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 settles to form a stagnant lower layer.

1 Introduction

At mid-ocean ridges, seawater sinks through cracks of oceanic crusts and exits near the ridges driven by the heat of cooling magma chambers lying underneath, forming 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 are the result of the heat transport and chemical reaction, which are in turn determined by the circulation structure.

Phase separation of seawater has been suggested as a major controlling factor of the circulation structure (Bishoff and Rosenbauer, 1989). It is particularly important around the ridge axis, where the underlying magma chambers heats seawater above the critical point. The phase separation generates fluids with Cl^- concentrations higher and lower than that of seawater. It leads to the change of Cl^- concentration of hydrothermal fluid. One of the evidence of the phase separation is the diversity of Cl^- concentrations of hydrothermal vent water (e.g. von Damm, 1995).

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 envisage 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 as a two-dimensional homogeneous porous media. The pore space is saturated with NaCl-H_2O two-component fluid. The phase diagram of the system is obtained from Pitzer et al.(1984) and Anderko and Pitzer(1993).

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

The mass conservation equation of Bousinnesq fluid is written as

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

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

The momentum conservation of 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, κ is the thermal diffusitivity of the fluid phase.

The material conservation are 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 wt%), C_l is the composition of the liquid phase, C_v is the composition of the vapor phase, and D is the coefficient of compositional diffusion. The liquid and vapor composition is obtained from the table.

In the equation (5), we assume chemical equillibrium is realized between the two phases so that we directry obtain the composition of two phases. And we assume that the less mass fraction phase has a shape of sphere which radius is a parameter. For the example, when the liquid mass fraction is more than 0.5, the vapor phase has a shape of sphere and the liquid phase is continuous,

We assume that the relative flux between the two phases obey the 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 a is the radius of the droplets.

We treat the seafloor as a free boundary(Wilcock,1998). The fluid can flows in/out through the boundary. When the fluid flows into the oceanic crust, the fluid has the seawater temperature and composition. And when the fluid flows out the system, the fluid remains the temperature and composition. And the bottom boundary is constant temperature and impermeable.

The calculations are started from initial state of no-flow, heat conduction, and constant composition, and are succeeded to the steady state. The main parameters of the calculations are the radius of the fluid sphere and the radius of the pore space. We calculate through wide ranges of these parameters.

3 Results and Discussion

We find that the mid-ocean ridge hydrothermal circulation has two-layered structure(Fig.1,3), which is contrasted with a traditional view without phase separation(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 stable density stratification, which prevents convection. The upper circultaion layer has Cl^- concentrations almost the same as that of seawater.

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 outflow fluid is close to the phase separation temperature of seawater.

The composition of 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. When the mean flow is domimnant, the composition of the outflow is almost same with that of seawater. When the relative motion is domimnant, fluids with compositions both higher and lower than that of seawater flow out of the seafloor.

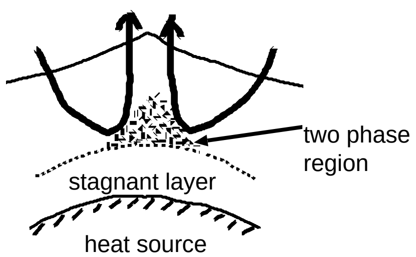

Fig. 1. A new picture of mid-ocean ridge hydrothermal circulation. The circulation is prevented from penetrating into the heat source area due to the formation of the stagnant layer.

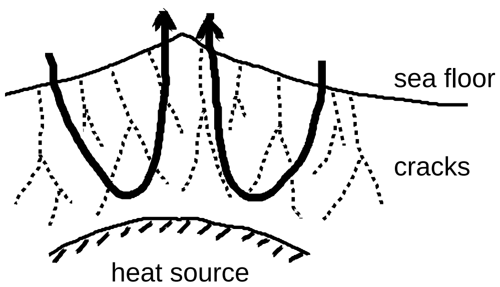

Fig. 2. A traditional picture of mid-ocean ridge hydrothermal circulation (no phase separation).

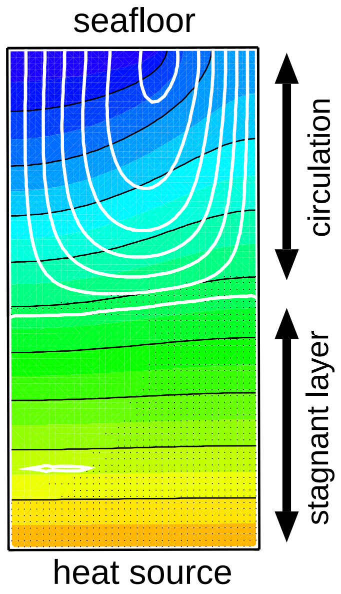

Fig. 3. A typical result of this work. The white thick lines are the streamlines. These lines do not penetrate into the lower stagnant layer.

4 Reference

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