured from zircon grains collected from 10 samples of gabbros, diorites and tonalites using LA-ICP-MS (Thermo Fisher Scientific ELEMENT XR). The zircon U-Pb ages obtained from all samples concentrate at approximately 35 Ma, regardless of the rock types. These ages are coeval with the Eocene to Oligocene arc magmatism in the IBM Arc.

The whole-rock chemistry of the plutonic rocks from the Mineoka-Setogawa Belts shows calc-alkali affinity and distinct negative anomalies of Nb and Ta in their trace element patterns, which indicates that these plutonic rocks were formed by arc magmatism. Comparing the plutonic rocks with the possible analogues of the IBM middle crust, the Tanzawa Plutonic Complex and the Komahashi-Daini Seamount (Tamura et al., 2009), the major and trace elements of the plutonic rocks from the Mineoka-Setogawa Belts are very similar to those of the Tanzawa Plutonic Complex and the Komahashi-Daini Seamount.

The zircon U-Pb ages and geochemistry of the plutonic rocks in the Mineoka-Setogawa Belts probably indicate that the ophiolitic fragments in the Mineoka-Setogawa Belts are derived from the crust and upper mantle of the IBM Arc. More thorough investigations of the ophiolitic fragments in the Mineoka-Setogawa Belts will help us to understand the petrological evolution of the crust and upper mantle beneath the IBM Arc.

キーワード：嶺岡・瀬戸川帯、ジルコンウラン鉛年代、深成岩

Keywords: Mineoka-Setogawa Belts, Zircon U-Pb age, Plutonic rocks

オマーンオフィオライトFizh岩体北部における蛇紋岩化プロセスの推定

Estimate of the serpentinization process in the northern Fizh block, the Oman ophiolite

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オマーンオフィオライトのマントルセクションは、蛇紋岩化したハルツバーチャイト、ダナイト、レルゾライトで構成される。オマーンオフィオライトは高速拡大軸の海洋リソスフェアの断片が衝上することで形成されたと考えられており、マントルセクションのかんらん岩は海洋底下での熱水活動を保存している可能性が高い。また、オマーンオフィオライト下底部分にはメタモルフィックソールと呼ばれる接触変成岩が分布しており、基底スラスト直上のかんらん岩は衝上時に流体の供給を受けた可能性がある。したがって、本研究ではオマーンオフィオライトのかんらん岩は複数の段階を経て熱水変質を被っていると考え、オマーンオフィオライトFizh岩体北部地域から採取したかんらん岩の蛇紋石鉱物の産状及び鉱物化学組成に基づき、オマーンオフィオライトが被った蛇紋岩化のプロセスを推定した。

オマーンオフィオライトでは、マントルセクション全域に渡って低温型蛇紋石であるリザダイトがメッシュ状、あるいは脈状に観察できる。さらに、一部の単斜輝石がトレモライトに変質していることと、高温型蛇紋石であるアンチゴライトが観察されないことから、約600~900°C程度の温度下で流体が供給されたと推定される。従来、海洋底における蛇紋岩化は400~500°C以下の低温で進行すると考えられてきたが、本研究結果はオマーンオフィオライトのような高速拡大軸における海水の浸透がより高温で起きている可能性を示唆する。

また、基底部のかんらん岩とマントルセクション内部~モホ遷移帯のかんらん岩を鏡下で比較した結果、基底スラスト直上の蛇紋石中にはその他の地域と比較して多量のマグネタイトが形成されていること、基底スラスト直上の斜方輝石の周囲に滑石が生じていることが明らかとなった。先行研究では蛇紋岩化作用は少なくとも二段階のプロセスを経て進行すると考えられており、マグネタイトの形成は蛇紋岩化の後期に起こるとされている。また、650~750°C(>6kbar)で斜方輝石に流体が供給されると滑石とフォルステライトが形成されることから、基底部のかんらん岩はオフィオライトの衝上の初期に比較的高温下で多量の流体の供給を受けたと推定される。

本研究では先行研究を参考にマグネタイトの形成とSiO₂活動度に関係があると仮説を立て、基底部とマントルセクション内部~モホ遷移帯の蛇紋石の組成をマグネタイトの有無や蛇紋石の組織(メッシュ組織・脈状組織)で比較した。マントルセクション内部のハルツバーチャイトにおいては、蛇紋石のメッシュ組織にはマグネタイトはほぼ見られず、蛇紋石の脈中にのみまれにマグネタイトが形成されている。これをEPMAで測定した結果、マグネタイトを形成する脈はマグネタイトを形成しない脈・メッシュ組織よりもSi+Al(O=7)の値が高く、Fe+Mg(O=7)の値が低い傾向が示された。これは、Bach et al. (2006)における高いSiO₂アクティビティ下でブルーサイトから蛇紋石とマグネタイトが形成(9Fe(OH)₂+SiO₂=2Fe₃Si₂O₅(OH)₄+Fe₃O₄+4H₂O+H₂)するという仮説と調和的である。また、基底部におけるマグネタイトと共存する蛇紋石のMg#は、マントルセクション内部におけるマグネタイトと共存する蛇紋石のMg#よりもやや低い値を示す。基底部では蛇紋岩化がマントルセクション内部よりもFe, Mgの拡散速度が速い高温下で起きたために、マグネタイトの形成に必要なFeをより広範囲の蛇紋石から得ることができたと考えられる。マントルセクション内部には一様にリザダイトが存在し、モホ面からの距離と蛇紋岩化の程度や産状に相関が認められないことから、低温下(<300°C)の蛇紋岩化作用は衝上後から現在にいたるまで天水等の浸透により進行したものと推測する。

キーワード：オマーンオフィオライト、蛇紋岩化作用、蛇紋石、リザダイト、磁鉄鉱
Keywords: Oman ophiolite, serpentinization, serpentine, lizardite, magnetite

オマーンオフィオライトのメタモルフィックソールの原岩としてのHaybi火山岩類の地球化学的検証
Geochemical evaluation of Haybi volcanic rocks as a protolith of amphibolites in the
metamorphic sole of Oman ophiolite

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本研究は、オマーンオフィオライト北部Fizh岩体Sumeini WindowのAsh Shiyah地域から得られたHaybi火山岩類とメタモルフィックソールの角閃岩の主成分および微量元素組成およびNd同位体を比較し、メタモルフィックソールの原岩の検討を行った。Haybi火山岩類は枕状溶岩とシート状溶岩の互層からなる。一部の火山岩類は、メタモルフィックソールの下位に分布する赤色チャートに包有されたブロック状の枕状溶岩として産する。一方、メタモルフィックソールは、角閃岩相から緑色片岩相の変成岩類からなる。これらの変成岩類の原岩は、メタモルフィックソールの下位に位置するHaybiコンプレックスとされている。

変質の影響を受けにくい元素を用いた組成判別図と希土類元素(REE)のC1コンドライト規格化パターンによる検討の結果、本地域の火山岩類は海洋島玄武岩(OIB)とEタイプ中央海嶺玄武岩(E-MORB)に分けられることが明らかになった。層序的に、OIBが下位に、E-MORBが上位に位置し、前者が枕状溶岩とシート状溶岩に、後者が赤色チャートに包有されたブロック状の枕状溶岩に対応する。一方、同様な検討の結果、角閃岩の原岩は、Nタイプ中央海嶺玄武岩(N-MORB)とE-MORBに分けられることが明らかになった。E-MORB的な角閃岩はE-MORB的な枕状溶岩と組成が似ている。Sumeini Windowを横断するワジに沿った角閃岩の分布では、タイプごとの系統性はとくに認められず、N-MORBとE-MORBが混在するところもある。また角閃岩の $\epsilon_{Nd(96Ma)}$ とLa/Yb比は緩やかな負の相関を示し、その分布はケルゲレーン諸島の玄武岩類と似ている。このような組成の玄武岩は、MORBソースマントルとNd同位体にエンリッチしたマントルを様々な割合で混合し、それらを様々な割合で溶融させることによって説明が可能である。

本研究の結果から、オマーンオフィオライトの下位に沈み込んだ海洋地殻上には、N-MORB、E-MORB、OIBが分布していたことが明らかとなった。これらのうち、N-MORBとE-MORBは深部まで沈み込み、オフィオライトの余熱による接触変成作用によって角閃岩に変成しつつ、オフィオライトの衝上によって基底部に付加した。OIBは接触変成作用を被っていないことから、N-MORBやE-MORBよりもあとに、低温でメタモルフィックソールの下位に付加し、Haybiコンプレックスを形成したと考えられる。

キーワード：オマーンオフィオライト、メタモルフィックソール、Haybi火山岩類、OIB、N-MORB、E-MORB

Keywords: Oman ophiolite, metamorphic sole, Haybi volcanics, OIB, N-MORB, E-MORB

オマーンオフィオライト, フィズ岩体底部で採取した軽希土類元素に富むかんらん岩の岩石学
Petrology and geochemistry of LREE-enriched fresh peridotite boulders from the basal part
of the Fizh block, the northern Oman ophiolite

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Oman ophiolite, showing a great exposure (~ 500 km long), is one of the most famous ophiolites in the world. Whole ophiolite sequence is well preserved and the emplacement age has been determined as Cretaceous, based on the K/Ar dating on hornblendes from underlying metamorphic-sole amphibolite (e.g., Searle & Cox, 2002). There have been reported island-arc related volcanic rocks mainly in the northern part of Oman ophiolite, and in the meanwhile, volcanic rocks comparable to typical N-MORB are dominant in the southern part of the Oman ophiolite (e.g., Alabaster et al., 1982). It is still debated that the Oman ophiolite is of mid-ocean ridge origin or of ridge axis on supra-subduction zone origin. Recently, highly depleted harzburgites have been reported in the northern Oman ophiolite (Kanke & Takazawa, 2004); they were interpreted as products of the secondary partial melting of residual harzburgites beneath the mid-ocean ridge, induced by H₂O-induced flux during detachment and intra-oceanic thrusting.

We found quite hard and fresh (LOI < 1.0) peridotite boulders at the southern basal zone of the Fizh block (e.g., Wadi Hayl). The texture is variable (mylonitic, porphyroclastic, equigranular, and coarse protogranular) and some porphyroclastic samples contain highly deformed fine-grained zones. It is difficult to determine the modal proportion of minerals due to the presence of fine-grained zone, but we can judge that they are mostly harzburgites and subordinately lherzolites, based on petrography of coarse-grained part of the samples and their whole-rock major-element compositions (SiO₂ = 43.5-46.4 wt.%, Al₂O₃ = 0.38-1.10 wt.%, and CaO = 0.49-1.68 wt.%). Chondrite-normalized (the values showing with subscript CN hereafter) whole-rock REE concentrations show LREE-enriched U-shaped patterns, and the (La/Sm)_{CN} and (La/Yb)_{CN} are variable: 3.5-10.3 and 2.0-11.0, respectively. These values are quite high relative to the reported harzburgites (0.02-0.11 and 0.44-0.70; Godard et al., 2000) and fertile lherzolite (0.09-0.11 and 0.04-0.06; Takazawa et al., 2001; 0.28-1.15 and 0.09-0.53; Khedr et al., 2014) from other localities of the Oman ophiolite. The U-shaped REE pattern of ophiolitic peridotites has been interpreted as a result of secondary processes, such as serpentinization, ocean-floor alteration, or contamination of crustal materials during ophiolite obduction (Gruau et al., 1998). Low LOI value (< 1.0) of our samples denies the contribution of serpentinization and alteration to their enrichment of LREE, and indicates possible metasomatic addition of LREE to the mantle tectonite during/before ophiolite obduction (at high-temperature stage).

キーワード：かんらん岩、インコンパティブル元素、マントル交代作用、オマーンオフィオライト

Keywords: fresh peridotite, incompatible trace elements, mantle metasomatism, Oman ophiolite

オマーンオフィオライトの初期島弧火山発達過程

Evolutionary processes of submarine volcano in an incipient arc reference from the Oman Ophiolite

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The Oman ophiolite belonging to the Tethys ophiolite zone is one of the best places to investigate magmatic and volcanic developing processes of an infant arc. The Ophiolite had formed on a spreading axis and followed by subduction stage magmatism at approximately 100 Ma. The volcanostratigraphy is similar to that of the Izu-Bonin-Mariana Arc (e.g. Starn, 2004). However, the latest U-Pb age of zircon in plutonic bodies shows that there is only 0.5 m.y. time gap between the spreading and subduction stages (Riuox et al., 2014), therefore, it seems to record short-spanned island arc magmatism. Progressive geochemical change from island arc tholeiite (LV2) to boninite (UV2) in this period showed us the evolutionary process of the high-T and ephemeral subduction zone (Kusano et al., 2015). To reveal the stress history during the subduction stage, we reconstructed accretionary process of the arc magmas at the northern Oman ophiolite.

The subduction stage volcanic rocks (V2) extend >350 km along the Oman Ophiolite. In Wadi Salahi area, the V2 consist of the 600-970 m thick lower LV2 and 0-140 m thick upper UV2. Pahoehoe and sheet flows are dominate in the LV2, while 50 m thick pyroclastic rocks are partly distributed upward. Plural flow units and sporadically distributed plugs and dikes at 1-3 km spaces are recognized in the LV2. These plugs are 1.5-3 m in diameter with cylindrical layering of fine-grained and coarse-grained parts. The distribution of plugs and dikes look unbiased in the stratigraphic horizon. Because the LV2 was erupted through cone sheets (Alabaster et al., 1982), these plugs might be distributed along the "ring conduit". Similar bulk rock compositions of the LV2 including lava flows and pyroclastic rocks suggest the share in the magma chamber. However, E-W concentration of strike of plugs and dikes would be resulted from the regional E-W compression (Umino et al., 1990).

キーワード：沈み込み帯発生、高温沈み込み帯、無人岩、オマーンオフィオライト、海底火山地質

Keywords: Subduction initiation, high-T subduction zone, Boninite, Oman Ophiolite, submarine volcano geology