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# Analysis of a conductive heat flow profile in the Ecuador Fracture Zone

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## ABSTRACT

We report 18 new conductive heat flow measurements collected from a sediment pond located in the inactive part of the Ecuador Fracture Zone in the Panama Basin. The data were collected along an east–west transect coincident with a multi-channel seismic reflection profile that extends from ODP Hole 504B to west of the sediment pond. Conductive models indicate that heat flow should decrease from $\approx 400$ mW m$^{-2}$ on the 1.5 Ma western plate to $\approx 200$ mW m$^{-2}$ on the 6 Ma eastern plate; however the observed heat flow increases nearly linearly toward the east from approximately 140 mW m$^{-2}$ to 190 mW m$^{-2}$. The mean value of 160 mW m$^{-2}$ represents an average heat flow deficit of $\approx 50\%$, which we attribute to lateral advective heat transfer between exposed outcrops on the western and eastern margins of the sediment pond. We apply the well-mixed aquifer model to explain this eastwardly flow, and estimate a volumetric flow rate per unit length in the north–south direction of $\approx 400 \pm 250$ m$^2$ yr$^{-1}$ through the basement aquifer. Using a Darcy flow model with the mean flow rate, we estimate permeabilities of $\sim 10^{-11}$ and $10^{-12}$ m$^2$ for aquifer thicknesses of 100 and 1000 m, respectively. The estimated permeabilities are similar to other estimates in young oceanic upper crust and suggest that vigorous convection within the basement significantly modifies the thermal regime of fracture zones. Additional heat flow data are needed to determine the prevalence and importance of advective heat transfer in fracture zones on a global scale.

## 1. Introduction

Thermal and mechanical processes affect the tectonic evolution of active oceanic transforms and their fracture zone extensions (e.g., Sandwell, 1984; Pockalny et al., 1996). In addition, these processes influence earthquake mechanics and rheology (e.g., Behn et al., 2007; Roland et al., 2010); and, when combined with fluid circulation, they control the alteration of oceanic crust and serpentinization of the upper mantle (e.g., Dziak et al., 2000) in these regions. In the inactive fracture zone region beyond the active transform, half-space cooling models provide some constraints on the thermal regime of the adjacent plates and the differences in plate age across the fracture zone provide first-order controls on topography (e.g. Menard and Atwater, 1969). The thermal and mechanical behavior of fracture zones is complicated, however, by lateral thermal conduction from the younger to the older plate (e.g., Louden and Forsyth, 1976) and by the development of an elastic layer that result in gravitational and topographical features not readily accounted for by simple models (e.g., Sandwell and Schubert, 1982; Sandwell, 1984; Pockalny et al., 1996).

Within and near transform faults and fracture zones heat flow data are sparse; and detailed knowledge of the thermal, mechanical, and possible hydrological regimes is limited. To our knowledge the only other heat flow data from within a fracture zone come from 23 measurements within the thickly sediment Vema transform and fracture zone (Langseth and Hobart, 1976). After correcting for the effects of sedimentation, they find heat flow to be uniform and higher than expected. Other data come from the Ascension fracture zone but are mostly along the flanks of ridge segments (Vacquier and Von Herzen, 1964; Langseth et al., 1966; Von Herzen and Simmons, 1972).

Early thermal models of fracture zones assumed conductive heat transfer. Louden and Forsyth (1976) constructed two-dimensional time dependent models of thermal conduction across an idealized fracture zone and used the resulting temperature structure to calculate free-air gravity anomalies. Behn et al. (2007)

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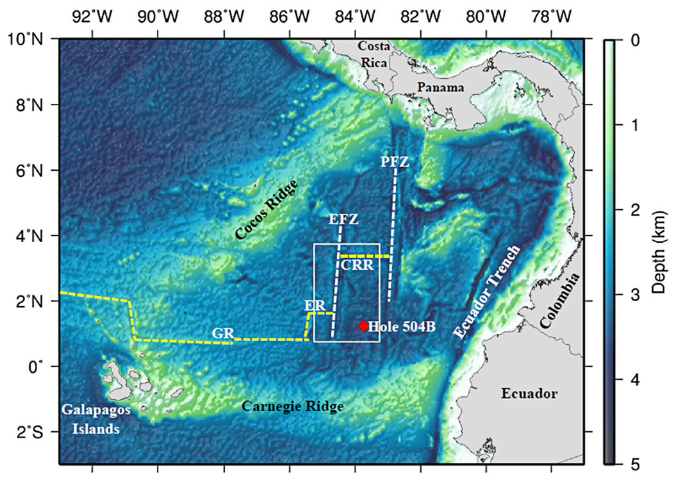

**Fig. 1.** Map of the Panama Basin. The basin is bounded by the Cocos Ridge to the N and W, the Carnegie Ridge to the S, and the Ecuador Trench and Americas to the E. The dashed yellow lines show the spreading axis (CRR = Costa Rica Rift; ER = Ecuador Ridge; GR = Galapagos Spreading Center). The transforms bounding the CRR, EFZ = Ecuador Fracture Zone; PFZ = Panama Fracture Zone, are labeled and shown in white dashed lines. Red diamond shows the location of the ODP Hole 504B. The white box encloses the area where geophysical measurements were made during cruises JC112, JC113 and Sonne 0238. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

constructed three-dimensional models of the thermal structure beneath transforms. These models used a rheology that incorporated brittle weakening of the lithosphere, resulting in elevated temperatures along the transform, and produced better agreement with observed seismicity. Roland et al. (2010) expanded these models to include shear heating and hydrothermal circulation and inferred that hydrothermal cooling has significant effect on the thermal structure of transform faults.

The thermal models of Behn et al. (2007) and Roland et al. (2010) focused on the large scale thermal regime at transform-ridge intersections. The thermal model of Louden and Forsyth (1976), which is more applicable to fracture zones, has not been tested by heat flow data. Relative to heat flow data obtained as a function of age along the flanks of mid-ocean ridges, there has been little attention paid to the details of heat flow and the thermal regime locally around transforms and their fracture zone extensions. Hence, there is essentially no information on heat flow patterns, fluid flow rates, extent of circulation, and subsurface fluid temperatures on a local scale in fracture zone settings.

In this paper, we report 18 conductive heat flow measurements collected across a sediment pond in the Ecuador Fracture Zone south of the Ecuador Rift during the cruises JC113 and JC114 of the OSCAR experiment in the Panama Basin. The data were collected along an east–west transect at a latitude of ∼1°14.0280′N coincident with a multichannel seismic line. We analyze the data using the well-mixed aquifer model.

## 2. Geologic setting

The Ecuador Fracture Zone (EFZ) consists of the active ridge-transform-ridge offset, that joins the Costa Rica Rift (CRR) in the center of the Panama Basin, the Ecuador Rift (ER) to the southwest of the CRR, and the inactive fracture zones extending to the north of the CRR and south of ER (Fig. 1). Swath bathymetry (Fig. 2) collected during the cruises shows the active and inactive parts of the fracture zone; the region of the heat flow survey, which is located in the inactive part of the EFZ, is depicted by the blue rectangular box. The bathymetry indicates that the EFZ is approximately 20 km wide and is characterized by two linear highs extending for several kilometers along strike. The two linear highs form ridges that may have resulted from diaperic uplift of serpentinized-peridotite caused by the intrusion of seawater into the upper mantle via the faults (Kastens et al., 1986; Dziak et al., 2000). In such fracture zones, complex processes shape the hydrogeologic and thermal regime. The sediment pond, where the heat flow measurements were conducted, extends for about 9.3 km in the east–west direction with its center at ∼1°14.0280′N, 84°35.6460′W. The crustal ages to the east and west of the sediment pond are ≈6 and ≈1.5 Ma, respectively, based on spreading rate estimates for the Costa Rica Ridge (Hey et al., 1977; Tuckwell et al., 1996) and distance from ridge axis. Co-locating the heat flow data with seismic reflection data allows us to analyze the heat flow data in the context of sediment thickness and underlying basement structure.

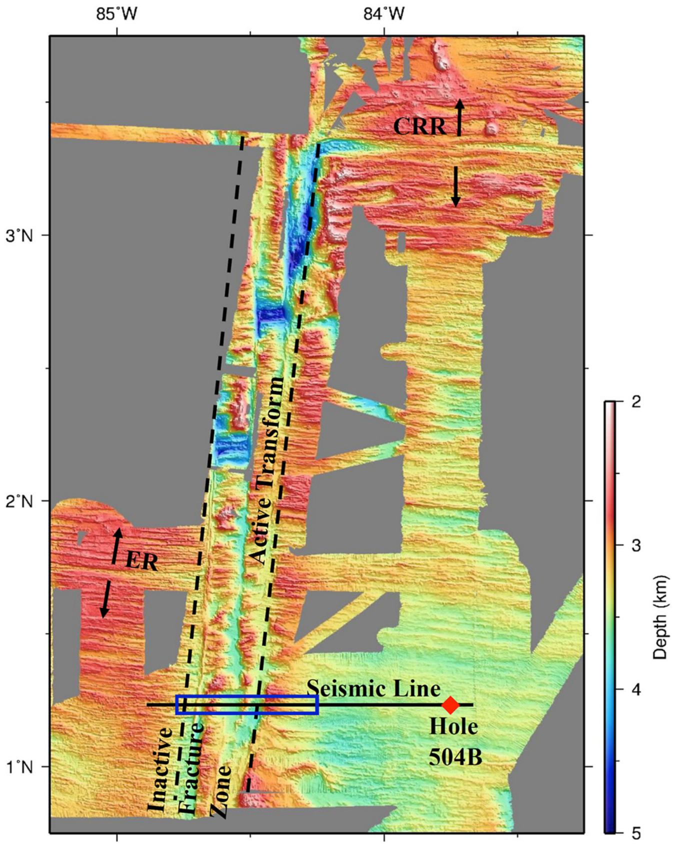

**Fig. 2.** Bathymetry data showing the EFZ (region bound by black dashed lines). CRR = Costa Rica Rift; ER = Ecuador Ridge. The seismic profile, reproduced in Fig. 3, extends to Hole 504B in the east. The blue box highlights the sediment pond and location of heat flow measurements. The heat flow measurements are collocated with the seismic reflection line. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

## 3. Results

### 3.1. Seismic reflection measurements

A high-resolution seismic profile imaging the sediment structure and top of oceanic crust was acquired using a high-frequency (20–200 Hz) GI airgun source recorded on a 4500 m long hydrophone array with 360 groups spaced at 12.5 m. After merging with the field geometry, the seismic data were high-pass filtered to suppress low-frequency surface wave and ship-tow noise. Figs. 3 and 4a were migrated to give a well-resolved image of the internal structure of the sediments and the sediment-basement interface. The sediment thickness generally increases from west to east across the sediment pond with a mean thickness of approximately