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Earth and Planetary Science Letters 243 (2006) 657 – 668

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Suppression and stimulation of seafloor hydrothermal convection by exothermic mineral hydration

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Received 19 July 2005; received in revised form 8 January 2006; accepted 11 January 2006
Available online 23 February 2006
Editor: Scott King

Abstract

The effect of serpentinization on hydrothermal convection is explored using a dynamic 2D numerical model. Serpentinization is a highly exothermic mineral hydration process that consumes large quantities of water. The reaction is ubiquitous in the oceanic lithosphere and is generally associated with hydrothermal activity. Here, the thermal and hydration effects are incorporated into conservation equations describing fluid flow and heat transfer in hydrothermal systems. Models representing two different geological scenarios are explored. The "permeability-initiated" case simulates rapid uplift of ultramafic basement rock accompanied by rock fracturing, while the "temperature-initiated" scenario simulates the uplift of an ultramafic complex followed by a magmatic event at depth. In both models, simulations of convection with and without serpentinization demonstrate that mineral alteration can have an important effect on hydrothermal flow patterns and vent temperatures. Two parameters determine the impact of serpentinization on the system: (1) the basal temperature (T_b), and (2) the dimensionless Rayleigh number (*Ra*). At $Ra < 50$ and $T_b < 170$, peak temperatures were only slightly affected by serpentinization and convection was initially suppressed due to the downward flow of water induced by the hydration reaction. At higher Rayleigh numbers and basal temperatures, serpentinization effectively stimulated the onset of convection and significantly affected transient vent temperatures; differences in peak vent temperatures between the standard convective case and that with serpentinization were found to be as high as 170 °C. Thus, together with the geothermal heat flux, serpentinization could act to control temperatures at seafloor hydrothermal sites.

Keywords: serpentinization; reaction model; mid-ocean ridges; Lost City

1. Introduction

Serpentinization is a common mineral hydration process in which olivine and pyroxene minerals in mafic and ultramafic rocks undergo hydration to serpentine and other alteration products. As well as being a highly exothermic process, releasing about 290 kJ of heat per kg of olivine, large quantities of water are also consumed during the reaction [1]. Serpentinized rocks are often found near mid-ocean ridges, and their abundance in these settings is typically associated with hydrothermal activity.

Much of the oceanic crust consists of sediment overlying volcanic basalt and sheeted dikes that in turn cover gabbroic basement rock. However, in some instances, peridotite from the upper mantle is exposed at the ocean floor by low-angle faulting [2]. High temperature hydrothermal systems hosted by peridotite

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doi:10.1016/j.epsl.2006.01.028

basement, such as the Rainbow and Logachev sites, have been known for some time [3]. More recently, a hydrothermal site hosted by peridotite and venting at low temperatures (40–75 °C) was identified at the Atlantis Massif near the Atlantic Mid-Ocean Ridge [4]. The high pH, high Mg concentrations, and the presence of serpentinized rocks dredged from the ocean floor suggest that serpentinization strongly affects the chemistry of vent fluids and it has even been proposed that mineral hydration itself could represent the main heat source driving the system [4–7].

Although it is tempting to attribute the heat source of the "Lost City" system to serpentinization, low temperature venting will occur in off-axis lithosphere even without the heat from mineral hydration, provided a sufficiently permeable crust and a high temperature gradient exist. Thus, rather than determining whether or not mineral alteration is capable of driving hydrothermal flow, it is more useful to examine how mineral alteration will impact more conventional hydrothermal convection.

To assess the influence of serpentinization, Lowell and Rona [6] used a heat balance model to demonstrate that heat released from hydration reactions can result in hydrothermal venting temperatures ranging from a few degrees Celsius to 300 °C depending on the heat input from below, the fluid flow rate, and the rate of serpentinization. More recently, calculations based on batch water–rock interaction ratios and equilibrium thermodynamics suggest that vent temperatures are raised only minimally by chemical alteration [8]. While such calculations provide an estimate of how average vent temperatures may be elevated, the coupled nature of flow and reaction kinetics requires an integrated multi-dimensional approach to predict the temporal and spatial changes occurring in these systems.

Recent numerical models of reactive hydrothermal flow at mid-ocean ridges have explored the influence of mineralization on the permeability of the porous matrix [9–11], but the effect of exothermal reactions, such as serpentinization, has yet to be examined. Here, dynamic conservation equations are used to explore how hydrothermal systems are affected by two processes associated with serpentinization: (1) heat production resulting from the enthalpy of reaction and (2) water consumption during mineral alteration. More specifically, the objective of the study is to assess the impact of these processes on vent temperatures and hydrothermal flow patterns. An idealized 2D system initiated by a conventional heat source is considered and simulations with and without mineral hydration are run over a range of physical parameters. Implications of the model results for the "Lost City" vents and other hydrothermal systems are also explored.

2. Methodology

2.1. Rate of serpentinization

To incorporate the effects of serpentinization into a dynamic model, the reaction rate must first be expressed in a functional form that can be used with conservation equations. Detailed in this section is the transformation of previously reported data concerning the rate of serpentinization into such a form.

The serpentinization of forsterite, the dominant form of olivine in many ultramafic rocks, is initiated at around 100 °C and reaches a peak at ~270 °C [12]. Above this temperature, the reaction exhibits retrograde kinetics, and mineral alteration effectively stops at temperatures greater than 400 °C. Expressing the reaction rate in functional form is complicated by the reaction mechanism of hydration. As has been pointed out in previous studies [1,12], once the alteration products have formed on the primary mineral surfaces, the reaction rate is effectively limited by the diffusion of water through the serpentine minerals to the reactive surface of the forsterite mineral. Here, it is proposed that the rate of alteration per unit volume (expressed in terms of the mass of forsterite per unit volume, ρ_m) is dependent on the reactive area of mineral per unit volume. Thus, the expression

$$\partial \rho_m / \partial t = -k_r S_v \tag{1}$$

can be used to represent the rate of serpentinization, where k_r is the area normalized rate coefficient and S_v is the reactive surface area of forsterite per unit volume of rock (see Table 1 for a summary of notation and parameter values).The S_v parameter is equivalent to the product of the surface area per unit mass of forsterite (S_m) and ρ_m, and as a first order approximation, S_m is assumed here to be constant throughout serpentinization. This approximation allows the rate law to be redefined as

$$\partial \rho_m / \partial t = -K_r \rho_m, \tag{2}$$

where $K_r = k_r S_m$.

Available kinetic data at different temperatures [12] suggest that the rate coefficient can be represented by a bell curve, and here an empirical function of the form $K_r = A e^{-b(T-c)^2}$ is adopted, where T is the absolute temperature. In this formulation, the b coefficient