Deep-Sea Research II ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Thermal response of mid-ocean ridge hydrothermal systems to perturbations

Shreya Singh, Robert P. Lowell

Department of Geosciences, Virginia Tech University, Blacksburg, VA 24060, United States

ARTICLE INFO

Keywords:
Hydrothermal systems
Diking
East Pacific Rise
Main Endeavour Field
Perturbation
Single-pass model
1-D model

ABSTRACT

Mid-ocean ridges are subject to episodic disturbances in the form of magmatic intrusions and earthquakes. Following these events, the temperature of associated hydrothermal vent fluids is observed to increase within a few days. In this paper, we aim to understand the rapid thermal response of hydrothermal systems to such disturbances. We construct a classic single-pass numerical model and use the examples of the 1995 and 1999 non-eruptive events at East Pacific Rise (EPR) 9°50′N and Main Endeavour Field (MEF), respectively. We model both the thermal effects of dikes and permeability changes that might be attributed to diking and/or earthquake swarms. We find that the rapid response of vent temperatures results from steep thermal gradients close to the surface. When the perturbations are accompanied by an increase in permeability, the response on the surface is further enhanced. For EPR9°50′N, the observed ~7 °C rise can be obtained for a ~50% increase in permeability in the diking zone. The mass flow rate increases as a result of change in permeability deeper in the system, and, therefore, the amount of hot fluid in the diffused flow also increases. Using a thermal energy balance, we show that the ~10 °C increase in diffuse flow temperatures recorded for MEF after the 1999 event may result from a 3–4 times increase in permeability. The rapid thermal response of the system resulting from a change in permeability also occurs for cases in which there is no additional heat input, indicating that hydrothermal systems may respond similarly to purely seismic and non-eruptive magmatic events.

1. Introduction

Hydrothermal systems essentially consist of a heat source and a fluid circulation system. For high-temperature hydrothermal systems at oceanic spreading centers, the heat comes primarily from the emplacement of magma bodies in the shallow crust. The circulating fluid is mainly seawater, with some input of magmatic volatiles. In the simplest scenario, seawater enters the crust through faults and fractures and descends along permeable pathways to near the top of the magma body where it reaches temperatures exceeding 400 °C (Kelley et al., 2012). The heated fluid then ascends through other permeable faults or fracture zones and emerges at the seafloor as mineral-rich "black smoker" vents. The temperature and composition of fluids collected at some of these vents may remain quasi-steady over months or even years (e.g., Bio9 vent, East Pacific Rise (EPR) 9°50′N (Von Damm, 2004), Main Endeavour Field (MEF), (Lilley et al., 2003).

Hydrothermal venting is intimately linked to the dynamic process of crustal accretion, and therefore, from time to time, the output of such systems is affected by perturbations. Crustal accretion at mid-ocean ridges is a complex process which, in the simplest scenario, is a diking event (e.g., Delaney et al., 1998), where magma is emplaced as a longitudinal intrusion into the overlying oceanic crust. Dikes are often detected due to an increase in seismicity in their vicinity. Such intrusions add localized heat to the system, and the changes in the near-field stress distribution may result in permeability changes that affect the circulation of the hydrothermal fluids (Craft et al., 2014). Both these factors lead to an increase in the output of the hydrothermal system resulting in changes to the temperature and salinity of the vent fluids. For small non-eruptive diking events, the hydrothermal system may return to its original or slightly altered pre-event state [e.g., EPR 9°50′N, Fornari et al., 1998]; however, in some cases, such perturbations may indicate a complete change in the thermal-fluid regime of the vent field and lead to permanent changes (e.g., MEF, Kelley et al., 2012). Additionally such events result in a change in seafloor fauna and vent chemistry (Shank et al., 1998; Lilley et al., 2003; Seyfried et al., 2004).

Since new oceanic crust is formed by episodic magmatic activity, mid-ocean ridge hydrothermal systems are often subject to these disturbances. However, due to the scarcity of in-situ data at vent fields, very few of these events have been monitored in real time. As these events provide us special insight into the physical, chemical and biological processes at vent fields, it is important to utilize the

http://dx.doi.org/10.1016/j.dsr2.2015.05.008
0967-0645/

available data to better understand how hydrothermal systems respond to magmatic and tectonic perturbations. In this paper, we construct relatively simple yet effective numerical models of a vent field for the purpose of understanding its response to small-scale disturbances. We construct a quasi-one-dimensional single-pass numerical model and use the examples of EPR 9°50′N and MEF 47°57′N, two vent fields that experienced non-eruptive diking in years 1995 and 1999, respectively, to test the model.

Sections 2 and 3 briefly describe the nature of non-eruptive events at EPR 9°50′N and MEF and the previous attempts made in order to understand the propagation of perturbations. Sections 4 and 5 entail the model and parameterization chosen to represent the EPR and MEF vent fields. The model is tested for various scenarios for both fields and the results are reported in Section 6. Section 7 contains the interpretation of the results, implications of using a simplified model and limitations of the model.

2. Response of hydrothermal systems to perturbations at mid-ocean ridges

In March 1995, an array of nine ocean-bottom seismometers deployed on the EPR detected a total of 283 microearthquakes situated north of the 9°50′N area and close to Bio9 and P vents (Sohn et al., 1999). Based on the hypocentral pattern, Sohn et al. (1999) considered a diking event unlikely and attributed the microearthquake activity to the release of thermal stresses at the base of the hydrothermal system. However, Ramondenc et al. (2008) and Germanovich et al. (2011) argue that the March 1995 seismic activity at 9°50′N could have resulted from a non-eruptive diking event. Germanovich et al. (2011) use numerical models to show that the dike is likely to propagate sub-vertically from the margins of the thin, lens-like magma chamber, which is characteristic of the magma chamber present below EPR. Using their model for dike propagation and hydrothermal circulation, they provide mechanical as well as hydrothermal evidence to suggest that the 1995 event was a diking event caused by magma replenishment between major eruption episodes in 1991/1992 (Sohn et al., 1998) and 2005/2006 at EPR 9°50′N (Fornari et al., 2012).

A similar period of elevated seismic activity was observed in June 1999 for the Endeavour Segment (Johnson et al., 2000; Lilley et al., 2003) in which the MEF was affected most strongly (Kelley et al., 2012). The activity lasted 5–11 days and spanned the along-axis region above the magma chamber (Johnson et al., 2000). Initially, this event was thought to be of tectonic origin (Johnson et al., 2000); however, the 1999 event also caused dramatic increases in CO_2 and H_2 concentrations in the vent fluids (Lilley et al., 2003). As these observations indicated high-temperature water/rock reactions, Lilley et al. (2003) argued that the chemical data from the hydrothermal fluids collected in September 1999 and June 2000 was more consistent with a magmatic event. Bohnenstiehl et al. (2004) showed that the seismic activity migrated southward 12 km along-axis at a rate of 1.1 km/h, thus indicating that the seismicity was the result of a lateral dike injection.

At the EPR, the temperature data collected by Sohn et al. (1998) for the Bio9 vent showed that vent temperature was stable for approximately 15 months prior to the March 1995 event at ~365 °C. After the March 22 event, the vent temperature increased by 7 °C over 8 days (Fig. 1), and gradually returned to normal after several months. Similarly at the MEF, temperatures had remained stable for nearly 10 months prior to the earthquakes after which Johnson et al. (2000) observed a temperature rise up to ~10 °C in the diffuse flow sites approximately 4–11 days after the first event on June 8, 1999 (Fig. 2). Many high temperature

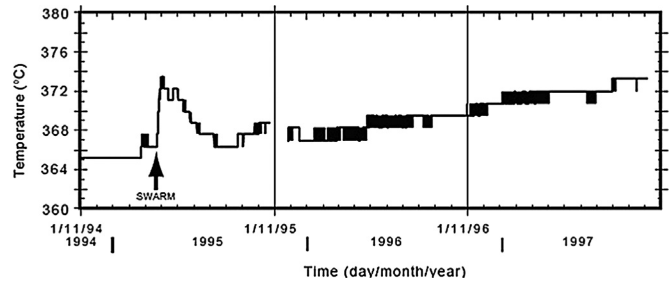

Fig. 1. Thermal response of the Bio9 vent at East Pacific Rise 9°50′N (from Sohn et al., 1998).

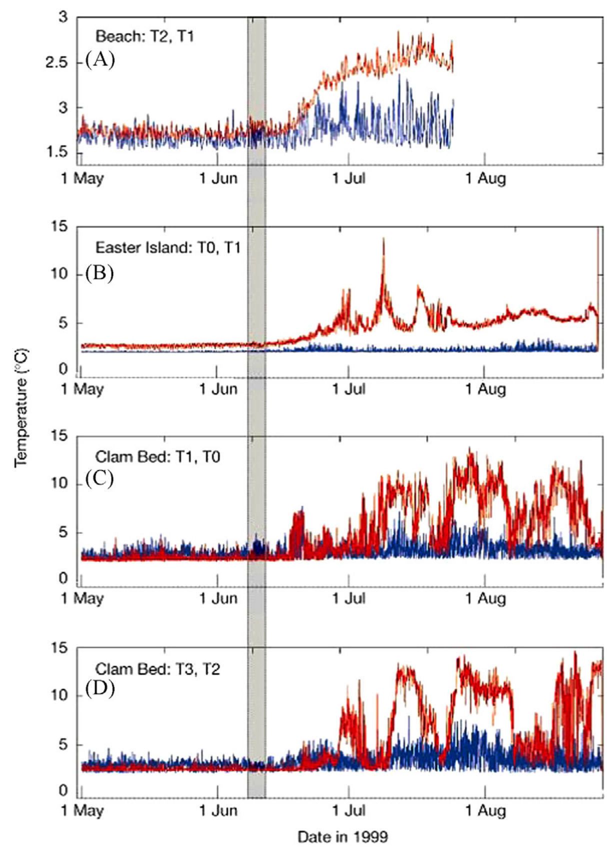

Fig. 2. Temperature data from the three Endeavour axial valley sites. Red traces, data from thermistors located within hydrothermal fluids from vents; blue traces, data from thermistors deployed in the adjacent (non-vent) bottom water at each site. (A) Data from the bio-column thermistors at the Beach site, located in a diffuse vent within a sediment pond 200 m south of the MEF. The earthquake activity (8 ± 15 June 1999) is marked by the vertical shaded bar. Note that the temperature scale for this site is different from the other three sites shown. (B) Temperatures from the EI/MEF site, showing the slow temperature rise after the 8 June event. (C) Data from one of the Clam Bed thermistor pairs, near the High Rise vent field. (D) Temperature data from the Clam Bed site, located only a few tens of meters from those in C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vents within the MEF increased by 15 °C and some vents emitted fluids that were nearly fresh (Lilley et al., 2003; Kelley et al., 2012).

The examples listed above illustrate that seafloor hydrothermal systems are sensitive to diking events and that the temperature response is quite rapid. This is in sharp contrast with numerical models of two-phase flow in porous media subject to changes in basal heat flux (Singh et al., 2013; Choi and Lowell, 2014), in which the temperature response is strongly damped and may not be manifest for months or years after the event. Hence, the nature of the response of these vent fields to diking events might provide new insights into magma-hydrothermal processes on the seafloor.

Please cite this article as: Singh, S., Lowell, R.P., Thermal response of mid-ocean ridge hydrothermal systems to perturbations. Deep-Sea Res. II (2015), http://dx.doi.org/10.1016/j.dsr2.2015.05.008