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# Heat flow, morphology, pore fluids and hydrothermal circulation in a typical Mid-Atlantic Ridge flank near Oceanographer Fracture Zone

V. Le Gal [b,d,*], F. Lucazeau [a], M. Cannat [a], J. Poort [b], C. Monnin [c], A. Battani [d], F. Fontaine [a], B. Goutorbe [e], F. Rolandone [b], C. Poitou [a], M.-M. Blanc-Valleron [f], A. Piedade [g], A. Hipólito [h]

[a] Institut de Physique du Globe de Paris/Sorbonne Paris Cité, UMR CNRS 7154, 1 rue Jussieu, 75238, Paris cedex 05, France
[b] iSTeP, Université Pierre et Marie Curie, 4 place Jussieu, 75252, Paris cedex 05, France
[c] Geosciences Environnement Toulouse, 14 Avenue Edouard Belin, 31400, Toulouse, France
[d] Geosciences, IFP Energies nouvelles, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, France
[e] Universidade Federal Fluminense, Niterói, Brazil
[f] Museum National d'Histoire Naturelle, CP 48, 57 rue Cuvier, 75231 Paris cedex 05, France
[g] School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, CF10 3AT Cardiff, United Kingdom
[h] Universidade dos Açores, Departamento de Geociências, Rua da Mãe de Deus, 9501-801 Ponta Delgada, Portugal

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ABSTRACT

Hydrothermal circulation affects heat and mass transfers in the oceanic lithosphere, not only at the ridge axis but also on their flanks, where the magnitude of this process has been related to sediment blanket and seamounts density. This was documented in several areas of the Pacific Ocean by heat flow measurements and pore water analysis. However, as the morphology of Atlantic and Indian ridge flanks is generally rougher than in the Pacific, these regions of slow and ultra-slow accretion may be affected by hydrothermal processes of different regimes. We carried out a survey of two regions on the eastern and western flanks of the Mid-Atlantic Ridge between Oceanographer and Hayes fracture zones. Two hundred and eight new heat flow measurements were obtained along six seismic profiles, on 5 to 14 Ma old seafloor. Thirty sediment cores (from which porewaters have been extracted) have been collected with a Kullenberg corer equipped with thermistors thus allowing simultaneous heat flow measurement. Most heat flow values are lower than those predicted by purely conductive cooling models, with some local variations and exceptions: heat flow values on the eastern flank of the study area are more variable than on the western flank, where they tend to increase westward as the sedimentary cover in the basins becomes thicker and more continuous. Heat flow is also higher, on average, on the northern sides of both the western and eastern field regions and includes values close to conductive predictions near the Oceanographer Fracture Zone. All the sediment porewaters have a chemical composition similar to that of bottom seawater (no anomaly linked to fluid circulation has been detected). Heat flow values and pore fluid compositions are consistent with fluid circulation in volcanic rocks below the sediment. The short distances between seamounts and short fluid pathways explain that fluids flowing in the basaltic aquifer below the sediment have remained cool and unaltered. Finally, relief at small-scale is calculated using variogram of bathymetry and compared for different regions affected by hydrothermal circulation.



## 1. Introduction

Oceanic heat flow is commonly affected by perturbations attributed to hydrothermal circulation (Lister, 1972). Although near-axis processes have more spectacular manifestations (black or white smokers), ridge-flank hydrothermal circulation also contributes to significant advective heat loss (Stein and Stein, 1992, 1994) and chemical fluxes (Fisher and Wheat, 2010) to the oceans. Because hydrothermal circulation affects mainly the uppermost part of the lithosphere, it has little effect on its subsidence. Therefore, conductive models (e.g. Sclater and Francheteau, 1970; Davis and Lister, 1974) are often used to define a theoretical heat flow value for a specific age of the sea-floor: Stein and Stein (1992) have shown, for instance, that heat flow measurements are statistically lower than theoretical values for ages younger than 60 Ma.

Low seafloor heat flow on young ridge flanks is commonly interpreted as a consequence of shallow hydrothermal circulation in the upper basaltic basement, which is much more permeable than the sediments. This process has been understood from observa-

* Corresponding author.
*E-mail address:* legal.vg@gmail.com (V. Le Gal).

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tions of regional studies (e.g. Davis et al., 1989, 1992, 1997; Fisher et al., 2003a; Wheat et al., 2004): in the eastern Juan de Fuca area where oceanic basement is covered by a thick sediment blanket (∼400 m), fluids can recharge or discharge at seamounts, and they can flow in the uppermost basalts over distance of several tens of kilometers (Fisher et al., 2003a). Surface heat flow is perturbed significantly near recharge and discharge areas, but is more or less close to the theoretical value at some distance from the seamounts: a simple well-mixed aquifer model (Langseth and Herman, 1981) gives estimates of this distance as a function of fluid velocity and aquifer thickness. On the eastern flank of the Juan de Fuca Ridge, this critical distance varies from 2–5 km in the Second Ridge area (3.5 M.y. seafloor) to about 20 km in the Hydrothermal Transition area (1.1–1.3 M.y. seafloor) (Hutnak et al., 2006). In other locations where sediment is thinner and less continuous, cold fluids mining surface heat flow might dominate because they have not had time to equilibrate with the host rock (Fisher et al., 2003b; Hutnak et al., 2008). Indeed, the statistical differences observed with conductive values for ages less than 60 Ma (Stein and Stein, 1992) suggest that most of oceanic heat flow data gathered in the global database are more affected by hydrothermal circulation than in the Second Ridge area of the eastern Juan de Fuca Ridge flank.

Heat flow in the mid-Atlantic (Langseth et al., 1966) or Indian (e.g. Crozet and Madagascar basin, Anderson et al., 1979) ridge flanks is statistically lower for the same age than heat flow in the Pacific. An exception was observed by Lucazeau et al. (2006) near the Lucky-Strike segment of the Mid-Atlantic-Ridge (MAR), where the sediment thickness is relatively continuous and the heat flow reaches conductive values in the same way as in the Hydrothermal Transition of the eastern Juan de Fuca Ridge flank. Where the morphology is rougher and the sedimentation in basins less continuous as in most of the Atlantic or Indian oceans, hydrothermal cooling appears much more important. For instance, data in the Atlantic site known as "North Pond" (Langseth et al., 1992; Schmidt-Schierhorn et al., 2012) shows that surface heat flow is uniformly low compared to the conductive values, which attests of a large scale depletion of heat, but increases from east to west (∼4 km from one flank of the pond to the other one).

Hydrothermal circulation also modifies the composition of fluids and rocks, through alteration or diagenetic processes. These changes in fluid composition can be detected by measuring the chemical concentration gradients in the sedimentary column. A typical reaction results from the alteration of basaltic glass into palagonite, smectite and then carbonate (Staudigel et al., 1981). Magnesium is removed from basalt and replaced by calcium extracted from seawater, which is conversely enriched in magnesium (Seyfried and Mottl, 1982). Therefore, fluids flowing within the basement can be progressively modified compared to seawater if reactions are rapid and/or residence time is sufficiently long, resulting in a gradient of concentration between bottom seawater and the basaltic aquifer. The amount of calcium and magnesium exchanged during these reactions depends on temperature and time, and Fisher and Wheat (2010) show that large flow rates and short residence times would result in smaller composition changes of the fluids. Near discharge areas, upward fluid flow in sediments may be detected, because this flow disturbs the linearity of otherwise diffusive $Ca^{2+}$ and $Mg^{2+}$ concentration gradients in the uppermost meters. Therefore, pore fluid geochemistry is a useful and complementary tool in oceanic heat flow measurements in order to understand hydrothermal systems.

This study presents new results of a marine survey on the flanks of the Mid-Atlantic ridge (MAR). This is the first systematic approach on a slow spreading ridge area with such a large number of heat flow data (208 measurements). The goal was to combine heat flow and pore fluid measurements that could compare, in term of scale and size, to the Juan de Fuca area but with a typical morphology of the Atlantic.

## 2. Geological context

The survey was carried out in the northern part of the Oceanographer-Hayes segment (OH1), where a previous geophysical study (SudAçores) was already available (Cannat et al., 1999; Rabain et al., 2001). The study area is adjacent to the first segment of the MAR south of the Oceanographer Fracture Zone (OFZ), a major right-lateral offset at approximately 35°N and 35–36°W, about 500 km of the Azores islands (Fig. 1). The MAR south of the OFZ is divided into four second-order segments OH1 to OH4 (Detrick et al., 1995), which are separated by broad left-lateral non transform offsets. The present study focuses on 5 to 14 Ma crust ages in the OH1 area. A pronounced mantle Bouguer gravity low is associated with the central part of OH1, attesting a thicker crust (8–8.5 km) compared to that at the end (3.5–5.0 km) of the segment (Rabain et al., 2001; Dunn et al., 2005). Oceanic accretion is accommodated by magmatism in the central part and by tectonic processes at the segment ends. The SudAçores survey acquired multibeam bathymetry, gravity and magnetic data that defines the structural evolution of OH1 (Rabain et al., 2001). A prominent seamount chain spreads on both flanks from the present axis to a seafloor age of ∼6 Ma. This chain is interpreted as a consequence of the focused magmatism, which also contributed to the acceleration of a southward propagation of this segment (Rabain et al., 2001). In the domain where this chain of seamounts is observed, there was not enough sediment to measure surface heat flow, but the morphology resulting from the enhanced volcanic activity should significantly contribute to the hydrothermal system. Sedimentary deposits are mainly detrital carbonates with foraminifer nanofossils (Bougault et al., 1985). The sediment thickness in the field area of the present study, based on the SudAçores seismic profiles, is 0 to 300 m.

## 3. Methodology

The Oceanograflu survey was carried out in May–June 2013 on R/V "l'Atalante". It was entirely devoted to the study of heat and fluid transfer on both ridge flanks south of the OFZ, and combined heat flow measurements and sampling of pore fluids for geochemistry. All measurements from this study were acquired along seismic and CHIRP profiles from the SudAçores geophysical survey (Cannat et al., 1999).

### 3.1. Heat flow

Oceanic heat flow, which represents the conductive heat loss rate per unit surface area of the Earth, can be determined as the product of the vertical temperature gradient and thermal conductivity. On ridge flanks, seafloor heat flow can be significantly perturbed by the redistribution of heat by fluid circulation. This allows heat flow data to be used to constrain the geometry and magnitude of perturbations caused by hydrothermal circulation in the underlying rocks. Two measurement techniques were used during Oceanograflu: conventional multi-penetration measurements and Küllenberg (piston) cores equipped with NKE®autonomous thermal probes mounted on outriggers. Both techniques give a temperature resolution of better than 5/1000 K. The multi-penetration instrument is derived from the Von Herzen's outrigger instrument (Von Herzen et al., 1989): it includes a five meter long barrel equipped with seven outrigger thermistors, and a 1.5 ton weight ensuring penetration into soft sediment. Data acquisition is real-time controlled by an acoustic system of communication, and the acquisition sequence is also recorded on a compact-flash