Numerical simulations of mid-ocean ridge hydrothermal circulation including the phase separation of seawater

KAWADA Yoshifumi, YOSHIDA Shigeo, and WATANABE sei-ichiro

kawada@eps.nagoya-u.ac.jp, yoshida@eps.nagoya-u.ac.jp, seicoro@eps.nagoya-u.ac.jp
Department of Earth and planetary sciences, Nagoya University, Japan

Abstract. Seawater circulates at mid-ocean ridges, driven by the heat of magma chambers lying underneath. We numerically investigated the hydrothermal circulation, including the phase separation of seawater. We found that the phase separation leads to two-layered structure. The seawater circulates vigourously in the upper layer, whereas dense brine sinks to form a stagnant lower layer.

1 Introduction

At mid-ocean ridges, seawater sinks through cracks of oceanic crusts and exits near the ridges, being driven by the heat of cooling magma chambers lying underneath. The outflowing hot water forms spectacular black smoker vents in some places. The flow is called mid-ocean ridge hydrothermal circulation. The circulation plays a major role in heat transport at the ridge area. Moreover, it nourishes deep-sea biotic communities, and causes hydrothermal alterations, which are commonly found in ophiolites. All of these phenomena are influenced by the structure of the circulation. For example, ecosystems are controlled by the temperature and compositions of the water, which result from the heat transport and chemical reaction, which are in turn determined by the circulation structure.

Phase separation of seawater has been suggested to be a major controlling factor of the circulation structure (Bishoff and Rosenbauer, 1989). It is particularly important around the ridge axis, where the underlying magma chamber heats seawater above the critical point. The phase separation generates fluids with Cl^- concentrations both higher and lower than that of seawater. It leads to the changes of Cl^- concentration of hydrothermal vent fluid. The phase separation is evidenced by the diversity of Cl^- concentrations of hydrothermal vent water (e.g. von Damm, 1995). The concentrations range from 0.2 to 6 wt%NaCl (Seawater has 3.2wt%NaCl). Ophioritic fluid inclusions show that the Cl^- concentration of the 'palaeo' hydrothermal system drastically changes at a trapping temperature of 500°C (Kelley et al., 1992). The concentrations are $1 \sim 10$wt% above the temperature, and $30 \sim 70$wt% below it. This implies a two-layered structure, if the temperature is interpreted as representing the depth.

We carry out numerical simulations of the circulation to clarify the dynamical aspect of the phase separation. Simulations which include phase separation explicitly have scarcely been performed so far despite its importance, because of various numerical difficulties. Thus we examine steady two-dimensional flow structures to obtain basic properties of the effect of phase separation. We model hydrothermal circulations near fast-spreading ridges, along which magma chambers exist continuously. The flow is driven by the heat conducted from cooling magma chambers. The seawater is treated as the NaCl-H_2O two-component system. We focus on the temperature and composition of hydrothermal fluid at the seafloor. Their observations may contain some information about the circulation structure and phase separation.

2 Model

We assume the oceanic crust to be a two-dimensional homogeneous porous media. The pore space is saturated with NaCl-H_2O two-component fluid. The equation of state and phase diagram of the solution are given by Pitzer et al. (1984), Tanger and Pitzer (1989), and Anderko and Pitzer (1993).

The basic equations consist of four consavational equations (mass, moment, energy, composition), and a constitutive equation (the relative flux). The basic equations are as follows.

The mass conservation equation of the Boussinesq fluid is written as

$$\nabla \cdot \boldsymbol{q} = 0, \tag{1}$$

where $\boldsymbol{q}$ is the local center-of-mass flux. This flux is defined by

$$\boldsymbol{q} = \omega_l \boldsymbol{q}_l + (1 - \omega_l)\boldsymbol{q}_v, \tag{2}$$

where $\boldsymbol{q}_l$ is the liquid phase flux, $\boldsymbol{q}_v$ is the vapor phase flux, and ω_l is the mass fraction of the liquid phase.

The momentum conservation in porous media is written as

$$\boldsymbol{q} = -\frac{K}{\mu}(\boldsymbol{\nabla} p + \rho_f \boldsymbol{g}), \tag{3}$$

where K is the permeability, μ is the viscosity of the fluid phase (liquid+vapor), p is the pressure, and $\boldsymbol{g}$ is the gravitational acceleration, and ρ_f is the mean density of the fluid phase.

The energy conservation is written as

$$\frac{\partial T}{\partial t} + \boldsymbol{q} \cdot \nabla T = \kappa \nabla^2 T, \tag{4}$$

where T is the temperature, and κ is the thermal diffusivity of the fluid phase.

The material conservation is written as

$$\phi \frac{\partial C}{\partial t} + \boldsymbol{\nabla} \cdot [C\boldsymbol{q} + \omega_l(1-\omega_l)(C_l - C_v)(\boldsymbol{q}_l - \boldsymbol{q}_v)] = D\nabla^2 C, \tag{5}$$

where ϕ is the porosity, C is the bulk composition (NaCl weight fraction), C_l is the composition of the liquid phase, C_v is the composition of the vapor phase, $\omega_l \equiv (C - C_v)/(C_l - C_v)$ is the mass fraction of the liquid phase, and D is the coefficient of compositional diffusion.

In Eq.(5), we assume that chemical equillibrium is realized between the two phases so that we directly obtain composition from the temperature and pressure. We assume that the phase whose mass fraction is less than the other is discontinuous, and forms bubbles or droplets. Their shape is assumed to be spherical. For example, when the liquid mass fraction is more than 0.5, the vapor phase forms droplets and the liquid phase is continuous.

We assume that the relative flux between the two phases obey Stokes' law, which is

$$\boldsymbol{q}_l - \boldsymbol{q}_v = \left(\frac{1}{a^2} + \frac{1}{K}\right)^{-1} \frac{\rho_l - \rho_v}{\mu} \boldsymbol{g}, \tag{6}$$

where ρ_l is the density of the liquid phase, ρ_v is the density of the vapor phase, and a is the radius of the droplets.

We treat the seafloor as a free boundary (Wilcock, 1998). The fluid can flow in or out through the boundary. When the fluid flows into the oceanic crust, the fluid has the temperature and composition of seawater. When the fluid flows out the system, the fluid keeps its temperature and composition. The bottom boundary is impermeable, and its temperature is constant.

The equations are non-dimensionized with the thickness of the porous media d as the length scale, the thermal conduction time d^2/κ as the time scale, the temperature difference between the seawater and the bottom boundary ΔT as the temperature scale, the compositional difference between H_2O and NaCl ($= 1$) as the composition scale, ρ_0 as the density scale, and $\kappa\rho_0/\mu K$ as the pressure scale.

The non-dimensionized equations are

$$\boldsymbol{\nabla} \cdot \boldsymbol{q} = 0, \tag{7}$$

$$\boldsymbol{q} = -\boldsymbol{\nabla} p + Ra\rho_f \boldsymbol{e}_z, \tag{8}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{\nabla} \cdot (\boldsymbol{q}T) = \nabla^2 T, \tag{9}$$

$$\phi \frac{\partial C}{\partial t} + \boldsymbol{\nabla} \cdot (\boldsymbol{q}C) + \frac{\partial}{\partial z} \frac{(C - C_v)(C_l - C)}{C_l - C_v}(\boldsymbol{q}_l - \boldsymbol{q}_v) = 0, \tag{10}$$

$$\boldsymbol{q}_l - \boldsymbol{q}_v = Raf(\rho_l - \rho_v)\boldsymbol{e}_z, \tag{11}$$

where $\boldsymbol{e}_z$ is the unit vector of vertical component. The nondimensional numbers are

$$Ra = \frac{\rho_0 g K d}{\kappa \mu}, \tag{12}$$

$$f = (1 + K/a^2)^{-1}. \tag{13}$$

The Rayleigh number Ra is the ratio of the buoyancy force to the resistance between the pore and the fluid, which is the scale of the mean flow. The other parameter f determines the magnitude of the relative flux.

We calculate these equations, proceeding in time, until the steady state is reached. The important parameters of the calculations are the radius of the fluid sphere and the radius of the pore space. We survey wide ranges of these parameters.

3 Notes on numerical scheme

We outline the numerical treatment of the advection terms. It is important in suppresing mesh-dependence of the results, namely, the numerical diffusion. Careful treatment of the advection terms are necessary for our problem because the concentration field has a steep gradient.

The center-of-mass advection terms in the energy and composition equation are solved by first-order skew-upwind method (Raithby, 1976). This method prevents numerical diffusion normal to the flow direction. We confirm that this method produces results less dependent on mesh size than ordinary high-order methods do (e.g. minmod TVD method). This is because the concentration field has steep gradients normal to stream lines.

The relative advection term in the composition equation is solved by the minmod TVD method.

One-dimensional (ordinary) higher-order method is used because this relative flow has only a vertical component.

This term has one more problematic point about numerical stability. It has the form

$$\frac{\partial}{\partial z}(C - C_v)(C_l - C) = 2\{C - 0.5(C_l + C_v)\}\frac{\partial C}{\partial z}, \quad (14)$$

if C_l and C_v are constant. To avoid numerical instability, the direction of the upstream should be chosen in accordance with the sign of the value $\{C - 0.5(C_l + C_v)\} \propto (\omega_l - 0.5)$.

4 Calculations

We make one circulation cell in the calculation area. The calculation area has a non-dimensional height of 1 and a non-dimensional horizontal length of 0.5, and has evenly-spaced meshes. The number of the meshs is 128 (horizontal) $\times$ 256 (vertical).

The calculations are carried out with the following parameters. The temperature of seawater is set at 0°C. The NaCl concentration of seawater is set at 3.2wt%. The bottom temperature is set at 600°C, which is the temperature of brittle-ductile transition of rocks. We ignore the pressure dependence of the equation of state, and the pressure is set at 400 bar in this study. The porosity is set at a constant value, 0.1. The other parameters we used are shown in Table 1.

We comfirm that the quantities of the result shown in Table 1 is converged within 3% by changing the number of the meshs.

Table 1. Parameters used in the calculations, and the results. D is the coefficient ratio of material diffusion to thermal diffusion, Nu is the Nusselt number, C_{min} is the minimum concentration, C_{max} is the maximum concentration, T_{max} is the maximum concentration, and δ is the mean thickness of the stagnant layer. Note that $f = 0$ corresponds to the thermal convection of a one-phase fluid.

Ra	f	D	Nu	C_{max} $\times 100$	C_{min} $\times 100$	T_{min}	δ
100	0	–	3.07	–	–	0.493	–
100	0.1	1	2.87	3.05	3.35	0.473	–
100	0.2	1	1.73	3.19	3.21	0.353	0.12
100	0.05	0.1	1.73	4.00	2.79	0.352	0.12
100	0.1	0.1	1.46	3.14	3.32	0.305	0.16

We roughly estimate the Rayleigh number of the hydrothermal system, using the estimates of parameters shown in Table 2. The result is $10^2 \sim 10^6$. We use the Rayleigh number around the lower limit, 100, because it is difficult to obtain reliable results for higher Rayleigh numbers.

Table 2. Estimation of the Rayleigh number.

	meaning	quantity	dimension
ρ	density of water	10^3	[kg m^{-3}]
g	gravity acceralation	10	[m s^{-2}]
d	depth of circulation	10^3	[m]
K	permeability	$10^{-11\sim-14}$	[m^2]
μ	viscosity of water	10^{-3}	[Pa s]
κ	thermal diffusivity	10^{-6}	[m^2 s]
Ra	Rayleigh number	$10^{2\sim6}$	[–]

The parameter f is difficult to estimate, because the radius of droplets or bubbles is highly uncertain. Moreover, the constitutive equation (6) is only valid when the size of the droplets/bubbles is far smaller than the pore size. We therefore treat this parameter as a free parameter, and use values from 0.05 to 0.2.

5 Results and Discussion

We find that the mid-ocean ridge hydrothermal circulation has two-layered structure (Fig.1,3), consistent with the structure inferred from the data of fluid inclusions. It disproves a traditional view which does not take the phase separation into account (Fig.2). The circulation is vigorous in the upper layer, and high Cl$^-$ concentration brine sinks to form a lower stagnant layer. The lower brine layer has a stable density stratification, which prevents convection. The upper circultaion layer has Cl$^-$ concentrations almost the same as that of seawater.

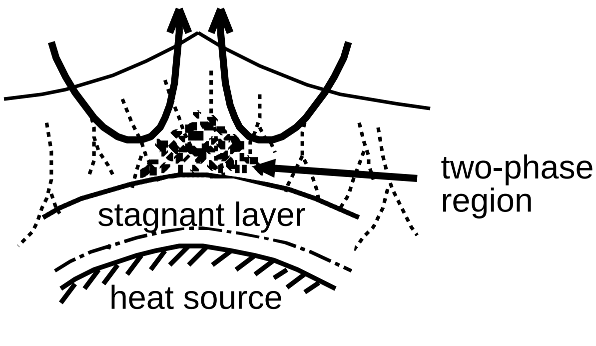

Fig. 1. A new picture of mid-ocean ridge hydrothermal circulation. The circulation is prevented from penetrating into the heat source area due to the formation of the stagnant layer.

The boundary between the two layers is almost the phase separation temperature of seawater, because the compostion of the upper layer is almost uniform and the same as that of seawater. Consequently, the temperature of the outflowing fluid is

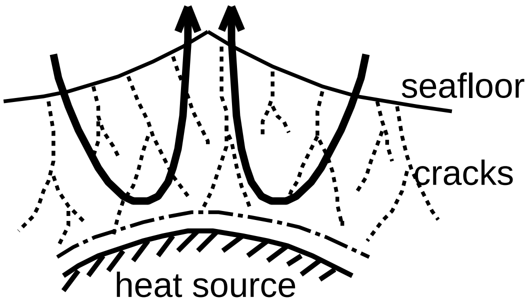

Fig. 2. A traditional picture of mid-ocean ridge hydrothermal circulation (no phase separation).

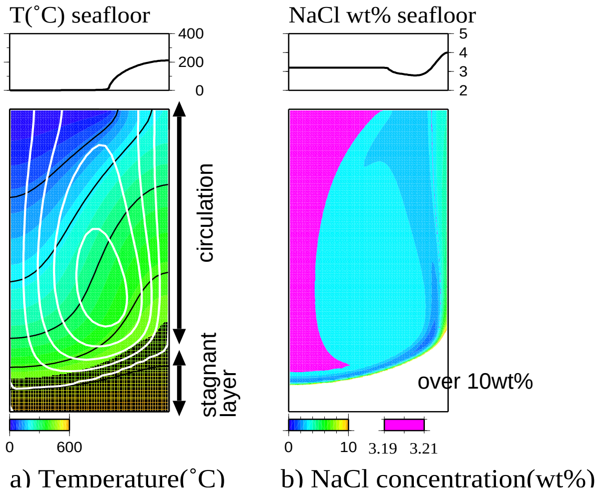

Fig. 3. A typical result of this work. The parameters are $Ra = 100$, $f = 0.05$, and $D = 0.1$. a)The temperature field is shown. The white thick lines are the streamlines. The black dotted area is the two-phase region. These streamlines penetrate into the two-phase region. The upper figure shows the temperature of the hydrothermal fluid at the seafloor. b)The NaCl concentration field is shown. The upper figure shows the NaCl concentration of hydrothermal fluid at the seafloor.

close to the phase separation temperature of seawater. The thickness of the stagnant layer is propotional to $(Nu)^{-1}$, because the top temperature of the layer is always the same (the condensation temperature of seawater).

The composition of the hydrothermal fluid at the seafloor is controlled by the structure of the transision region between the two layers. A two-phase region develops especially in the upwelling area in the transision region. The two phases separate because of their density difference, changing the composition of the circulating fluid. The competition between the advection by the mean flow and the relative motion of the two phases determines the composition of the outgoing fluid.

The results are classified in three types by the composition of hydrothermal fluid at the seafloor. When the mean flow is dominant, the composition of the outflow is almost same as that of seawater. This is because the denser phase does not separate from the other phase. This structure is similar to that of the simple thermal convection of a one-phase fluid. When the relative motion is dominant, the composition of the outflow is also almost the same with that of seawater. In this case, the denser phase rapidly sinks and separates from the upper circulation. When the mean flow and the relative motion are comparable, fluids with compositions both higher and lower than that of seawater flow out of the seafloor. In this case, a fluid element of the denser phase on a streamline moves to an outer streamline, because the brine sinks and, at the same time, is advected by the mean flow.

6 Reference

Anderko,K., and K.S.Pitzer, Equation-of-state representation of phase equilibria and volumetric properities of the system NaCl-H_2O above 573 K, *Geochim.Cosmochim.Acta*, **57**, 1657-1680, 1993.

Bischoff, J.L., and R.J. Rosenbauer, Salinity variations in submarine hydrothermal system by layered double-diffusive convection, *J.Geol.*, **97**, 613–623, 1989.

von Damm,K.L., Controls on the chemistry and temporal variability of seafloor hydrothermal fluids, *in Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions, Geophys.Monogr.Ser.*, **91**(Eds. S.E.Humphris et al.), 222-247, AGU, Washington,D.C., 1995.

Kelley,D.S., and P.T.Robinson, and J.G.Malpas, Process of brine generation and circulation in the oceanic crust: Fluid inclusion evidence from the Troodos Ophiolite, Cyprus, *J.Geophys.Res.*, **97**, 9307-9322, 1992.

Pitzer,K.S., J.C.Peiper and R.H.Busey, Thermodynamic properities of aqueous sodium chroride solutions, *J.Phys.Chem.Ref.Data*, **13**, 1-102, 1984.

Reithby,G.D., Skew upstream differencing schemes for problems involving fluid flow, *Comput.Methods in Appl.Mech. and Engng.*, **9**, 153-164, 1976.

Tanger,J.C., and K.S.Pitzer, Thermodynamics of NaCl-H_2O: A new equation of state for the near-critical region and comparisons with other equations for adjoining regions, *Geochim. Cosmochim. Acta*, **53**, 973-987, 1989.

Wilcock, W.S.D., Celluler convection models of mid-ocean ridge hydrothermal circulation and the temperatures of black smoker fluids, *J. Geophys. Res.*, **103**, 2585-2596, 1998.