

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.

Keywords: hydrothermal system, Central Indian Ridge, oceanic core complex (OCC), mantle rock, geophysical mapping

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.

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

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

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The hydrothermal chemistry in the Iheya hydrothermal field, mid-Okinawa Trough, is characterized by high methane concentration. For the origin of high concentration methane, Kawagucci et al. (2011) hypothesized the microbially produced methane at lower temperature basin-filling sediments surrounding the Iheya hydrothermal field is recharged together with the source fluid into the deep hydrothermal reaction zone.

We investigated carbon cycle mediated by hydrothermal circulation and microbial activity at the Iheya hydrothermal field based on stable isotope chemistry of methane, acetate, dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) in the core samples obtained by D/V Chikyu during IODP Exp. 331 in 2010.

At Site C0014 located 450 m east off the main hydrothermal vent, the carbon isotopic compositions and hydrogen isotopic compositions of methane are ca. -55 permil and ca. -125 permil, respectively. These values corresponded to those in the reported value from hydrothermal vent. While, in the depth around 8.5 m below sea floor (mbsf) at Site C0014B, the values of $\delta^{13}\text{C}$ -methane and δD -methane increased to -55 permil and +199 permil, respectively, with decrease of methane concentration to 8 micro-M. It suggests that the isotopic fractionation by anaerobic methane oxidation (AOM) in which ^{12}C and H in methane are selectively oxidized. The ratio of isotopic change between hydrogen and carbon with decrease of methane concentration was ca. 10. It corresponds to the reported ratio of hydrogen versus carbon discrimination ($\delta\text{H}/\delta\text{C}$) (Feisthauer et al., 2011). The acetate concentrations ranged from 6 to 170 micro-M. The concentrations were relatively high compared to those in the ordinary marine sediments (less than 15 micro-M). The carbon isotopic compositions of acetate ranged from -47 to -17 permil. The lower $\delta^{13}\text{C}$ -acetate values than those in typical organic matter from -27 to -20 permil indicate that the some contribution of homo-acetogenesis to total acetate production, because homo-acetogenesis results in ^{13}C depletion of the acetate produced. However, the low $\delta^{13}\text{C}$ -acetate values less than -27 permil were also observed at higher temperature zone (more than 120°C) where microbes cannot survive. It suggests that some portion of acetate in the high temperature zone was not produced in-situ but produced by a microbial activity at lower temperature area and recharged with source fluid in a similar way of the recharged microbially produced methane hypothesized by as Kawagucci et al. (2011).

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

A model of appearance of iron-based microbial ecosystem in deep-sea hydrothermal system and its experimental evaluation

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It is hypothesized in the project TAIGA that there are unseen aquifers below the seafloor, called sub-seafloor TAIGAs (great rivers) (Urabe et al., 2009). Chemosynthetic ecosystems supported by chemical energy supplied from Earth may be present in the sub-seafloor TAIGAs. The sub-seafloor TAIGAs are classified into four representatives based on the energy sources, i.e., hydrogen, sulfur, methane and iron. Iron is abundant in oceanic crusts. Iron-based ecosystems are thought to be present in sub-seafloor aquifers (Bach and Edwards, 2003), i.e., iron-based TAIGA. The distribution of the iron-based TAIGA is much wider than that of the others. The iron-based TAIGA could significantly affect the energy flux and elemental cycling on the global ocean. However, our knowledge of the iron-based TAIGA is extremely limited.

We examined geochemical and microbiological characteristics of hydrothermal fluids and deposits in the Southern Mariana Trough, a back-arc basin hydrothermal field. We showed that Zetaproteobacteria including iron-oxidizers are predominant in crustal fluids up to 30°C (Kato et al., 2009). Thermodynamic calculation with the chemical compositions of the collected fluids indicated that the bioavailable energy yield by iron oxidation is higher than those by hydrogen, methane or sulfur oxidation. Based on the microbiological, geochemical and thermodynamic analyses, for the first time, we proposed a model of appearance of iron-based microbial ecosystem in deep-sea hydrothermal system (Kato et al., 2012).

Furthermore, we developed a novel flow-type hydrothermal apparatus to simulate the iron-based TAIGA in laboratory. We were successful to monitor iron dissolution of basalts in high-temperature and high-pressure conditions (Kato et al., in press). Further modifications and experiments are needed to simulate the iron-based TAIGA.

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

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.

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

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