Earth and Planetary Science Letters 501 (2018) 138–151

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Three-dimensional models of hydrothermal circulation through a seamount network on fast-spreading crust

Rachel M. Lauer [a,b,c,*], Andrew T. Fisher [b,c], Dustin M. Winslow [b,c,d]

[a] Department of Geoscience, University of Calgary, Calgary, Alberta, Canada
[b] Earth and Planetary Sciences Department, University of California, Santa Cruz, 95064, USA
[c] Center for Dark Energy Biosphere Investigations, University of California, Santa Cruz, 95064, USA
[d] GrowthIntel, 25-27 Horsell Road, London N5 1XL, UK

ARTICLE INFO

Article history:
Received 25 February 2018
Received in revised form 17 July 2018
Accepted 14 August 2018
Available online xxxx
Editor: M. Bickle

Keywords:
hydrothermal circulation
ridge flank
low-temperature
coupled modeling

ABSTRACT

We present results from three-dimensional, transient, fully coupled simulations of fluid and heat transport on a ridge flank in fast-spread ocean crust. The simulations quantify relationships between rates of fluid flow, the extent of advective heat extraction, the geometry of crustal aquifers and outcrops, and crustal hydrologic parameters, with the goal of simulating conditions similar to those seen on 18–24 M.y. old seafloor of the Cocos plate, offshore Costa Rica. Extensive surveys of this region documented a $\sim$14,500 km^2 area of the seafloor with heat flux values that are 10–35% of those predicted from conductive cooling models, and identified basement outcrops that serve as pathways for hydrothermal circulation via recharge of bottom water and discharge of cool hydrothermal fluid. Simulations suggest that in order for rapid hydrothermal circulation to achieve observed seafloor heat flux values, upper crustal permeability is likely to be $\sim 10^{-10}$ to 10^{-9} m^2, with more simulations matching observations at the upper end of this range. These permeabilities are at the upper end of values measured in boreholes elsewhere in the volcanic ocean crust, and higher than inferred from three-dimensional modeling of another ridge-flank field site where there is less fluid flow and lower advective power output. The simulations also show that, in a region with high crustal permeability and variable sized outcrops, hydrothermal outcrop-to-outcrop circulation is likely to constitute a small fraction of total fluid circulation, with most of fluid flow occurring locally through individual outcrops that both recharge and discharge hydrothermal fluid.

1. Introduction: ridge-flank hydrothermal circulation through outcrops

Seamounts and basement outcrops are common features of the global ocean floor (Hillier and Watts, 2007; Wessel et al., 2010) and can influence hydrothermal circulation in the volcanic ocean crust (Anderson et al., 2012; Davis et al., 1992; Fisher et al., 2003a; Fisher and Wheat, 2010; Hutnak et al., 2006; Villinger et al., 2002; Winslow and Fisher, 2015). The volcanic ocean crust on the flanks of mid ocean ridges is commonly blanketed by low-permeability sediment that limits direct fluid exchange between the ocean and underlying crustal aquifer (Fisher and Wheat, 2010; Spinelli et al., 2004). Seamounts form pathways for fluids to enter and exit the seafloor, bypassing the sedimentary boundary layer, (e.g., Davis et al., 1992; Fisher et al., 2003b; Stein and Fisher, 2003; Wheat and Fisher, 2008; Wheat et al., 2013). Subseafloor hydrothermal circulation is responsible for $\sim$15–25% of global heat loss (Hasterock et al., 2013; Mottl, 2003; Stein and Stein, 1994), and influences the thermal and geochemical state of subducting plates, the formation and sustainability of the deep biosphere, and the geochemical evolution of the oceans (e.g., Edwards et al., 2012; Spinelli and Wang, 2008; Wheat and Mottl, 2004).

Based on analyses of satellite gravimetric data, bathymetric (swath) maps and ship-based profile data, the global seamount population is 10^4–10^5 (Kim and Wessel, 2011; Wessel et al., 2010). Most seamount locations are poorly known because they are too small (height <1 km and/or diameter <3.5 km) for identification by satellite. Some field studies have explored the roles of seamounts in facilitating heat loss on ridge flanks (e.g., Fisher et al., 2003a, 2003b; Hutnak et al., 2006; Villinger et al., 2002), and modeling studies have examined the influence of single- and multiple-

* Corresponding author at: Department of Geoscience, University of Calgary, Calgary, Alberta, Canada.
E-mail address: rachel.lauer@ucalgary.ca (R.M. Lauer).

https://doi.org/10.1016/j.epsl.2018.08.025
0012-821X/

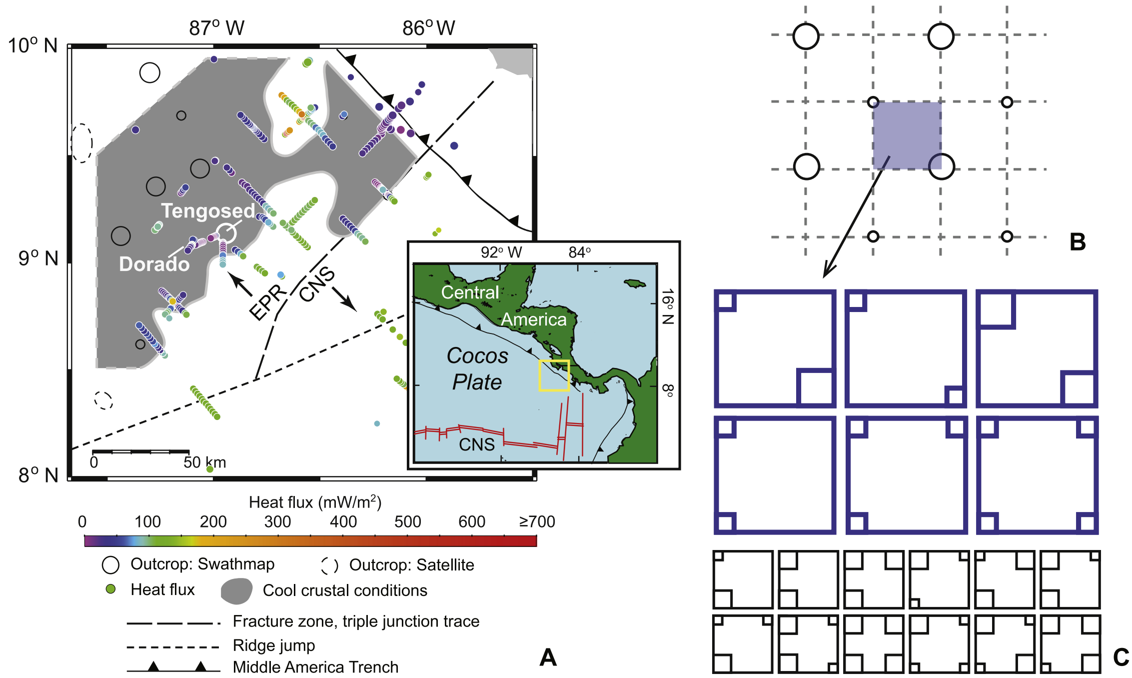

Fig. 1. Maps and cartoons illustrating field site and simulation approach. (A) Regional map showing the general location of study area (inset), and cool part of the Cocos Plate, shaded gray area (modified from Hutnak et al., 2008). This 14,500-km^2 region of ∼18–24 Ma seafloor formed at the fast-spreading East Pacific Rise, and containing 11 mapped outcrops (black circles), has seafloor heat flux that is just 10–35% of lithospheric values. (B) Modeling conceptualization of an outcrop network, with highlighted area representing a single simulation domain having one small and one large outcrop located at the corners. (C) Summary of potential grid configurations based on having two, three, and four outcrops at the corner of the rectangular domains, with two outcrop sizes (small, large). The simulated outcrops comprise 1/4 of actual outcrop size, based on symmetry of the domain with respect to an outcrop network. The six outcrop configurations included in the current study are highlighted in thick, blue lines.

outcrop geometries (e.g., Anderson et al., 2012; Harris et al., 2004; Hutnak et al., 2006; Kawada et al., 2011; Winslow and Fisher, 2015).

Ridge-flank hydrothermal circulation between recharging and discharging seamounts is driven by the pressure difference between cool (descending) and warm (ascending) columns of crustal fluids, forming a "hydrothermal siphon" (Fisher et al., 2003a; Fisher and Wheat, 2010). There are two regions where hydrothermal circulation influenced by seamounts has been studied especially intensively: the eastern flank of the Juan de Fuca Ridge (JFR, central Juan de Fuca Plate, summarized briefly in this section), and the eastern flank the East Pacific Rise (EPR, eastern Cocos Plate, the focus of this paper, described in the next section). Thick sediments cover young basement rocks across much of the first region because of rapid Pleistocene sedimentation and trapping of sediment by abyssal hill topography (Davis et al., 1992; Underwood et al., 2005). Detailed studies have focused on ∼3–4 Ma seafloor located 90–110 km east of the JFR, where isolated volcanic outcrops penetrate the sediment, several of which are known sites of hydrothermal discharge and recharge (Davis et al., 1992; Fisher et al., 2003a; Hutnak et al., 2006; Wheat et al., 2000).

The best-studied discharge site in this area is Baby Bare outcrop, the tip of a volcanic edifice from which ∼5–20 L/s of low-temperature (∼25 °C) hydrothermal fluids flow (Mottl et al., 1998; Thomson et al., 1995; Wheat et al., 2004). Baby Bare fluids are highly altered following reaction with basement rocks at ∼60–65 °C. These fluids recharge through Grizzly Bare outcrop, a much larger edifice located 52 km south-southwest (e.g., Fisher et al., 2003a; Hutnak et al., 2006; Wheat et al., 2013; Wheat and Mottl, 2000). Numerical simulations of outcrop-to-outcrop hydrothermal circulation in this setting suggested that the volcanic crustal aquifer is relatively thin (≲300 m) and has permeability on the order of 10^{-13} to 10^{-12} m^2 (Winslow et al., 2016). These models also showed that recharge is favored through larger outcrops and discharge is favored through smaller outcrops. There is presently no regional, seafloor heat-flux deficit caused by the circulation of hydrothermal fluids from Grizzly Bare to Baby Bare, because the fluid flow rate is low and little heat is extracted advectively (Fisher et al., 2003a; Hutnak et al., 2006). There were more basement outcrops in this region, and likely more vigorous hydrothermal circulation, when sediment cover was thinner and less complete (Hutnak and Fisher, 2007).

In this study, we focus on a contrasting hydrothermal system, located on ∼18–24 Ma seafloor of the Cocos Plate (Fig. 1). The physical geometry of outcrop-to-outcrop hydrothermal circulation in this area is similar to that around Grizzly Bare and Baby Bare, but the systems are different in terms of fluid flow rates, the efficiency of lithospheric heat extraction, and the properties of the volcanic crust.

2. Advective heat loss from the western Cocos Plate

This study was motivated by extensive seismic reflection profiles, swath mapping, coring, and heat flux surveys made on 18–24 Ma seafloor offshore of Costa Rica, eastern Equatorial Pacific Ocean (Fig. 1) (Fisher et al., 2003b; Hutnak et al., 2007). This part of the Cocos Plate comprises lithosphere generated by the fast spreading East Pacific Rise (EPR) and the intermediate spreading Cocos Nazca Spreading Center (CNS) (Barckhausen et al., 2001). CNS-generated seafloor has heat flow that is consistent (on average) with conductive lithospheric cooling models. In contrast, part of the EPR-generated seafloor, having an area of 14,500 km^2, has heat flux that is 10–35% of predictions from conductive lithospheric cooling models, a regional deficit of 1.0–1.5 GW (Hutnak et al., 2008). Both of these areas (warmer and cooler) exhibit anomalous heat flux values compared to global means for 18–24 Ma seafloor, which tends to have a heat flux that is 40–90% of conductive predictions (e.g., Hasterock, 2013; Stein and Stein, 1994).