Earth and Planetary Science Letters 450 (2016) 355–365

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Cross-hole tracer experiment reveals rapid fluid flow and low effective porosity in the upper oceanic crust

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ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 21 June 2016
Accepted 25 June 2016
Available online 13 July 2016
Editor: M. Bickle

Keywords:
hydrothermal circulation
borehole observatory
tracer injection experiment
ocean crustal properties
Juan de Fuca Ridge flank
abyssal hills

ABSTRACT

Numerous field, laboratory, and modeling studies have explored the flows of fluid, heat, and solutes during seafloor hydrothermal circulation, but it has been challenging to determine transport rates and flow directions within natural systems. Here we present results from the first cross-hole tracer experiment in the upper oceanic crust, using four subseafloor borehole observatories equipped with autonomous samplers to track the transport of a dissolved tracer (sulfur hexafluoride, SF_6) injected into a ridge-flank hydrothermal system. During the first three years after tracer injection, SF_6 was transported both north and south through the basaltic aquifer. The observed tracer transport rate of ~2–3 m/day is orders of magnitude greater than bulk rates of flow inferred from thermal and chemical observations and calculated with coupled fluid-heat flow simulations. Taken together, these results suggest that the effective porosity of the upper volcanic crust through which much tracer was transported is <1%, with fluid flowing rapidly along a few well-connected channels. This is consistent with the heterogeneous (layered, faulted, and/or fractured) nature of the volcanic upper oceanic crust.

1. Introduction and setting

Hydrothermal circulation through the oceanic crust extracts ~20% of Earth's lithospheric heat and ~30% of the heat lost from oceanic lithosphere (Stein and Stein, 1992), cycles the volume of the ocean through the seafloor every 10^5 to 10^6 yr (Johnson and Pruis, 2003), transfers organic and inorganic solutes between the subseafloor and ocean (Alt, 2003), and helps to support a deep biosphere (Edwards et al., 2011). Many studies have assessed hydrothermal systems on or near seafloor spreading centers and other areas of active volcanism, where the intrusion and eruption of magma generates enormous thermal, pressure, and chemical gradients, driving the focused discharge of hot (>250 °C) fluids from seafloor vents (Spiess et al., 1981). Globally, much larger volumes of fluid circulate at lower temperatures through the crust of ridge flanks (Wheat and Mottl, 2004), far from the direct magmatic and tectonic influence of lithospheric creation. These ridge-flank hydrothermal systems are driven primarily by upward heat transport from the underlying lithosphere (Stein and Stein, 1992; Johnson and Pruis, 2003). Despite the importance of coupled flows within all of these crustal systems, the nature of fluid pathways and rates of transport remain poorly understood.

Natural tracers such as heat, major ion concentrations, radiocarbon, and stable isotopes from sedimentary and crustal pore fluids have been used to assess rates and patterns of hydrothermal fluid flow through oceanic ridge flanks (Baker et al., 1991; Davis et al., 1992b; Hutnak et al., 2008; Wheat et al., 2000, 2004; Williams et al., 1979). The spatial distributions of natural tracers have also been used to constrain analytical and numerical models of coupled (fluid-heat, fluid-solute) transport (Fisher et al., 2003; Langseth and Herman, 1981; Stein and Fisher, 2003; Wheat and Fisher, 2007). In addition, tracers have been introduced into sealed crustal boreholes to calculate fluid exchange with the surrounding volcanic rocks (Wheat et al., 2010).

Multi-hole tracer injection experiments have not previously been conducted in the oceanic crust, but this approach has a long history of application on land (e.g., Becker and Shapiro, 2000; Clark et al., 2004; Tsang et al., 1991), allowing assessment of transport rates through an aquifer, the nature of transport pathways, and hydrogeologic properties such as the effective porosity (the fraction of rock through which most flow and transport occurs).

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http://dx.doi.org/10.1016/j.epsl.2016.06.048
0012-821X/

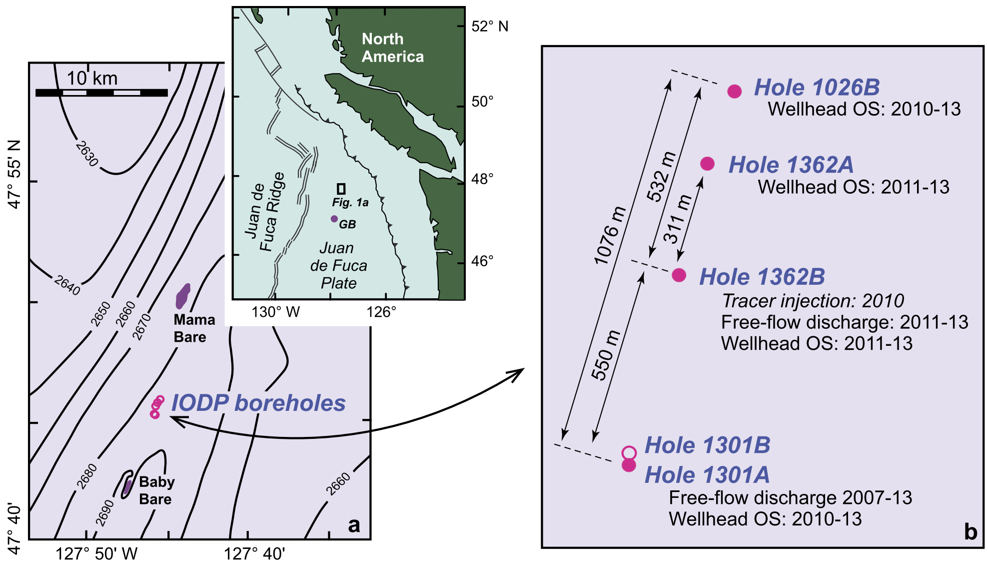

Fig. 1. Site Maps. (a) Map of region surrounding experimental boreholes (Expedition 301 Scientists, 2005; Expedition 327 Scientists, 2011a; Shipboard Scientific Party, 1997) on the eastern flank of the Juan de Fuca Ridge. Inset index map shows location of Grizzly Bare outcrop (purple dot, "GB"), a known site of hydrothermal recharge (Wheat et al., 2000; Fisher et al., 2003; Hutnak et al., 2006). (b) Detail map showing distances between boreholes and timing for key tracer test operations described in the main text and Table 1.

We report initial results from the first cross-hole tracer injection experiment in the oceanic crust. This experiment was conducted on the eastern flank of the Juan de Fuca Ridge, using sulfur hexafluoride (SF_6) as the injected tracer, an array of sealed subseafloor borehole observatories (CORKs), and autonomous fluid sampling systems (OsmoSamplers) operating for several years (Fig. 1, Fisher et al., 2011a, 2005; Jannasch et al., 2004).

Ridge-flank volcanic basement terrain is dominated by elongated abyssal hills up-thrown by ridge-parallel normal faults that develop in young crust near the seafloor spreading axis in response to plate extension (Macdonald et al., 1996). In time, abyssal hills on ridge flanks are buried beneath accumulating sediments. Insulation provided by a thick cap of relatively impermeable sediment can increase the thermal gradient and enable large convective flow systems to develop within the underlying volcanic basement (Baker et al., 1991; Davis et al., 1992). On sediment-blanketed ridge flanks, seamount volcanoes or other volcanic basement outcrops that penetrate the sediment cap may provide pathways for fluid exchange with the overlying ocean (Davis et al., 1992b; Hutnak et al., 2008; Fisher et al., 2003; Thomson et al., 1995).

Hydrothermal circulation in volcanic crust in the area of the tracer experiment includes both outcrop-to-outcrop flow and local convection that homogenizes upper crustal temperatures (Davis et al., 1989, 1992b; Fisher et al., 2003; Hutnak et al., 2006; Winslow and Fisher, 2015; Winslow et al., 2016). Crustal boreholes with CORKs were installed on 3.5 M.y. old seafloor in this area, extending a lateral distance of 1 km along the crest of a sediment-buried abyssal hill (Fig. 1, Table 1) (Expedition 301 Scientists, 2005; Expedition 327 Scientists, 2011a; Shipboard Scientific Party, 1997). Although the boreholes are arrayed along a trend of N20E, subparallel to the Endeavor segment of the Juan de Fuca Ridge to the west, we refer for simplicity to directions "north" and "south" along this trend. The holes are located midway between two volcanic edifices (now magmatically inactive) that are known sites of ridge-flank hydrothermal discharge, Baby Bare and Mama Bare outcrops (Davis et al., 1992b; Wheat et al., 2000). The primary site of hydrothermal recharge for this system is thought to be Grizzly Bare outcrop, located 52 km to the south (Fig. 1, Wheat et al., 2000, 2013; Fisher et al., 2003; Hutnak et al., 2006; Winslow and Fisher, 2015).

2. Borehole and CORK configuration and history

2.1. Overview

Boreholes drilled into the volcanic oceanic crust are often cased through the sedimentary section to help maintain open-hole conditions, permitting greater access to crustal rocks below. CORKs were designed to allow the surrounding formation to a return to its predrilling state, and to facilitate long term monitoring, sampling and experiments (Davis et al., 1992; Wheat et al., 2011). A seafloor reentry cone guides the drillstring during multiple reentries, allowing a long sequence of drilling, coring, casing, downhole measurements, and CORK operations. Additional casing strings are deployed as part of CORK systems, facilitating installation of instruments and collection of data and samples from depth.

The holes used for the tracer experiment discussed in the present study were drilled during Ocean Drilling Program (ODP) Leg 168 ([Hole 1026B, Shipboard Scientific Party, 1997]), Integrated Ocean Drilling Program (IODP) Expedition 301 ([Hole 1301A, Expedition 301 Scientists, 2005]) and IODP Expedition 327 ([Holes 1362A and 1362B, Expedition 327 Scientists, 2011a]). CORK systems used for the tracer experiment were installed in these holes on IODP Expedition 301 ([Holes 1026B and 1301A, Fisher et al., 2005]) and IODP Expedition 327 ([Holes 1362A and 1362B, Fisher et al., 2011a]) (Fig. 2). These boreholes penetrate 236 to 265 m of turbidites and hemipelagic mud and extend 48 to 318 m into the underlying volcanic crust (Table 1, Expedition 301 Scientists, 2005; Expedition 327 Scientists, 2011a; Shipboard Scientific Party, 1997).

2.2. Hole 1026B

Hole 1026B was drilled during ODP Leg 168 with a 0.41-m outer diameter (OD) casing attached to a reentry cone, and completed to basement with 0.27-m OD casing (Fig. 2). The deepest part of the hole extended ~48 m sub-basement (msb), but upper basement here was rubbly and unstable. For this reason, a piece of drill pipe was installed in the base of the hole as a "liner" to hold the hole open and maintain a hydrologic connection between the cased hole and the deeper crustal rocks. The CORK system deployed in Hole 1026B on ODP Leg 168 provided limited fluid sampling capability, and was recovered and replaced on IODP