Numerical simulation-based clarification of a fluid-flow system in a seafloor hydrothermal vent area in the middle Okinawa Trough

Shohei Albert Tomita[1], Katsuaki Koike[1], Tada-nori Goto[2], and Katsuhiko Suzuki[3]

[1]Kyoto University
[2]University of Hyogo
[3]Japan Agency for Marine-Earth Science and Technology

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Abstract

Despite many studies on seafloor hydrothermal systems conducted to date, the generation mechanism of seafloor massive sulfide (SMS) deposits is not yet fully understood. To elucidate this mechanism, this study clarifies the three-dimensional regional temperature distribution and fluid flow of a seafloor hydrothermal system of the Iheya North, middle Okinawa Trough. Lateral flow and boiling of hydrothermal fluids below the seafloor were the main features found by the simulation, leading to an interpretation of two-layered SMS deposit generation as follows. Hydrothermal fluids discharging from black smokers first formed the upper SMS deposits on the seafloor. Caprocks formed below the seafloor, and the above-mentioned occurrences were then induced under the caprocks. In the present system, vapor-rich hydrothermal fluids poor in metals are discharged from the vents as white smokers, whereas liquid-dominated hydrothermal fluids rich in metals flow laterally below the caprocks, forming lower SMS deposits tens of meters below the seafloor.

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S. A. Tomita[1], K. Koike[1], T. Goto[1, *], and K. Suzuki[2]

[1]Department of Urban Management, Graduate School of Engineering, Kyoto University, Kyoto, Japan

[2]Submarine Resources Research Center, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kanagawa, Japan

*Now at Graduate School of Life Science, University of Hyogo, Hyogo, Japan

Corresponding author: S. A. Tomita (tomita.shohei.57n@st.kyoto-u.ac.jp)

Key Points:

- Numerical simulation of multiphase fluid flow revealed regional temperature, fluid-flow patterns, and physical property distributions.
- Integration of results with geologic interpretations provided a plausible generation mechanism of seafloor massive sulfide deposits.
- Formation of caprocks below the seafloor induces boiling and lateral flow of hydrothermal fluid and consequently, the deposit generation.

Abstract

Despite many studies on seafloor hydrothermal systems conducted to date, the generation mechanism of seafloor massive sulfide (SMS) deposits is not yet fully understood. To elucidate this mechanism, this study clarifies the three-dimensional regional temperature distribution and fluid flow of a seafloor hydrothermal system of the Iheya North, middle Okinawa Trough. Lateral flow and boiling of hydrothermal fluids below the seafloor were the main features found by the simulation, leading to an interpretation of two-layered SMS deposit generation as follows. Hydrothermal fluids discharging from black smokers first formed the upper SMS deposits on the seafloor. Caprocks formed below the seafloor, and the above-mentioned occurrences were then induced under the caprocks. In the present system, vapor-rich hydrothermal fluids poor in metals are discharged from the vents as white smokers, whereas liquid-dominated hydrothermal fluids rich in metals flow laterally below the caprocks, forming lower SMS deposits tens of meters below the seafloor.

Plain Language Summary

Seafloor hydrothermal activity occurs in a system, called seafloor hydrothermal system, in which the seawater heated by magma circulates under the seafloor, forming seafloor massive sulfide (SMS) deposits. Recently, SMS deposits attract interests as a new metal resource. To develop SMS deposits efficiently, specification of candidate sites by considering their origins is uppermost important. Although many studies on the seafloor hydrothermal systems have been implemented so far, generation mechanism of SMS deposits is not yet fully understood. To understand this mechanism, we applied a hydrothermal flow simulation and clarified the temperature distribution and fluid flow in the Iheya North hydrothermal field, southwestern Japan. The result revealed that lateral flow and boiling of hydrothermal fluids occur below the seafloor, which suggested a generation mechanism as follows. In the old hydrothermal system, hydrothermal fluids rich in metals flowing out from the vents formed SMS deposits on the seafloor. Then, impermeable caprocks formed below the seafloor, resulting in lateral flow and boiling of the hydrothermal fluids under the caprocks. In the present system, vapor-rich hydrothermal fluids poor in metals are flowed out from the vents, while liquid-dominated hydrothermal fluids rich in metals flow laterally below the caprocks, forming SMS deposits below the seafloor.

1 Introduction

Recent rapid expansion of the world economy, population growth, rising demand for and prices of metals, and uneven distribution of resources induce global risks against the stable supply of metal resources (Lusty & Gunn, 2015; Bardi et al., 2016). For the supply, in the exploration of metal deposits, deeper and deeper parts of the crust are being explored, and efforts are extending to the seafloor from the land. In these zones, finding new deposits becomes more and more difficult because of decreases in the amount and spatial resolution of survey data.

Because hydrothermal circulation below the seafloor promotes chemical reaction, heat transfer, and mutual interaction between the crust and ocean (Stein & Stein, 1992; Alt, 1995; Tivey, 2007), more than 300 high-temperature vent sites, which are potential fields of metal deposits, have been found to date in mid-ocean ridges (65%), along volcanic arcs (12%), and at back-arc spreading centers (22%) (Hannington et al., 2011). Seafloor massive sulfide (SMS) deposits are the most typical type formed in such hydrothermal systems accompanying high contents of base metals (copper, zinc, and lead) and precious metals (silver and gold) (Spagnoli et al., 2016). SMS deposits are regarded as important near-future mining targets because of their considerable reserves and high metal grades (Lipton, 2012). For efficient mining and development, understanding the locations, configurations, grade distributions, and genesis of such deposits is of the utmost importance.

Of particular interest in SMS deposits is the presence of two types, one formed in seafloor mounds and black smoker chimneys under oxic environments and another formed below the seafloor by mineral replacement (Tornos et al., 2015). Co-existence of these types was estimated recently from a two-layered low resistivity zones (of 0.2 Ohm-m or less) by a marine electrical resistivity tomography in the Iheya North Knoll in the mid-Okinawa Trough, southwest of Japan (Ishizu et al., 2019). The structure was interpreted as two mineralization zones on the seafloor and at about 40 m below seafloor (mbsf). In addition, similar two or multi-layered SMS deposits were also found by drillings in the Okinawa Trough (Saito et al., 2015; Yoshizumi et al., 2015). To date, various SMS mineralization models have been developed (Tornos et al., 2015). However, most are based on qualitative, geological observations, and the concrete physical setting that caused generation of the deposits (temperature, pressure, heat flux, and fluid flow) has not yet been elucidated; for example, the above-mentioned two-layered mineralization structure has not been explained by any quantitative models. The physical setting can be elucidated only through numerical simulation, because it is not possible to accurately observe the setting and the phenomena that occur there under progress over a long time and a wide area below the seafloor.

Based on that background, this study aims to build a three-dimensional (3D) numerical model that can correctly represent a seafloor hydrothermal system in a back-arc basin with geological, hydrological, and thermal constraints, clarify the above physical setting, and present a generation mechanism of the two-layered SMS structure by selecting the Iheya North Knoll as a case area (Figure 1a). Two or more mineralization styles are commonly mixed in SMS deposits (Tornos et al., 2015). Therefore, this study, perhaps the first study conducted for the above purposes, can contribute to understanding the generation setting of complex (two-layered or multilayered) SMS deposits in other areas.

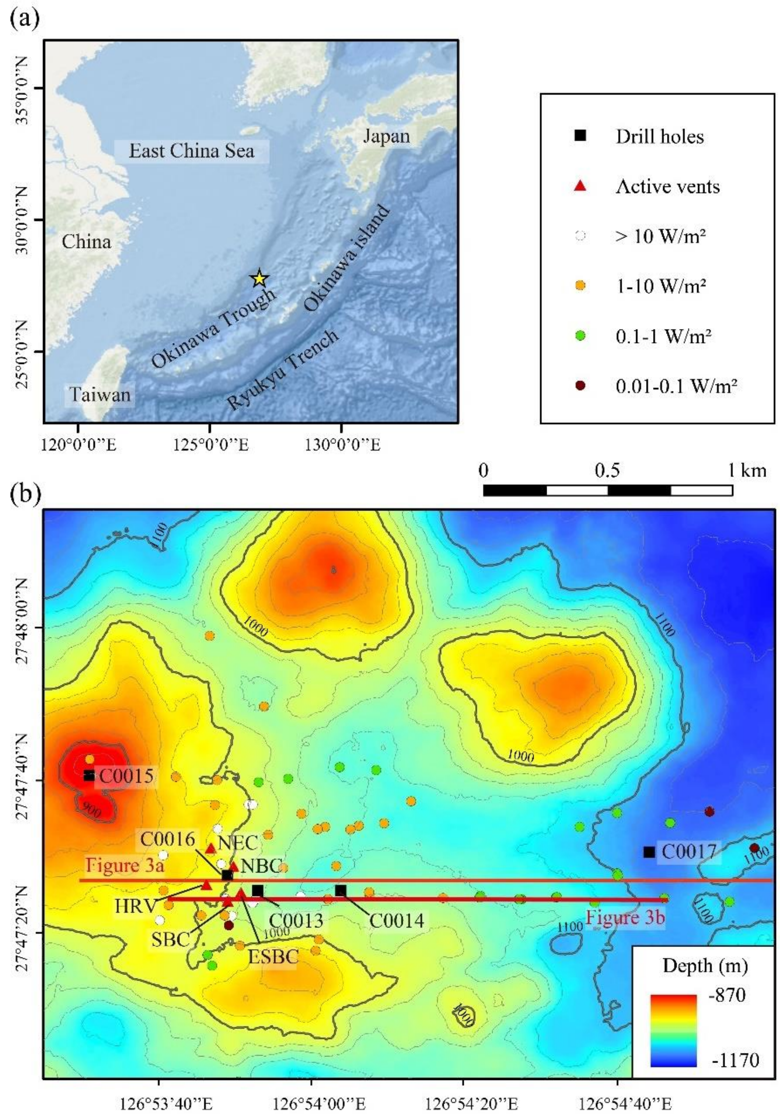

Figure 1. (a) Location of the Iheya North hydrothermal field in the middle Okinawa Trough marked by a star symbol and (b) bathymetry map of the study area with IODP drilling sites (black squares), active vent sites (red triangles), and heat flux measurement points (circles as in the legend, after Masaki et al., 2011). Two red lines show the locations of Figures 3a and b.

2 Data and Methods

The study area is situated in a back-arc basin between the Ryukyu arc-trench system and the Eurasian continent (Figure 1a); the main hydrothermal area is 500 m × 300 m in size (Figure 1b). Nine sites of representative active hydrothermal vents have been discovered in this area (Kawagucci et al., 2011); among them, the North Big Chimney (NBC) is known to have the highest temperature (311°C) and the largest flow rate recorded thus far (Takai & Nakamura, 2010), suggesting that the NBC is located on the main flow path.

The Iheya North Knoll is composed of i) volcanic rocks forming knolls and ii) thick sediments over the rocks in the central depression; volcaniclastic pumiceous deposits with widely distributed hard layers, perhaps impermeable caprocks, are estimated to be the main sedimentary components based on seismic survey results (Tsuji et al., 2012). Detailed lithology was revealed by drilling surveys at five sites in a program of the Integrated Ocean Drilling Program (IODP) Expedition 331 (Figure 1b) (Takai et al., 2011): the sediments are alternating sequences of hard low-porosity and porous pumiceous layers, mainly composed of pelagic and hemipelagic mud and volcaniclastic pumiceous deposits with hydrothermal alteration. Abundant anhydrite greatly reduces the porosity by filling voids in sediments, and consequently forms the low-porosity layers. Anhydrite precipitates from hydrothermal fluid when mixed with seawater (Lowell & Yao, 2002; Lowell et al., 2003). Low-porosity layers rich in anhydrite are regarded to act as impermeable caprocks that blocks vertical fluid flows.

Because back-arcs exist under extensional tectonic settings, normal faults, tensile fractures, and fracture zones develop parallel to the extension axis and act as fluid conduits (Sahlström et al., 2018). Following this general rule, several N–S faults are developed in the study area, on which the main hydrothermal mounds are located (Figure 1b). Research on modern (Tivey & Johnson, 2002; Arai et al., 2018) and fossil hydrothermal systems (Coogan et al., 2006) has drawn an image wherein hydrothermal upflows are concentrated in tube-like conduits, which presumably continue to the reaction zone (Tivey & Johnson, 2002). In fact, several tube-like conduits under mounds were detected from the seismic survey results in the Okinawa Trough (Arai et al., 2018; Tsuji et al., 2012), including a tube-like seismically transparent structure, which probably represents a conduit, under the NBC mound (Takai et al., 2010).

Using the above-mentioned accessible geological and geophysical data, a numerical model of the study area, 1.2 km (N–S) × 4.0 km (E–W) × 1.6 km (vertical below the seafloor) in size, was constructed (Figure 2) to simulate hydrothermal fluid flow based on Darcy's law and the mass and energy conservation equations. The TOUGH2 software was used for the simulation because of its high capability of analyzing gas–liquid two-phase flow and 3D heat flow (Pruess et al., 1999). A buffer zone 10 km in size was set around the model domain (Figures 2a and c), and the domain was discretized by Voronoi cells with 0.5 m to 500 m thickness from the shallow to deep parts and 30 m to 2000 m side length from the middle conduit to domain peripheral zones (Figure 2a). The bathymetric data of the top of the domain were acquired by a multibeam echosounder system (MBES) during several cruises. We set the initial conditions as hydrostatic pressure and 4℃ at the seafloor with the average thermal gradient in the study area, 0.12 ℃/m, except for the vent sites thermal gradient (Masaki et al., 2011); the surface boundary condition was set as a permeable boundary of the seafloor with constant temperature, 4℃, and hydrostatic pressure, and the side and bottom boundaries were set as impermeable.

To clarify the general fluid flow pattern and temperature and pressure distributions, the model domain was simply divided into four geologic elements, conduit, caprock, sediment, and volcanic basement, by excluding geological and hydrological heterogeneities. These elements were assigned in the model domain based on the drilling and seismic survey data. A highly permeable conduit 300 m in diameter was set vertically from the seafloor to the bottom of the model domain as the main discharge area, by locating the NBC as the center of conduit (Figure 2b). Distributions of the volcanic basement, sediment, and a continuous caprock layer 5 m to 100 m in thickness were set following the report of Takai et al. (2011) (Figure 2c). In addition, for the physical rock properties, the density, porosity, and thermal conductivity of the four elements were set based on drilling survey data, and permeability was set based on the literature data described in Text S1 (see also Table S1).

The validity of the constructed calculation model was checked by comparing the calculated temperature and heat flux with those obtained by measurement. A wide range of heat flux (0.01–100 W/m^2) was observed at 78 points with exceedingly high values around the NBC mound (Masaki et al., 2011). A noteworthy trend was that heat flux decreased with increasing distance from the mound (Figure 1b) to very low heat flux (< 0.1 W/m^2) 2 km from the mound, suggesting an occurrence of several-km-scale fluid circulation. In addition, temperature logging data were obtained at Sites C0014 and C0017 (Figure 3d) (Takai et al., 2011). Temperature data obtained at the distal flank at Site C0017 showed 44°C at 112 mbsf and 90°C at 151 mbsf, which imply cold seawater recharge into the hydrothermal system. In contrast, the temperature at Site C0014 at the intermediate flank was 22°C at 6.5 mbsf, and a high thermal gradient was observed below 10 mbsf with temperatures of 55°C at 16 mbsf, 150°C at 47 mbsf, and 210°C at only 50 mbsf. The temperature profiles at Sites C0014 and C0017 did not show simple increases with depth, suggesting the occurrence of lateral flow.

The injection rate and discharge rate at the conduit from the bottom and top boundaries, respectively, and the permeabilities of the four elements were adjusted with trial-and-error approaches so that the heat flux and temperature differences would be acceptably small with consideration of heat balance, as explained in Text S2. The resultant injection rate and discharge rate with the best matches were 27 kg/s (= 4 × 10^{-4} kg/(s·m^2)) of 350°C fluid and 32 kg/s (= 45 MW heat flow), respectively. Under those conditions, the steady state was simulated.

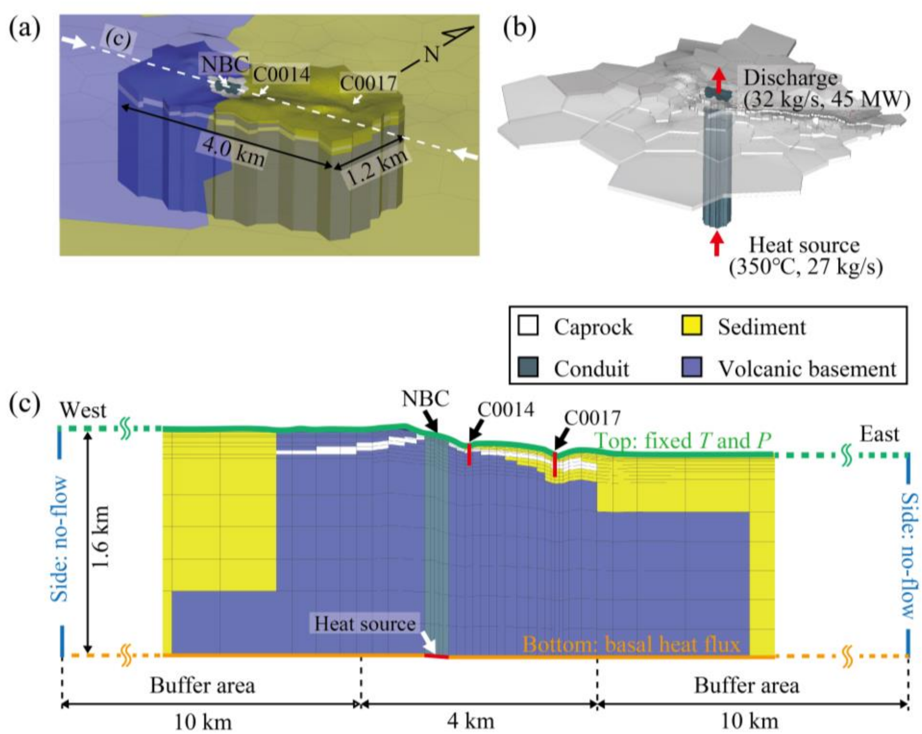

Figure 2. Calculation model. (a) Perspective view of the model domain with a buffer zone of 10 km, shown as semitransparent, set around the domain. Voronoi cell sizes become smaller toward the domain center. The broken white line shows the location of Figure 2c. (b) Distributions of a

caprock layer and a vertical conduit zone. (c) Detailed configuration of cells and geologic structure composed of four elements along an E–W cross-section in Figure 2a with the model size and boundary conditions. The cell thickness was set as 0.5 m (thinnest) near the seafloor (the top boundary), because the heat fluxes were measured at the top subsurface below the seafloor (Masaki et al., 2011), and the thickness gradually increases with depth, with 0.5 m for top five layers, 10 m for the next five layers, 25 m for six layers, and 200 m for the bottom seven layers.

3 Results and Discussion

The steady state flows are mostly upflows along the conduit and discharge from the seafloor, and partly lateral flows along the caprock form a mushroom-shaped high-temperature region (Figure 3a; see also Figure S1 in a cross-section view). Another main flow is descending low-temperature seawater from the seafloor near the volcanic ridge, about 2 km away from the NBC mound at the eastern Site C0017, toward the conduit, which subsequently induces flow circulation. The occurrences of lateral flow below the caprock and downward seawater flow in that place agree with interpretations based on the chemical compositions of the pore waters (Ishibashi et al., 2017) and heat flux and seismic survey data (Masaki et al., 2011; Tsuji et al., 2012).

The correctness of the simulation results can be confirmed by the findings that the calculated heat fluxes almost agree with the measured ones (Figure 3b) and that the calculated temperatures generally agree with the measured ones except for the underestimation for the deepest, 50 mbsf data of Site C0014 (Figure 3d). The consistency of heat flux can be more clearly confirmed by a cross-plot of the calculated and measured heat flux values (Figure 3c). The differences between the calculation and measurement results are attributed to the simplified geologic model that did not incorporate local changes in hydraulic parameters.

A noteworthy feature revealed by the simulation is an occurrence of boiling in the depth range between the surface of the NBC and 150 mbsf in the conduit, caused by a pressure drop at the top of the ascending hydrothermal fluids (Figure 3e). The gas saturation rate reaches a maximum (10%) just below the NBC and decreases gradually toward the surroundings. This occurrence of boiling in the uppermost subseafloor near the NBC can be confirmed by consistency with the observations that all the vents in the study area, including the NBC, emit white fumes (i.e., white smokers) (Chiba et al., 1996) and that many of the vent fluids in this area were Cl-depleted (Kawagucci et al., 2011).

To further check the validity of the calculation model, a sensitivity analysis was implemented as described in Text S3 (see also Figures S2 and S3). Models without either the conduit or caprock could not reproduce the measured temperatures and heat fluxes. This mismatch was caused by the nonoccurrence of lateral flows in the shallow subseafloor. Consequently, the importance of the conduit and caprock for hydrothermal fluid flow and their correct setting in this study are demonstrated.

Distributions of massive and granular sulfide minerals were observed near the NBC seafloor (Site C0016) and near the shallow subseafloor of Sites C0013 and C0014 (Yeats et al., 2017), and the formation of two-layered SMS deposits was estimated by Ishizu et al. (2019), as mentioned above. This two-layered structure can be considered to have been caused by the boiling of hydrothermal fluids and lateral flows in the shallow subseafloor. Both the simulation result and field observations suggested the occurrence of two-phase separation into vapor- and liquid-rich fluids in the uppermost subseafloor near the NBC. Through this phase separation, metal components in the fluids become concentrated in the liquid phase, and sulfide minerals precipitate (Kawagucci et al., 2013) by the fractionation of chemical species, the pH of the fluids increases, and metal solubility decreases (Drummond & Ohmoto, 1985). The vapor-rich, light fluids poor in metal components ascend and are probably discharged from the vents, which is concordant with the fact that all the vents in the study area are white smokers, as mentioned above, in which sulfide minerals are scarcely contained. Therefore, sulfide minerals on the seafloor probably precipitated from past black smokers. At the same time, the liquid-rich fluids are trapped below the caprock, as confirmed through a drilling survey (Kawagucci et al., 2013), and their lateral flows must have caused sulfide mineral precipitation.

Based on the above considerations, we propose a two-stage generation scenario of the two-layered SMS deposit in the Iheya North Knoll as follows. In the early stage, high-temperature hydrothermal fluids ascended along the conduit and discharged from the vents as black smokers without boiling below the seafloor, and considerable amounts of sulfide minerals then precipitated on the seafloor from the black smokers by mixing with the seawater (Figure 4a). Long-term precipitation formed a mound, and that mound acted to seal the hydrothermal fluid flows in the later stage; consequently, the fluid flows became concentrated in the vent (Tivey, 2007; Fouquet, 1997). The sealing was intensified by the distribution of low-permeability hemipelagic sediments in the shallow subseafloor around the mound. Through mixing of the hydrothermal fluids with the seawater in the mound, anhydrite precipitated and filled the rock voids under fluid temperatures of 200°C or more (Fouquet, 1997; Ishibashi et al., 2017). In addition, the rocks were hydrothermally altered and changed partly to clay minerals with decreasing permeability (Takahashi, 1995). These rocks containing anhydrite and clay minerals in voids became impermeable caprock, which blocked mixing of the hydrothermal fluids and seawater; in addition, the conduit top gradually became less permeable, resulting in flow being diverted horizontally (Koski et al., 1994; Tivey et al., 1995) into the highly permeable volcaniclastic layer (Figure 4b). Because of the effect of the caprock to suppress mixing, the fluid temperature increased, and consequently, boiling occurred at the conduit top, and vapor-rich fluids were discharged from the vents as white smokers, as is occurring at present. At the same time, the liquid-rich fluids rich in metal components flowed laterally under the caprock and precipitated sulfide minerals, mainly by boiling and/or by conductive cooling.

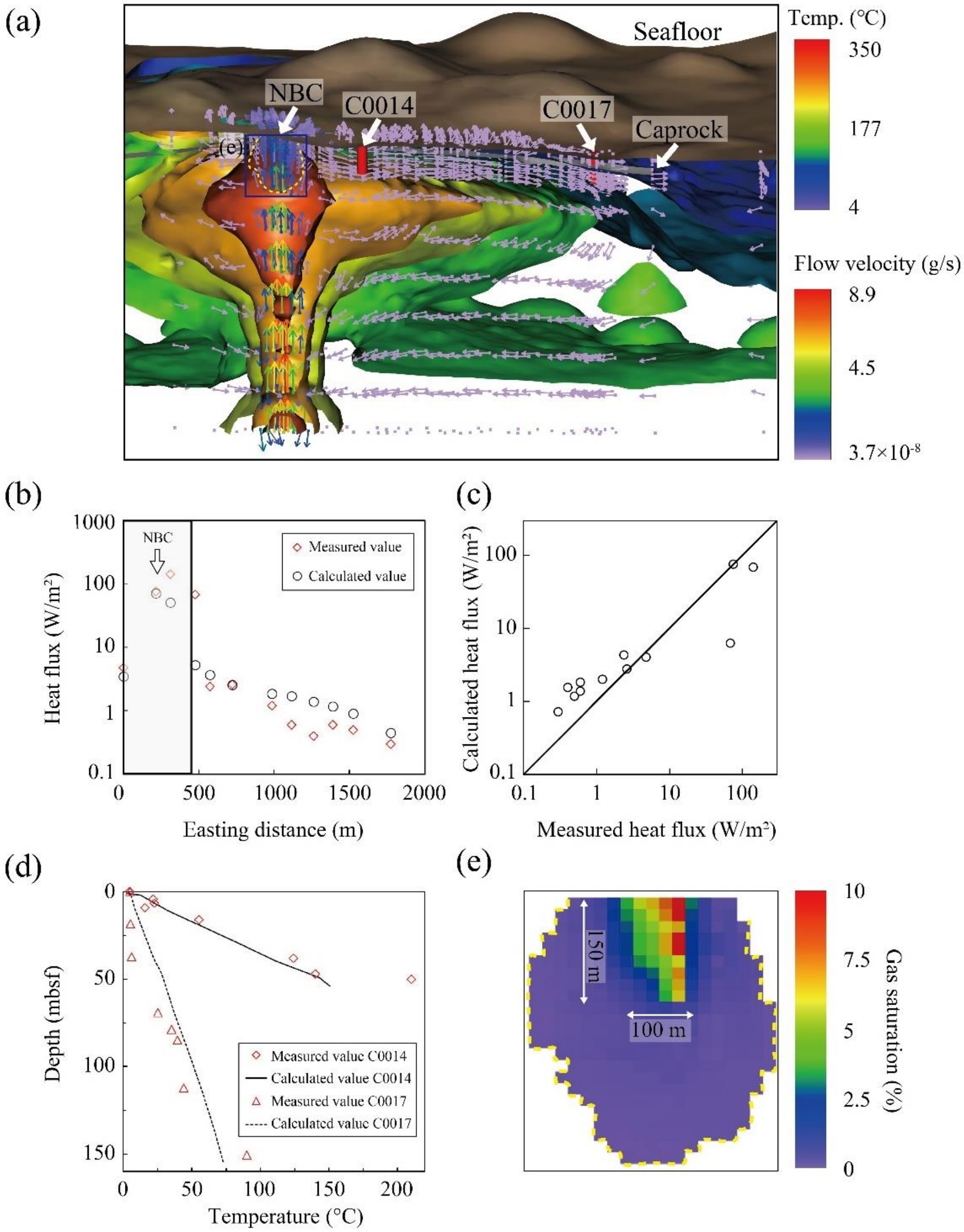

Figure 3. Simulation results and verification. (a) 3D view of iso-temperature surfaces and fluid flow vectors (arrows) on an E–W cross-section along the profile shown in Figure 1b. Boiling zone around the NBC is delineated by the broken yellow line. The thick red lines, brown surface, and gray surface in the shallow subseafloor denote the seafloor drillings with site names, the seafloor, and the caprock layer, respectively. (b) Comparison of calculated heat fluxes with the measurement data after Masaki et al. (2011). The easting distance is along the profile shown in Figure 1b. The gray hatched part from 0 to 450 m distance denotes the active hydrothermal area. (c) Cross-plot of calculated heat flux and measured ones. (d) Comparison of calculated temperatures with the measurement data at Sites C0014 and C0017 after Takai et al. (2011). (e) Vertical cross-section of gas saturation distribution in the boiling zone shown in Figure 3a.

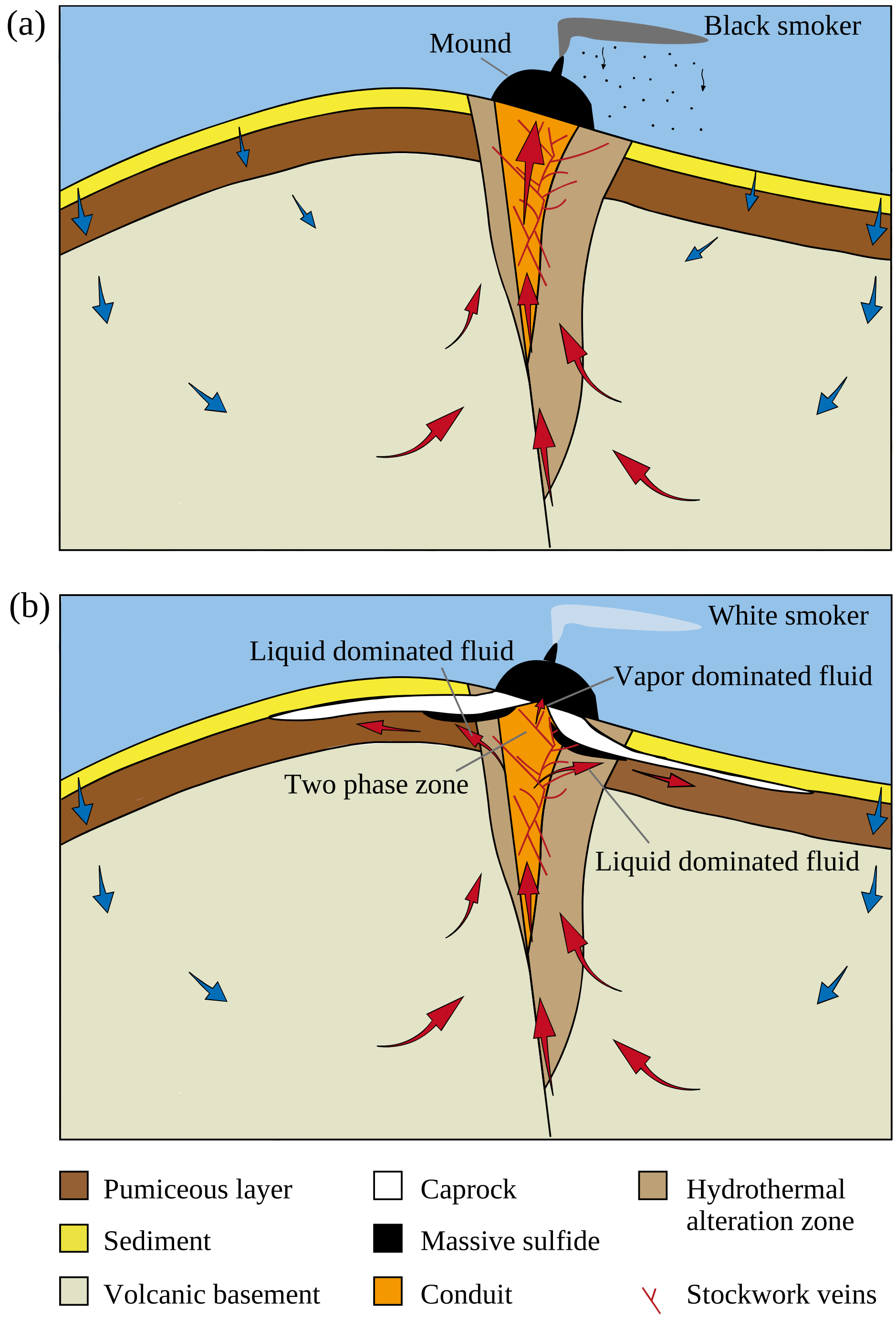

Figure 4. Conceptual model of the two-stage mineralization process. (a) Early-stage mineralization model in which black smokers discharging from the seafloor were cooled by the seawater and sulfide minerals precipitated from the vents, forming SMS deposits on the seafloor. Long-term precipitation formed a mound around the vent. (b) Late-stage mineralization model in which impermeable portions composed of anhydrite and the clay minerals-bearing mound, and sediment induce lateral flows and boiling of fluids in the conduit top. Gas-phase dominated fluids are discharged from the vent as a white smoker. In contrast, liquid-phase dominated fluids rich in metal components flow laterally below the caprock and form the lower ore body because of boiling

and/or conductive cooling. The blue and red arrows denote fluid flows of relatively low- and high-temperature seawaters, respectively.

4 Conclusions

In this study, a simple, but essential subseafloor geologic model was constructed to clarify the regional temperature, fluid-flow patterns, and physical property distributions in a hydrothermal system of a back-arc basin, by selecting the Iheya North Knoll, middle Okinawa Trough, southwest Japan as an example. This clarification was achieved by a numerical simulation of multi-phase fluid using TOUGH2 with geological, hydrological, and thermal constraints. The most important finding of this study is that the fluid flow is essentially controlled by the presences of a caprock layer and conduit. The resultant flow features were that the hydrothermal fluids ascend along the conduit toward the seafloor and a portion of them flow laterally below the caprock, as observed by a drilling survey. Because of the presences of the caprock and conduit, the calculated temperatures and heat fluxes were consistent with the measured ones, and the boiling location was in accord with the observed one.

In the study area, development of the two-layered SMS deposit in the study area was interpreted using electrical resistivity tomography. Based on the simulation results and the preceding measurements and observations, a generation mechanism of this two-layered SMS deposit was proposed as formation by two stages of mineralization. In the early stage, hydrothermal fluids were discharged as black smokers rich in metals, and by mixing with the seawater, sulfide minerals from the smokers were deposited on the seafloor. In the later stage, the conduit gradually became less permeable over time, which induced lateral flows in a highly permeable volcaniclastic layer, and consequently, caprock was generated by the precipitation of anhydrite and clay minerals in the layer. Because of the caprock, the temperature of the hydrothermal fluids increased and boiling occurred. The vapor-rich fluids were discharged as white smokers from the vents, whereas the liquid-rich fluids, flowing laterally below the caprock, formed the lower SMS deposits mainly by boiling.

Acknowledgments, Samples, and Data

Data is available through Takai et al. (2011) and Masaki et al. (2011). This work was supported by the Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Next-generation technology for ocean resources exploration" (Funding agency: Japan Agency for Marine-Earth Science and Technology, JAMSTEC).

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Supporting Information for

Numerical simulation-based clarification of a fluid-flow system in a seafloor hydrothermal vent area in the middle Okinawa Trough

S. A. Tomita[1], K. Koike[1], T. Goto[1, *], and K. Suzuki[2]

[1]Department of Urban Management, Graduate School of Engineering, Kyoto University, Kyoto, Japan

[2]Submarine Resources Research Center, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Kanagawa, Japan

*Now at Graduate School of Life Science, University of Hyogo, Hyogo, Japan

Contents of this file

Introduction

Text S1 describes literature data of rock permeabilities.

Text S2 describes heat balance for the setting of discharge rate of hydrothermal fluid in the simulation.

Text S3 describes the sensitivity analysis for confirming the suitability of the geologic structure model.

Text S1.

The setting of permeability to 10^{-14} m^2 for the volcanic basement was based on several previous studies (e.g., Fehn & Cathles, 1979; Fisher et al., 1994; Coumou et al., 2008), and that of 10^{-17} m^2 for the caprock was based on several references (Bear, 1972; Magri et al., 2010; Raharjo et al., 2016). Because the cracks and fractures in the rocks are mostly vertical, the vertical permeability of the conduit (10^{-12} m^2) (e.g., Yang et al., 1996; Gruen et al., 2014) was set as one order of magnitude larger than the horizontal permeability (10^{-13} m^2). Because the drilling surveys revealed multiple impermeable layers in the sediments (Takai et al., 2011), the horizontal permeability (10^{-14} m^2) of the sediment was set as two orders of magnitude larger than the vertical permeability (5.0×10^{-16} m^2), after Freeze & Cherry (1979).

Text S2.

Because the heat balance is indispensable to include in the simulation, the amount of heat flow associated with convection in the study area was estimated as follows. Heat flow was divided into two components: one caused by high-temperature venting and another caused by lower-temperature diffuse flow (Elderfield & Schultz, 1996). The orifice area of the vent and the flow velocity and temperature of venting fluids are necessary for estimating the former heat flow. The orifice area of the NBC was observed as 12 cm^2 with a radius of about 2 cm according to a seafloor survey (Kawagucci et al., 2011). The flow velocity was estimated as 1 m/s by a seafloor observation, which is equivalent to the reported velocities at other hydrothermal vents (Schultz & Elderfield, 1999; Kawagucci et al., 2011). The temperature of venting fluids was observed as 311°C (Takai & Nakamura, 2010). Using those values, the former heat flow through the NBC vent was calculated as 1 MW, following the method of Converse et al. (1984). Total heat flow of 5 MW was derived by applying the same method and the orifice area of the NBC to the other eight vents identified in the study area. The flow rates of the eight vents were set to be lower, 0.6 m/s, based on the observations that the NBC had the highest flow rate and that the flow velocities at other submarine hydrothermal systems ranged from 0.6 to 3 m/s (Converse et al., 1984; LaFlamme et al., 1989).

The latter heat flow is one order of magnitude greater than the heat flow caused by high-temperature venting (Rona & Trivett, 1992; Elderfield & Schultz, 1996), and may be greater than the former heat flow by a factor of 5 or more, as observed in the Endeavor hydrothermal area at the Juan de Fuca Ridge (Schultz et al., 1992) and its ASHES vent field where the total heat flow associated with high-temperature venting was 4.4 ± 2 MW, versus the diffuse heat flow of 15–75 MW (Rona & Trivett, 1992). Based on those observations and through trial and errors, we set the diffuse heat flow to be eight times larger than the heat flow caused by high-temperature venting.

Text S3.

The suitability of the constructed geologic structure model was checked by the following sensitivity analysis. The first check was the importance of the conduit setting. Deleting the conduit from the model greatly decreased the ascending velocity of hydrothermal fluids as well as the supply amount of hydrothermal fluids to the discharge zone. In addition, lateral flows did not occur (Figure S2a). As the result, both the heat flux and temperature became much lower than the measured ones (Figures S2b and c).

The second check was the importance of the caprock setting. Deleting the caprock from the model induced deep infiltration of the seawater (Figure S3a), and consequently caused a significant temperature drop and excessive underestimation of the heat flux and temperature (Figures S3b and c), without an occurrence of boiling. Most hydrothermal fluids flowed out from the discharge zone and the surrounding seafloor, and the occurrence of lateral flow was limited.

These results demonstrate the suitability of the constructed geologic structure model and the essential roles of the conduit and caprock for controlling the fluid flow pattern.

Figure S1.

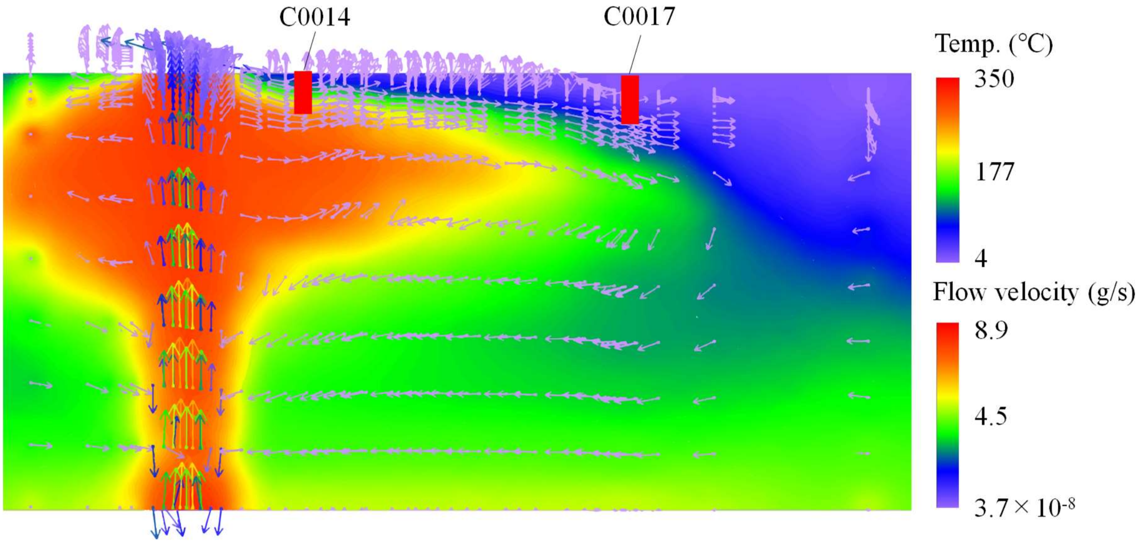

Figure S1. Vertical cross-section of simulation result of the model shown in Figure 3a with the distributions of temperature and fluid flow vectors. The thick red lines denote the seafloor drillings.

Figure S2.

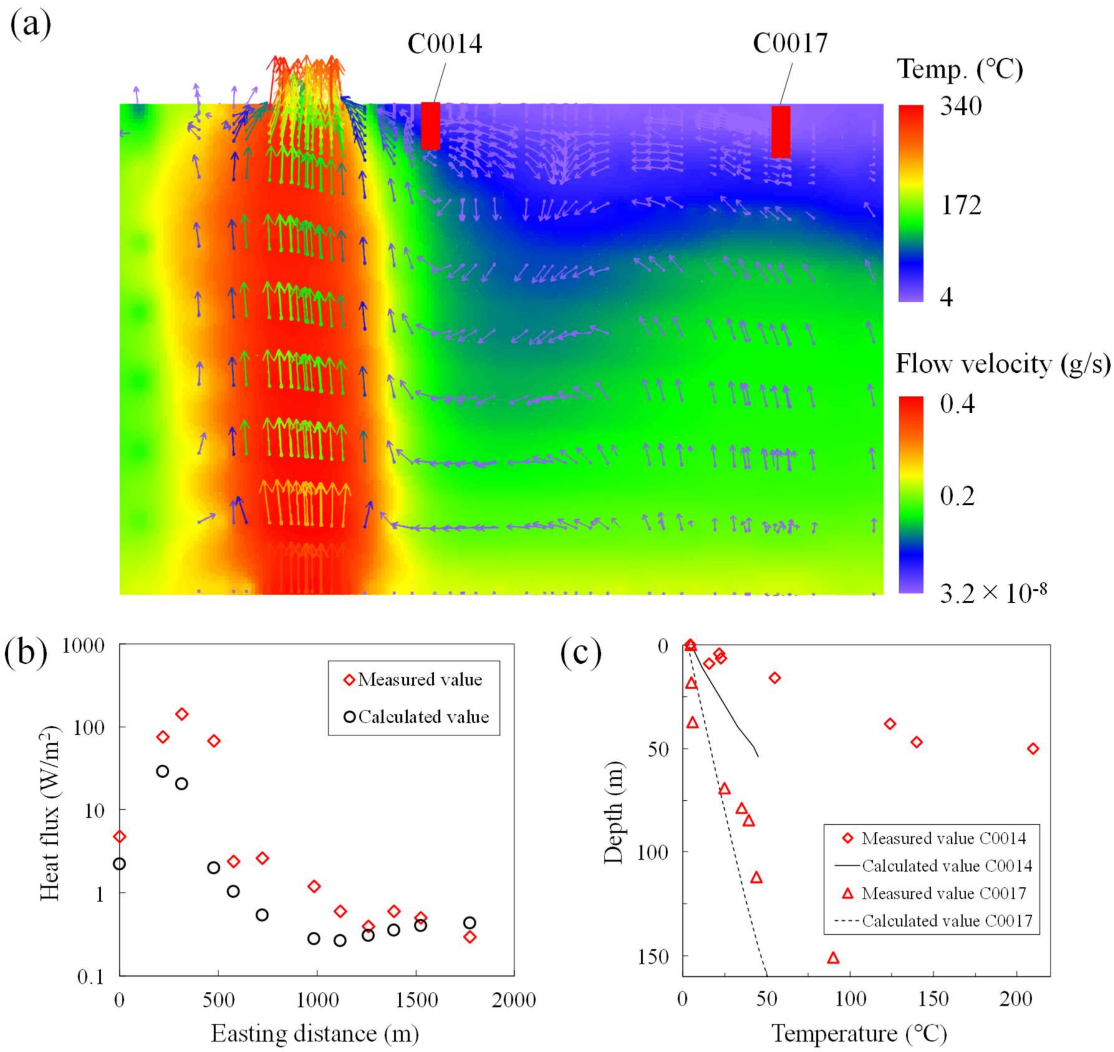

Figure S2. Simulation results of a model without the conduit setting. (a) Distributions of temperature and fluid flow vectors shown in a form of a cross-section same as that in Figure 3a. The thick red lines denote the seafloor drillings. (b) Comparison of calculated heat fluxes with the measured data. The location of the profile in Figure S2b is the same as that in Figure 3b. (c) Comparison of calculated temperatures with the measured data at Sites C0014 and C0017.

Figure S3.

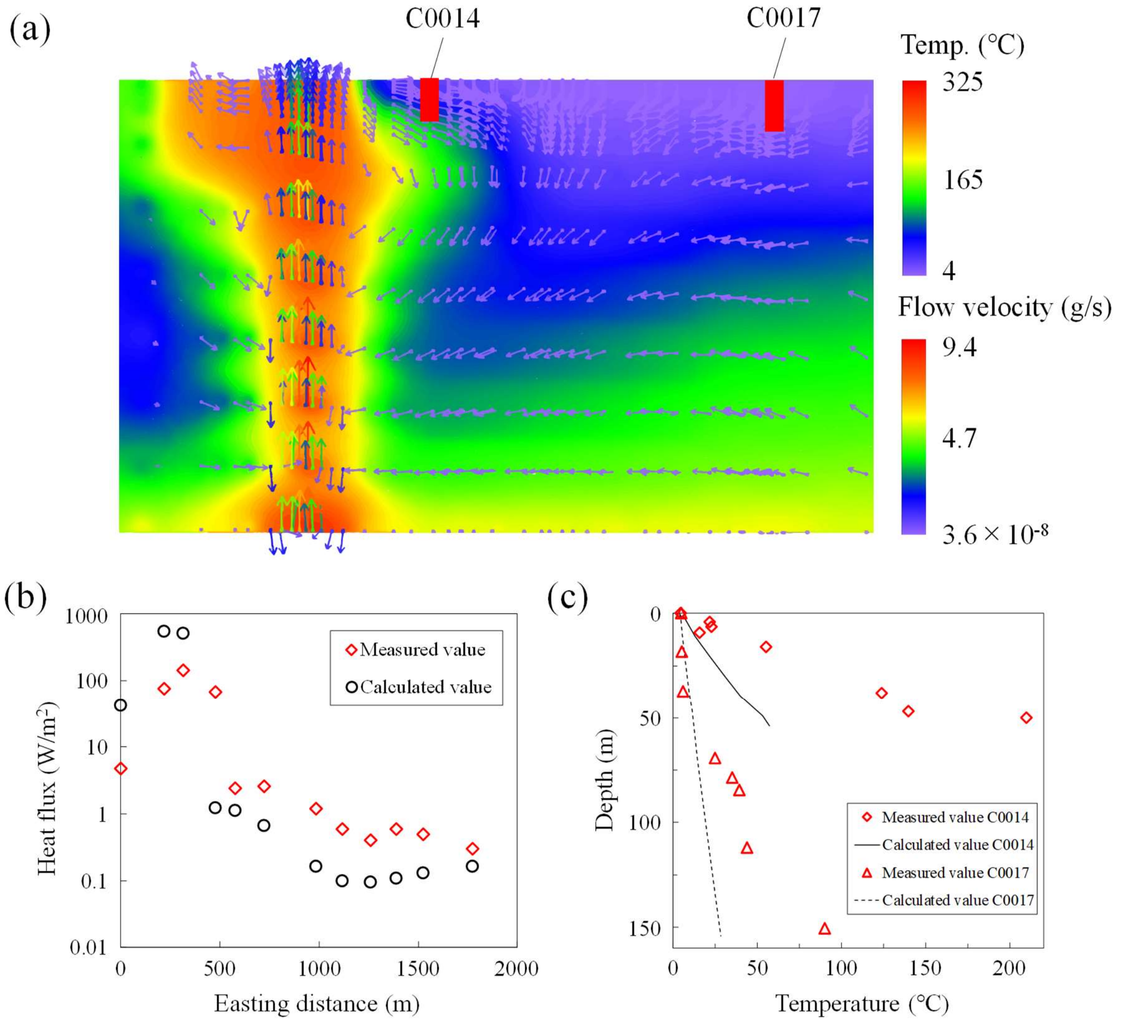

Figure S3. Simulation results of a model without the caprock setting. (a) Distributions of temperature and fluid flow vectors shown in a form of a cross-section same as that in Figure 3a. The thick red lines denote the seafloor drillings. (b) Comparison of calculated heat fluxes with the measured data. The location of the profile in Figure S3b is the same as that in Figure 3b. (c) Comparison of calculated temperatures with the measured data at Sites C0014 and C0017.

Table S1. Physical property values assigned to the four geologic elements for the numerical simulation. *X*, *Y*, and *Z* denote the easting, northing, and vertical directions, respectively.

Parameters	Volcanic basement	Caprock	Conduit	Sediment
Permeability (m^2)	1.0×10^{-14}	1.0×10^{-17}	X, Y: 1.0×10^{-13} Z: 1.0×10^{-12}	X, Y: 1.0×10^{-14} Z: 5.0×10^{-16}
Density (kg/m^3)	2800	2750	2750	2750
Porosity	0.4	0.01	0.6	0.3
Thermal Conductivity (W/(m·K))	2.0	2.0	2.0	2.0
Specific Heat (J/(kg·K))	1000	1000	1000	1000