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Clarification of Regional Seafloor Hydrothermal System in a Japan Back-Arc Basin by Numerical Simulation with TOUGH2

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ABSTRACT

Hydrothermal activity occurs by a fluid circulation system heated by magma, forming a variety of economically important mineral deposits. To identify the dynamic behavior of seafloor hydrothermal systems, a number of numerical modeling have been constructed in the past three decades. However, the large-scale temperature distribution and hydrothermal flow pattern have not yet been clarified. These thermal characteristics are quite important to estimate the high potential zones of important metal minerals, because metal-bearing minerals can be formed in the system largely depending on temperature. Based on that background, we selected the Iheya North Knoll as a case study, and applied hydrothermal flow simulation using TOUGH2 to reveal distribution of physical properties and hydrothermal flow pattern in the seafloor hydrothermal system of Japan back-arc basin.

In the numerical model, we set seafloor as the top boundary where temperature and pressure were fixed at 4 °C and hydrostatic condition, respectively, and optimized the physical properties of rocks from the field survey data. This simulation yielded a plausible large-scale temperature distribution and flow pattern of the hydrothermal fluids, which correspond to the observed values even around the discharge area where the flow tends to be complicated. The effectiveness of the model was verified through the sensitivity analysis, and the location and physical properties of the conduit and the permeability of volcanic basement were identified as significant factors controlling the accuracy of hydrothermal flow simulation. Our next step is to build a more advanced numerical model considering the thermal alteration and chemical reaction of rocks with fluids.

1. INTRODUCTION

Seafloor massive sulfide (SMS) deposits gather attraction as a new metal resource of Zn, Cu, Pb, Ag, Au, and other useful metal minerals recently. According to Halada et al. (2007), it is envisioned that Au, Ag, Cu, Pb, Zn, and Sn will exceed the reserve base, which is amount of resources that can be technically mined but not targeted for economic reasons, and the demand of Ni, Mn, Li, In, and Ga is expected to be more than double the existing reserves by 2050 with the rapid increase of global resource demand. Hence, it is quite important to discover and develop new metal deposits such as the SMS deposits. To develop the SMS deposits efficiently, it is necessary to narrow down high potential zones of metal resources based on the generation mechanism, and for that purpose, it is required to elucidate the hydrothermal circulation system. Thus, in this research, to clarify the hydrothermal circulation of the seafloor hydrothermal system, we focused on the hydrothermal flow simulation.

Hydrothermal flow simulation has advantages that it can reproduce a series of hydrothermal circulation system such as seawater penetration from the seafloor, heating and rising of fluid, and dissolution/precipitation of metal components. However, although hydrothermal flow simulation has a great deal of experience on land, applications for the seafloor hydrothermal systems have been still limited, particularly in back-arc basins (Gruen et al., 2014). Consequently, the large-scale temperature distribution and hydrothermal flow pattern in the seafloor hydrothermal systems have not yet been clarified. These thermal characteristics are quite important to estimate the high potential zones of important metal minerals, because metal-bearing minerals can be formed in the system largely depending on temperature. Based on that background, we selected the Iheya North Knoll as a case study, and applied numerical simulation of multi-phase fluid flow using TOUGH2 to reveal distribution of physical properties and hydrothermal flow pattern in the seafloor hydrothermal system of Japan back-arc basin.

2. REVIEWS OF THE IHEYA NORTH KNOLL

Iheya North Knoll is one of the promising seafloor hydrothermal deposits in Japan, since it was discovered at nearly 150 km NNW from Okinawa main island in 1995 (Fig. 1) (Momma et al., 1996). The main hydrothermal area is distributed in the range of 500 m north to south and 300 m east to west along the slope on the west side of Central Valley (Fig. 2). Additionally, several hydrothermal mounds have been found, among which the highest temperature (311 °C) and the highest heat flux have been observed over 10 years in North Big Chimney (NBC) (Takai et al., 2010b). This suggests that the hydrothermal fluids discharging from NBC flow from the main hydrothermal path in this area.

In addition, heat flux observation has been carried out in the sediment-covered Central Valley (Fig. 3), and it has been confirmed that temperature and heat flux decrease as the distance from NBC increases (Masaki et al., 2011). Furthermore, a vertical temperature profile indicating penetration of seawater was found in the low heat flow area, implying that several km scale fluid movement occurs under the seafloor of the Central Valley.

In Expedition 331, drilling was conducted at five sites on the mountain slope where the NBC mound is located (Fig. 1) (Takai et al., 2010a). It has been verified by drilling that the Iheya North Knoll is a volcanic body, and the materials covering the mountain are volcaniclastic sediments.

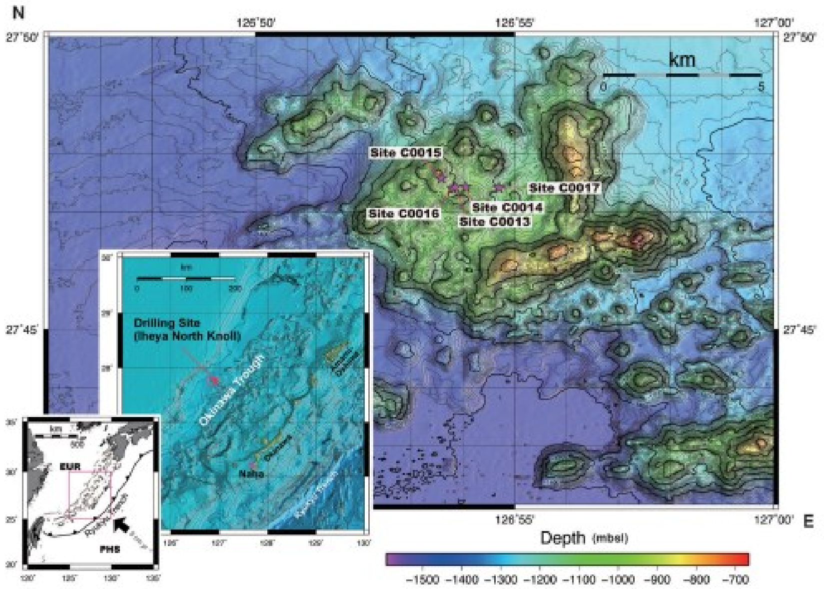

Figure 1: Area map of the Iheya North Knoll (Takai et al., 2012). Red stars indicate the locations of Sites C0013-C0017, which are borehole sites obtained in the Expedition 331.

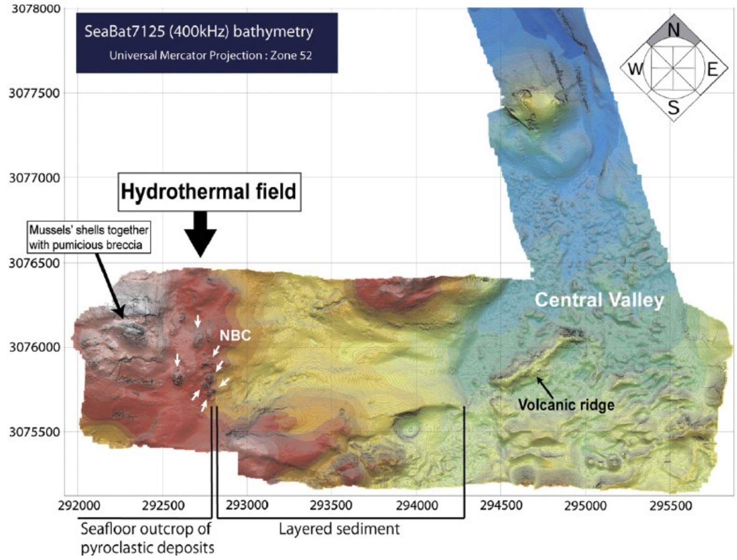

Figure 2: Bathymetry map around the Iheya North Knoll (Tsuji et al., 2012). White arrows show the locations of hydrothermal mounds.

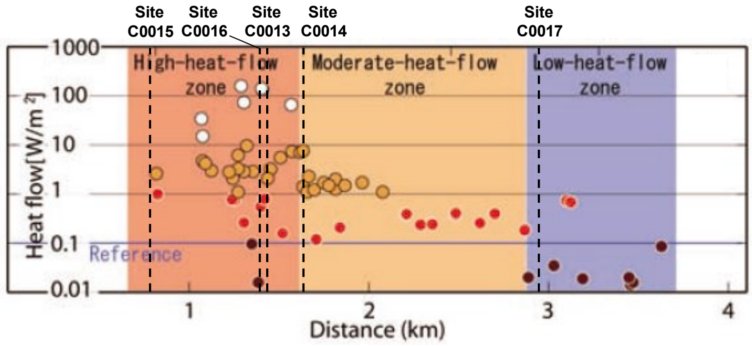

Figure 3: Heat flux distribution on the seafloor around the Iheya North Knoll (modified from Masaki et al., 2011).

3. HYDROTHERMAL FLOW SIMULATION IN THE IHEYA NORTH KNOLL

3.1 Materials and Methods

In the numerical simulation, we used TOUGH2 which can analyze gas-liquid two-phase flow and three-dimensional heat flow. The size of study area is 1.2 km from north to south, 4 km from east to west, 2 km along the vertical direction, and a 10 km buffer area was set around it (Fig. 4a). As the boundary condition, the seafloor was set as a permeable top boundary where temperature and pressure were fixed, and the side and bottom boundaries were set to be impermeable boundaries. In terms of initial condition, we set the hydrostatic pressure and 4 °C at the surface with thermal gradient 0.12 °C/m, which is the average gradient in this area except for the vent sites. Physical properties of rocks were set by referring to the field survey data (Table 1; Takai et al., 2011). The values of discharge rate, mass in rate, and permeability (hereinafter termed *k*) were adjusted appropriately through trial and error. To build a simple model, only the following three geologic structures were incorporated into the model (Fig. 4). To realize the vertical flow of hydrothermal fluid from the deep part, a conduit with $k = 10^{-13}$ m² was placed along the vertical direction from the bottom to surface. Moreover, a caprock with $k = 10^{-16}$ m² was distributed near the surface to enable lateral hydrothermal flow. Anisotropic *k* of the volcanic basement was set so that the horizontal *k* was one order larger than the vertical *k*, by considering a fact that thin impermeable layers were observed several times in the volcanic basement by the surveys (Takai et al., 2011). Under those conditions, we implemented the natural state simulation.

Table 1: Physical properties of rocks (Takai et al., 2011)

Parameters	Volcanic basement	Caprock	Conduit
Density (kg/m^3)	2800	2750	2750
Porosity (%)	40	1	60
Permeability (m^2)	XY:1.0E-14	1.0E-16	1.0E-13
	Z:1.0E-15		
Heat Conductivity (W/(m·K))	2.0	2.0	2.0
Specific Heat (J/(kg·K))	1000	1000	1000

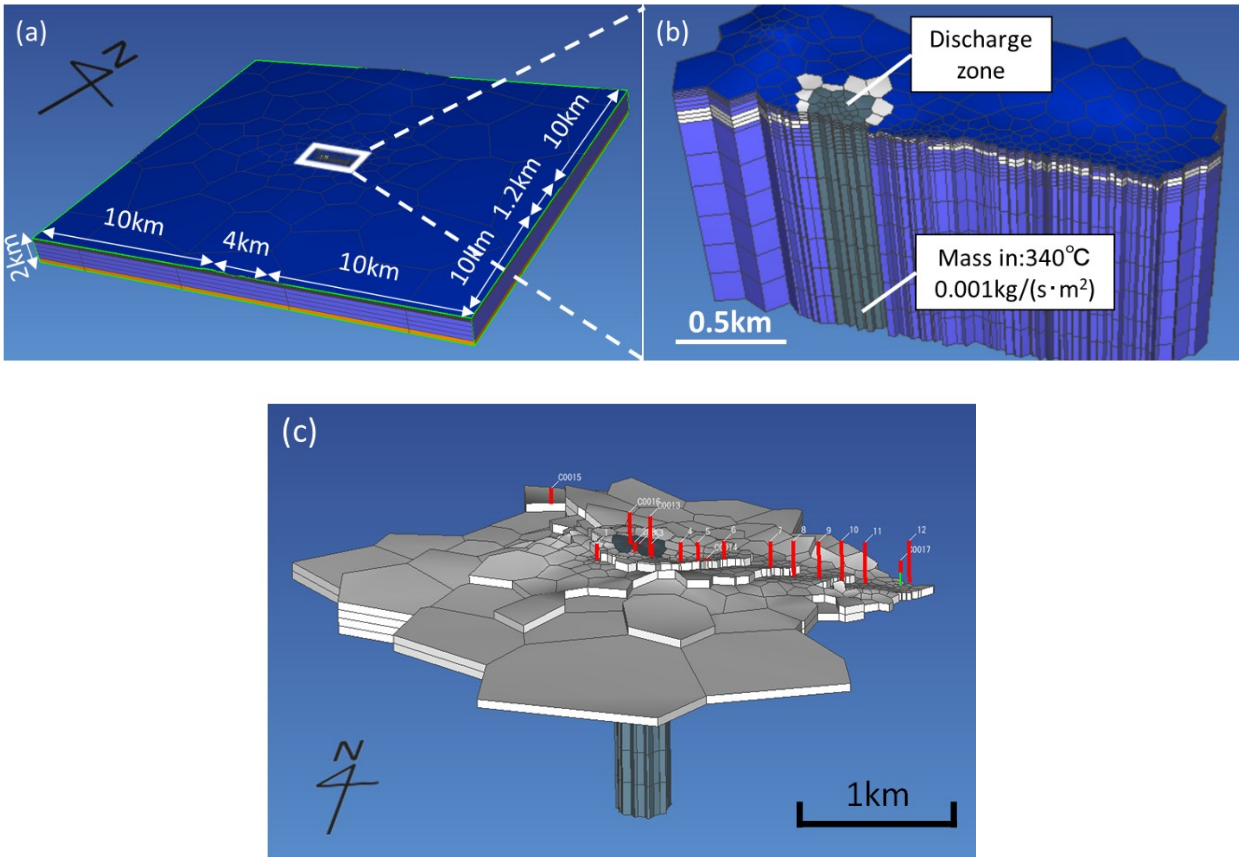

Figure 4: (a) Overall image of the model in the Iheya North Knoll. (b) An enlarged view of the white rectangle in Figure 4a. The blue, white, and gray cells indicate volcanic basement, caprock, and conduit, respectively. (c) Location of caprock and conduit in the model. The red lines represent the points at which heat flux and temperature profiles were obtained.

3.2 Simulation Results

Through the simulation, a plausible temperature distribution and hydrothermal flow pattern were obtained (Fig. 5a), and the calculated heat fluxes were compared with the measured values. As a result, the calculated heat fluxes generally corresponded with the measured values, even around the discharge area in which the flow tends to be complicated (Fig. 5b).

The effectiveness of the present model was verified by the following two points. By a model without the conduit, the hydrothermal fluid did not ascend to the seafloor along the vertical direction. Accordingly, the tendency of measured heat flux could not be reproduced. Besides, by a model with isotropic permeability of the volcanic basement ($k = 10^{-15}$ m²), lateral hydrothermal flow could not be expressed, and trends of heat flux were far away from the measured values. Consequently, the location and physical properties of the conduit and the permeability of the volcanic basement were specified as significant factors controlling the accuracy of hydrothermal flow simulation.

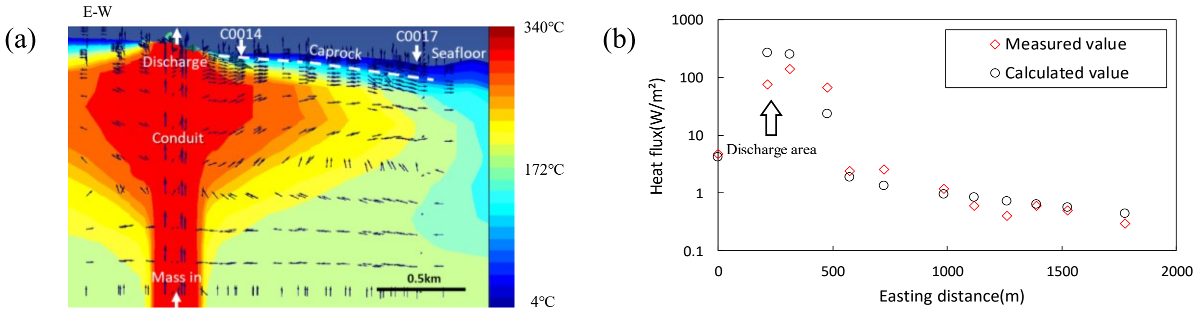

Figure 5: (a) Temperature distribution and hydrothermal flow pattern along an EW cross section. The white broken line indicates the location of caprock installed in the model. (b) A comparison of heat flux data with calculated values. Observed values are after Masaki et al. (2011).

4. CONCLUSION

We constructed a simple model to reveal the seafloor hydrothermal system in the back-arc basin, the Iheya North Knoll. Through the numerical simulation, the temperature distribution and the hydrothermal flow pattern were estimated, and the calculated heat fluxes mostly corresponded with the observed values. The effectiveness of the present model was verified through the sensitivity analysis, and it became clear that the location and physical properties of the conduit and the permeability of volcanic basement were the significant parameters controlling the preciseness of the hydrothermal flow simulation.

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