

インド洋 Kairei 熱水フィールドの地質・地球物理学的背景—大河プロジェクトの成果—

Tectonic background of a unique hydrogen-rich Kairei Hydrothermal Field, Central Indian Ridge: Results from Taiga Project

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The Central Indian Ridge (CIR) is slow-intermediate spreading systems and its southern end forms a R-R-R triple junction with SWIR and SEIR. Kairei Hydrothermal Field (KHF) is unique hydrothermal system, located at the southern end of CIR. The fluids venting from the KHF are characterized by its high concentration of hydrogen with low methane/hydrogen ratio, and a hydrogen-based hyperthermophilic subsurface lithoautotrophic microbial ecosystem was confirmed (Takai et al., 2004). The KHF lies on basaltic lava area on the shoulder of ridge axial wall, being different from other hydrogen-rich hydrothermal fields hosted by ultramafic rocks. We selected this area as an integrated site for the Taiga Project, and conducted series of research cruises to characterize this unique system and to understand how the tectonic setting controls the fluid and ecosystem.

We discover that the KHF itself is located above basaltic lava field but gabbro and ultramafic rocks are widely exhumed around the KHF. Besides a previously known oceanic core complex, small oceanic core complexes exist just east of the KHF (Kumagai et al., 2008) and the NTO massif north of the KHF shows peridotite exposure on its top. The unique fluid geochemistry of the KHF can be attributed to serpentinization of troctolites around or beneath the KHF and subsequent hydrothermal reactions with basaltic wall rocks (Nakamura et al., 2009). We also find several small hills where we collect deep crustal and mantle rocks. These hills suggesting melt-limited environment extends mainly along 2nd order segment boundary from the axial valley to 30km off-axis, i.e. ~1.7 Ma. Detailed gravity analysis shows that the OCCs are accompanied by very high residual Bouguer anomaly (RMBA) and that the KHF is situated at the edge of high RMBA area centered at the Uraniwa OCC. This suggests that the dense material may exist in shallow subsurface and magmatic budget may increase toward the axis. Deep-tow magnetic profile across the area indicates the asymmetric spreading, that are consistent with the detachment faulting. The seismic profiles across the axis, KHF and the Uraniwa OCC shows that the vent site is located along a inward faces steep scarp of normal fault and the fault may play an important role of circulation path and the heat is likely mined from axial magma. The basalt samples collected from the axial valley are normal MORB, while the samples around the KHF is highly depleted in highly incompatible elements. It probably suggests that the source mantle is highly depleted and is difficult to melt. The collected peridotites might preserve relics of older partial melting events, resulting in the formation of heterogeneous mantle material beneath the current CIR axis. The latest stage of decompression melting beneath the CIR might be limited because the presence of depleted peridotite formed by ancient partial melting.

We also discover dead chimneys on the NTO massif north of the KHF. The AUV-attached magnetometer detects a higher positive magnetization around the chimney sites, suggesting hydrothermal alteration of ultramafic rocks. Although densely operated CTD tow-yo surveys do not detect clear evidence of another active hydrothermal vent, an ultramafic-hosted hydrothermalism exists or at least existed on the NTO massif.

All these observations indicate that the KHF is supported by both serpentinization of olivine rich rocks and reaction with basalt maybe in shallow subsurface. The heat source is likely on-axis magmatic heat and inward facing fault can help the circulation. This magma assisted, hydrogen rich hydrothermalism has implications for global incidence and hydrothermal activities and for hydrothermalism in early stage of the Earth history. Our last survey in Taiga project in this area has conducted in January to March, 2013. The preliminary results from this cruise, including submersible dives and OBS and OBEM experiments, will also be presented.

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南部マリアナ背弧海盆の地球物理学成果：マントルから熱水活動域まで Geophysical results of the Southern Mariana Trough back-arc basin: From mantle to hydrothermal vent sites

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The southern Mariana Trough back-arc basin shows an EPR type axial relief in morphology and constant low mantle Bouguer anomaly along the spreading axis (Kitada et al., 2006), suggesting abundance of magma supply, even though the full spreading rate of 35 km/Myr is categorized as slow spreading. Further, five hydrothermal vent sites exist within 5 km near the spreading axis at 13 N; two sites on the spreading axis, one site at the eastern foot of the axial high, and two sites on an off-axis knoll. We selected this area as one of three integrated target sites for the Taiga Project, and we conducted series of JAMSTEC research cruises for four different types of geophysical survey, together with dive observation and samplings by the submersible Shinkai6500. The geophysical surveys consists of 1) a marine magnetotelluric (MT) survey of a 130 km length transect across the spreading axis using 10 ocean bottom electro-magnetometers, 2) a 15 km scale seismic reflection/refraction survey and seismicity observation using 9 ocean bottom seismometers (OBS), 3) near-bottom acoustic and magnetic mapping around all the hydrothermal sites using the AUV Urashima, and 4) a magnetometric resistivity (MMR) survey around the on-axis hydrothermal sites.

Two-dimensional electrical resistivity structure of the upper mantle from the MT analysis shows highly asymmetry, which may be affected by hydration driven by water release from the subducting slab; that may result in abundant magma supply to support EPR type axial morphology. Three-dimensional crustal velocity structure from the seismic refraction analysis shows low velocity at the central part of the spreading ridge and high velocity under the off axis seamount. The high velocity under the off axis seamount is interpreted as thick layer 3, suggesting past magma intrusion from the mantle. The reflection survey results show that some reflectors exist under the hydrothermal area. Three months OBS observation shows that the seismicity near the hydrothermal vent sites is very few, suggesting that hydrothermal activities are not related to tectonic stress. Moreover, the morphology of the mound and knoll near the three off-axis hydrothermal sites shows undeformed features without any faults, suggesting that their formation is closely related to an off-axis magma upwelling system rather than fault systems. The two on-axis hydrothermal sites (the Yamanaka and Snail sites) are located near the end of a 4th order spreading segment based on the observed offset of the neo-volcanic zone, suggesting that they are possibly locally developed in association with diking events in the segment. But the diking is probably an episodic event to provide heat source for each hydrothermal site, because of very few seismicity. Clear magnetization low at four hydrothermal vent sites except the Yamanaka site suggests that the hydrothermal activities have continued for long enough periods in wide enough areas to reduce the magnetic remanence of the crustal rocks. The different feature in the Yamanaka site suggests its activity has been short and/or small. The MMR results support this difference because low electrical resistivity region with 200 meter scale is located only at the Snail site but not at the Yamanaka site; the low resistivity region is probably due to the existence of hot crustal pore fluid.

キーワード: 背弧海盆, 海床拡大, 海底熱水系, マントル構造, 地殻構造, 地震活動度

Keywords: back-arc basin, seafloor spreading, hydrothermal activity, mantle structure, crustal structure, seismicity

沖縄トラフ伊平屋熱水域の炭素循環

Carbon cycle at Iheya hydrothermal field, mid-Okinawa Trough, Japan

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沖縄トラフ伊平屋熱水域の熱水は、高いメタン濃度に特徴づけられる。この高濃度メタンの起源として、Kawagucci et al. (2011) は、熱水噴出孔から遠く離れた場所から海水が海底下に染み込み、熱水へと変わっていく海底下熱水循環の途上で微生物由来のメタンが付加している可能性を指摘している。

2010年に統合国際深海掘削計画第331次航海 (IODP, Expedition 331) において、沖縄トラフ伊平屋熱水域で、熱水域海底下の生命圏の探査を目的として、地球深部掘削船「ちきゅう」により掘削が行われた。本研究では、掘削によって得られたコア試料中のメタンの濃度、炭素・水素安定同位体比、および間隙水中の酢酸、溶存有機物、全炭酸の濃度・炭素同位体比を測定し、熱水循環および、微生物を介した炭素循環について考察を行った。

熱水噴出孔より450mの距離にある掘削地点 (Site C0014B) では、メタンの炭素同位体比は約-55‰、水素同位体比は約-125‰で、熱水噴出孔のメタンとほぼ同様の値を示し、海水のリチャージにより堆積物中で付加された微生物起源のメタンであると考えられる。しかし、硫酸濃度が25mMまで上昇し、海水の水平方向への流入が示唆される海底下8.5m付近では、メタンの濃度が8 μMまで減少すると共に、炭素・水素同位体比が、それぞれ-23‰、+199‰まで大きくなる。これは微生物による嫌氣的メタン酸化により、軽い¹²C, Hが選択的に酸化されることにより、残りのメタンの同位体比が重くなったことによると考えられる。メタン濃度の減少に伴う炭素同位体比の変化に対する水素同位体比の変化の比はおよそ1対10であり、これは嫌氣的メタン酸化に伴う、炭素同位体の分別に対する水素同位体の分別の比の報告値 (8-10) と整合的である (Feisthauer et al., 2011)。

酢酸の濃度は6-170 μMで、一般的な海底堆積物中の酢酸濃度 (<15 μM) よりも高い値を示し、炭素同位体比は、-47--17‰であった。発酵により生成される酢酸は有機物の炭素同位体比とほぼ同じであり、一般的な海洋の有機物の炭素同位体比 (-27--20‰) よりも低い酢酸の炭素同位体比は、二酸化炭素との大きな炭素同位体分別 (-59‰) を伴うホモ酢酸生成の寄与を示唆する。このような微生物起源と考えられる同位体比の低い酢酸は、生物の生息限界とされる120°C以上のところでも検出されており、Kawagucci et al. (2011) で提唱されているメタン同様、海水のリチャージにより堆積物中で付加された微生物由来の酢酸が熱水域まで運搬されてきた可能性が高い。

キーワード: 熱水, 炭素循環, メタン, 酢酸, 安定同位体

Keywords: hydrothermal fluid, carbon cycle, methane, acetate, stable isotope

観測データに基づく「鉄の大河」の出現モデルの提唱とその実験的検証 A model of appearance of iron-based microbial ecosystem in deep-sea hydrothermal system and its experimental evaluation

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TAIGA 計画において、海洋地殻内流体の移流を「海底下の大河」と呼ぶことが提案された（浦辺他、2009）。「海底下の大河」には、地球内部から供給される化学エネルギーに依存した巨大な化学合成微生物生態系が存在すると予想される。その生態系を支える主なエネルギー源に注目して「海底下の大河」を4つに分類し、それぞれ「水素の大河」、「硫黄の大河」、「メタンの大河」、「鉄の大河」と呼んでいる。海洋地殻玄武岩には鉄が多く含まれる。この鉄に支えられた生態系の存在する海洋地殻内流体があるとすれば、それが「鉄の大河」である。「鉄の大河」はその分布範囲において他の3つの大河とは比べ物にならないほど広く、海洋全体のエネルギー・物質循環を考える上でも無視できない存在となる可能性がある。しかしながら、その実態はほとんど明らかになっておらず、4つの大河のうち最も理解の進んでいない大河といえる。

これまで演者らの研究グループは、南部マリアナトラフ熱水域において集中的に熱水化学・微生物分析を行ってきた。その結果、鉄酸化菌を含む系統群 Zetaproteobacteria が比較的低温（ $\sim 30^{\circ}\text{C}$ ）の地殻内流体中に優先して存在することを見いだした（Kato et al., 2009）。その流体の化学分析結果をもとにして、流体中の還元型化学種の酸化から獲得しうるエネルギー量を熱力学計算により推定したところ、鉄酸化によって得られるエネルギー量が他の3つの元素（すなわち、水素、メタン、硫黄）の酸化によって得られるエネルギー量を上回ることが示された。これらの結果を統合し、「鉄の大河」が出現するモデルを世界で初めて提唱した（Kato et al., 2012）。

さらに、そのモデルを実験的に検証するために、「鉄の大河」を実験室内で再現するフロー型熱水系模擬装置を作製し、玄武岩からの鉄の溶出をモニタリングすることに成功した（Kato et al., in press）。現段階においては、鉄に依存した微生物生態系を再現するまでには至っていないが、今後、室内実験の長所を生かして様々な物理化学条件下での「鉄の大河」の再現を目指し、そこでどのような化学・微生物反応が起こるのかを定量的に解析していく予定である。

キーワード: 海底下の大河, 鉄酸化バクテリア, 微生物生態系, 海底熱水系, フロー型熱水系模擬装置

Keywords: Sub-seafloor TAIGA, Iron-oxidizing bacteria, Microbial ecosystem, Hydrothermal system, Flow-type hydrothermal apparatus

上部海洋地殻の温度構造が示唆する熱水循環系 Hydrothermal circulation deduced from the thermal structure of the upper oceanic crust

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We have restored the thermal structures in the upper oceanic crust by using geothermometers based on crystal size and metamorphic minerals of the sheeted dikes from the Oman Ophiolite, which gives ambient temperatures at the time of dike intrusions and subsequent hydrothermal alteration. The Oman Ophiolite is regarded as an analog of fast-spreading ridge system. Samples were collected along transects through the sheeted dikes in a paleoridge segment from northern Oman. Pervasive hydrothermal alteration yielded metamorphic mineral assemblages of typical greenschist facies with some relict secondary hornblende, indicating that some sheeted dikes experienced amphibolite facies metamorphism, which was overprinted by greenschist facies alteration. In spite of pervasive alteration, primary igneous textures are generally preserved.

The crystal-size geothermometer is based on the models of Toramaru (2001) and Toramaru et al. (2008), which show the number density of crystals N is proportional to the $3/2$ power of cooling rate of magma. Cooling rate in a dike at a distance of D from the dike margin is $\sim(T_m - T_h)/T_m/D^2$, where T_m and T_h are temperatures of the magma and the host rock at the time of the dike intrusion. Volumetric fraction F of a specified crystal phase depends on the bulk magma composition and can be assumed to be almost identical to the sheeted dikes of interest. Then, $F = rL^3N$, r is aspect ratio of the crystal with a dimension $L \times L \times rL$. $T_h = AD^2/L + T_m$, where A is a constant relevant to F and r . By taking a reference dike whose host rock temperature T_{h0} is known, A is eliminated from the equation; $T_h = (T_{h0} - T_m)\{(L_0/D_0)/(L/D)\}^2 + T_m$

The estimated geotherm through the dikes at a paleoridge segment end shows constantly low but variable temperatures in the upper dikes and a remarkably high gradient in the lower dikes toward the gabbros. The thermal structure at the segment end indicates advective heat transfer by hydrothermal circulation of cold seawater in the upper dikes and conductive heat transfer in the lower dikes. The estimated geotherm at the segment center is 800-900 C, much higher than that at the segment end and does not show any stratigraphic variation. The high geotherm in the segment center cannot be reconciled with heating by hydrothermal fluids but requires high heat supply by repeated dike intrusions.

On the contrary, metamorphic mineral assemblages and chlorite and hornblende geothermometer give consistently lower temperatures than the crystal-size geothermometer, indicating that low-T hydrothermal alteration continued as the crust moves off-ridge.

キーワード: 中央海嶺, 海洋地殻, オマーンオフィオライト, シート状岩脈群, 温度構造, 結晶粒径

Keywords: Mid-ocean ridges, Oceanic crust, Oman Ophiolite, Sheeted dikes, Thermal structure, Crystal size

バライト中のセレンを用いた新しいレドックス計の開発 Application of selenium coprecipitated with barite as a new redox indicator

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Redox potential (Eh) is an important factor controlling chemical processes in hydrosphere on the earth, because redox reaction is related to the behaviors of many major and minor species in natural waters. A number of the previous studies have suggested that Eh was estimated by the solid-water distributions of redox-sensitive elements based on the effect of valence change such as a relative enrichment-depletion profile of particular elements. However, the estimation of redox conditions based on previous indicators may not be reliable because (i) trace elements concentrations are influenced by many factors and mechanisms such as secondary adsorption-desorption and/or diagenetic processes and (ii) the redox condition was relatively evaluated by the depth profiles of particular elements. Thus, the aim of this study is to propose a new redox indicator using the valence ratio of redox sensitive element itself in the mineral which can be directly used to estimate the particular redox condition at the time of the mineral formation. Here, we examined the incorporation behavior of selenium (Se) species to barite. Selenium is well known as a redox-sensitive element which is dissolved in water as selenate (SeO_4^{2-}) or selenite (SeO_3^{2-}) oxyanion under oxic and suboxic condition, respectively. On the other hand, barite can work as a host phase of Se in the environment. Thus, if barite can incorporate both Se(IV) and Se(VI), the ratio of Se(VI)/Se(IV) may possibly reflect the ratio in the coexistent water, which consequently indicates the redox condition in the environment. The aim of this study to understand the incorporation behaviors of Se(IV) and Se(VI) into barite in co-precipitation experiments with the information of the oxidation states both in water and barite to utilize it as a redox indicator for oxic-suboxic condition.

Coprecipitation experiments of Se with barite were conducted to investigate the influence of the Se oxidation state on its immobilization into barite at pH 8.0 and pH 4.0. Barite was precipitated from a mixture of artificial seawater (ASW) and $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ solution. The initial pH of ASW was adjusted to 4.0 and 8.0 before the barite precipitation. These two pH conditions were adopted considering typical pH for hydrothermal water (3.0-4.0) and seawater (8.0). Total concentrations of Se in the remaining solution and precipitates were measured by ICP-MS. The Se(VI)/Se(IV) ratio in the precipitates and water were determined by HPLC-ICP-MS and X-ray absorption near-edge structure (XANES) at Se K-edge, respectively.

It was found that the Se(VI)/Se(IV) ratio in barite reflects the Se(VI)/Se(IV) ratio in water, which suggests that the oxidization state of Se in barite can work as a redox indicator showing redox condition at the time of barite formation. Selenium(IV) is incorporated into barite under suboxic condition below the redox boundary of Se(VI)/Se(IV). Selenium(VI), on the other hand, is incorporated under oxic condition above the redox boundary of Se(VI)/Se(IV). These trends are observed at pH 4.0 and 8.0, regardless of the different distribution behaviors of Se to barite at both pH systems. Based on the distribution behavior of Se to barite in the pH 4.0 and 8.0 systems, we conclude that the Se(VI)/Se(IV) ratio in barite can be used as a redox indicator whether barite was precipitated below or above the redox boundary of Se(VI)/Se(IV), the Eh region of which is different from the Fe(III)/Fe(II) and Mn(IV)/Mn(II) boundaries often employed as a signature of redox condition. Thus, the redox indicator using the Se(VI)/Se(IV) ratio in barite could provide more detailed redox information on the depositional environment.

Keywords: redox indicator, selenium, barite, coprecipitation, XAFS