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The response of two-phase hydrothermal systems to changing magmatic heat input at mid-ocean ridges

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ABSTRACT

We develop numerical simulations of two-phase flow in a NaCl–H_2O fluid subject to time varying basal heat flux boundary conditions in order to understand the response of hydrothermal vent temperature and salinity to changing magmatic heat input. The results show that periodic changes in basal heat input on a time scale of several years will not be detected in a continuous time series record of temperature measurements. Fluctuations in vent salinity may be recorded, however. For models with monotonic decay of the magmatic heat flux, a decline in vent temperature may not be observed for several years; however, once single phase conditions are established at the base of the system, a pulse of brine-derived fluid is expected to appear at the surface, followed by a gradual decline of salinity to the seawater value. The pulse of brine salinity is expected to occur before an observed decline in vent temperature. Observed rapid changes in vent temperature and salinity associated with either eruptive or non-eruptive magmatic events are not likely a result of changes in basal heat flux.

1. Introduction

The linkage between the magmatic heat source and the overlying hydrothermal system at mid-ocean ridges is a subject of considerable scientific interest. As oceanic plates spread apart, upwelling mantle beneath the ridge undergoes decompressional melting, and melt is transported to a narrow zone of crustal formation. Seismic data shows that a zone of partially molten crust underlies a thin, mostly liquid lens of magma situated approximately 1–3 km beneath the seafloor (Detrick et al., 1987; Kent et al., 1990; Collier and Sinha, 1992; Singh et al., 2006; Jacobs et al., 2007; Van Ark et al., 2007; Carbotte et al., 2013). Heat transfer from the sub-axial magma lens (AMC) by conduction across a thin impermeable boundary layer drives the overlying hydrothermal system that discharges fluids with temperatures of ≈ 300–$400\,^{\circ}$C (e.g., Cann and Strens, 1982; Lowell and Germanovich, 1994, 2004). Replenishment of the magma lens, commonly called the AMC (axial magma chamber), may result in diking events and magmatic eruptions (Germanovich et al., 2011). Moreover, Liu and Lowell (2009) have shown that relatively frequent magma replenishment is needed to maintain the observed temperature and heat output on decadal time scales. A key question concerns the response of the hydrothermal system to changes in magmatic heat input. Hydrothermal responses to other perturbations such as earthquakes, diking events, and changes in permeability have been addressed elsewhere (e.g., Germanovich et al., 2011; Wilcock, 2004; Ramondenc et al., 2008; 2011; Singh and Lowell, 2015)

To investigate mass, heat, and solute transport in a mid-ocean ridge hydrothermal system, seawater is generally assumed to be equivalent to a 3.2 wt% NaCl–H_2O solution (Bischoff and Rosenbauer, 1984). At the pressure and temperature conditions encountered near the top of the AMC, such a fluid would typically be in the two-phase, liquid-vapor region of the NaCl–H_2O phase diagram. Fig. 1 shows the NaCl–H_2O phase diagram in P–T–X space. The highest point of the two-phase liquid-vapor region as a function of P–T–X is shown by the solid red line called the critical isotherm. This curve connects the locus of critical points, which change with P–T–X conditions. For seawater the critical point is at approximately 407 °C and 298 bars (Bischoff and Rosenbauer, 1988). The liquid–vapor equilibrium region lies beneath an isotherm below the critical point, and the salinity of the liquid and vapor in equilibrium at a given P–T are given by a horizontal tie line that intersects the vapor and liquid boundaries of the isotherm. High salinity liquid (commonly called brine) has a high density compared to bulk density, and thus it tends to remain at depth near the top of the AMC. Low salinity vapor is buoyant and tends to rise. This process is called phase separation. As low salinity vapor mixes with non-phase separated fluid during its ascent to the seafloor, it results in a fluid venting at the seafloor with salinity less than seawater. If some of the high salinity brine mixes with non-phase separated seawater and rises, the salinity of the resulting fluid exiting the seafloor is greater than seawater. Consequently, the

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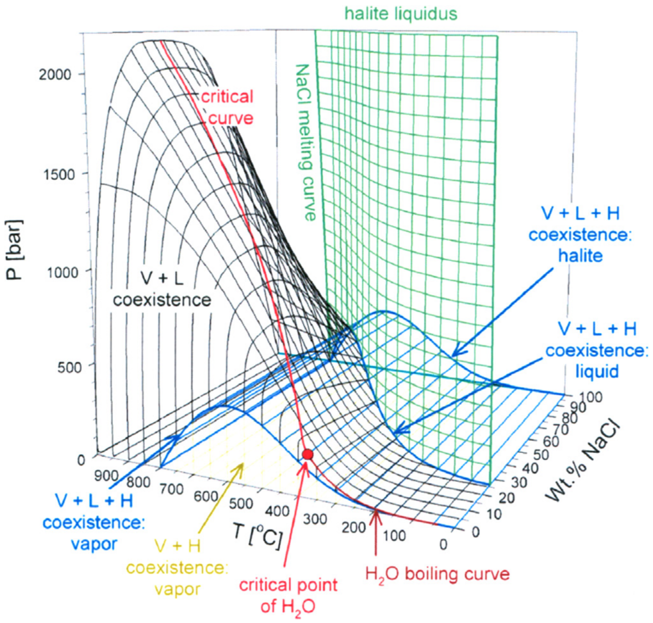

Fig. 1. Phase diagram for NaCl–H_2O (from Driesner and Heinrich, 2007).

salinity of vent fluids may vary with time and episodically vent vapor-derived and brine-derived fluids. A high-density layer at the base of hydrothermal system may act as a barrier between the overlying hydrothermal system and the magma chamber. In addition, diking events, whether eruptive or not, may result in phase separation in regions above the AMC. The salinity of a vent fluid phase separating at a shallow depth below the seafloor may be low shortly after a diking event, to be followed by a higher salinity fluid (Butterfield et al., 1997).

Models of two-phase flow in NaCl–H_2O fluids have only been developed recently (e.g., Bai et al., 2003; Kawada et al., 2004; Lewis and Lowell, 2004, 2009a, 2009b; Driesner and Geiger, 2007; Coumou et al., 2008a, 2008b, 2009a, 2009b; Han et al., 2013; Singh et al., 2013). These simulations assumed fixed temperature or constant heat flux at the base of hydrothermal system. The fixed temperature condition assumes that magma serves as an infinite reservoir of heat and hydrothermal heat transport is controlled by the vigor of the hydrothermal system, which is characterized by the Rayleigh number (e.g., Bejan, 1995; Lowell and Germanovich, 2004). Hydrothermal heat output in the presence of a constant heat flux condition, however, is controlled by the rate at which the heat is conducted from the magma body (e.g., Lowell and Germanovich, 1994, 2004). Neither of these boundary conditions is entirely realistic because heat transfer from a convecting magma body initially at its liquidus will result in cooling and crystallization leading to a decrease in heat output as a function of time (e.g., Cann and Strens, 1982; Liu and Lowell, 2009). Although Liu and Lowell (2009) considered heat transfer from a convecting, crystallizing, replenished magma chamber to the hydrothermal system, two-phase hydrothermal flow was not considered, and the hydrothermal system was assumed to respond instantly to changes in magmatic heat input. The principal objective of this study is to investigate the link between time dependent magmatic heat transfer and the evolution of vent temperature and salinity in a two-phase seafloor hydrothermal system.

In the next section of this paper, we present the mathematical formulation of the problem and discuss the basic features of the FISHES code. The results for a variety of time varying basal heat flux distributions are given in Section 3, and the implications of these results and main conclusions of this work are discussed in Section 4.

2. Mathematical formulation

2.1. The FISHES code

FISHES (Fully Implicit Seafloor Hydrothermal Event Simulator) is a FORTRAN code that uses the finite control volume method (Patankar, 1980) to solve the governing nonlinear partial differential equations for conservation of mass, momentum, energy, and salt in a Darcian porous medium in a NaCl–H_2O hydrothermal system (Lewis, 2007).

The mass continuity equation is written as follows:

$$\frac{\partial \phi\rho}{\partial t}+\nabla\cdot(\rho_v\vec{v}_v+\rho_l\vec{v}_l)=0 \tag{1}$$

where ϕ is the porosity, ρ is bulk density, $\vec{v}$ is the Darcian velocity, and t is the time; subscripts v and l refer to the vapor and liquid phases, respectively. Table 1 provides a list of symbols and values of pertinent parameters. Darcy's law is written for the vapor and liquid phases as follows:

$$\vec{v}_v=-\frac{kk_{rv}}{\mu_v}(\nabla P-\rho_v\vec{g}) \tag{2}$$

$$\vec{v}_l=-\frac{kk_{rl}}{\mu_l}(\nabla P-\rho_l\vec{g}) \tag{3}$$

where k is the permeability, k_r is the relative permeability, P is the pressure, μ is the dynamic viscosity, and $\vec{g}$ is the gravitational acceleration, respectively. FISHES describes the relative permeabilities for the vapor and liquid phases using a linear relation for the volume saturations of vapor and liquid, respectively, with residual saturations set equal to zero. The bulk density ρ is given by the following equation:

Table 1
List of parameters used in the equations, their definition, values, and units.

Symbol	Definition	Value	Units
a^*	Effective thermal diffusivity	10^{-6}	m^2/s
c	Specific heat	10^3	J/kg °C
d	Depth of the system	1500	m
D	Diffusivity of salt	10^{-9}	m^2/s
g	Acceleration due to gravity	9.8	m/s^2
h	Specific enthalpy		J/kg
H	Heat flux		W/m^2
k	Permeability	10^{-13}	m^2
P	Pressure		Nt/m^2
S	Volume saturation		
t	Time		s
T	Temperature		°C
v	Darcian velocity		m/s
X	Salinity		wt%
	Greek Symbols		
α	Thermal expansion coefficient	10^{-3}	1/°C
ϕ	Porosity	0.1	
λ_m	Thermal conductivity of the porous medium	2	W/m.C°
μ	Dynamic viscosity of fluid		Pa-s
ν	Kinematic viscosity of the fluid	10^{-7}	m^2/s
ρ	Bulk density of the fluid		kg/m^3
τ	Conductive time scale		s
ω	Angular frequency		s^{-1}
	Subscripts		
l	Liquid		
r	Rock		
v	Vapor		

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