ISSN 1028-334X, Doklady Earth Sciences, 2018, Vol. 482, Part 2, pp. 1345–1348. © Pleiades Publishing, Ltd., 2018.
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GEOPHYSICS

Heat Flow Asymmetry of the West Indian Ridge

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Submitted by Academician M.A. Fedonkin March 5, 2018

Received March 12, 2018

Abstract—Statistically significant asymmetry of geothermal data was established by statistical analysis of the heat flow density along the geotraverses intersecting the West Indian Ridge in the southwestern part of the ocean. To compare the samples of the heat flow density, the Cramer–Welch criterion was applied. It was found that the heat flow on the western slope of the ridge and in the adjacent abyssal basins is higher than in the same structural elements located east of the ridge axis. Asymmetry in the crust structure and in the magnetic field is also noted. To explain this phenomenon, a model that takes the Coriolis force into consideration was proposed. The Coriolis force affects the ascending magma flux in the divergent zone of the ridge.

DOI: 10.1134/S1028334X18100112

The heat flow was measured in the area of the geotraverses intersecting the Mid-Atlantic Ridge and the East Pacific Rise (Mid-oceanic ridge). The statistical analysis of the measurements showed the asymmetry of the heat flow relative to the axis of the Mid-oceanic ridge. The fact of the geothermal asymmetry was proved and confirmed by statistical comparison of heat flow samples for the uniform structural elements of the ocean floor: ridge slopes, adjacent abyssal basins, and passive parts of transform faults [1–3]. It is important that the asymmetry is observed not only in the thermal field, but also in other geophysical fields: magnetic [4] and gravity [5], and in the structure of the crust [6, 7].

The origin of this phenomenon has been discussed repeatedly, and different geological–geophysical models have been proposed to explain the asymmetry. Some of researchers point to various spreading rates of the oceanic plates on the opposite sides of the ridge axes. Others assume that the geodynamic processes differ in the adjacent plates; and on one of the plates, the setting of the primary extension was reversed to a contraction resulting in the development of shariage-overthrust structures typical for a contraction [6, 9]. We also cannot ignore the Coriolis force in the noninertial system of the rotating Earth. This force deflects the ascending flux of fractionally molten mantle material to the west relative to a material point on the planet surface. This fact explains the relative increase in the mean values of the heat flow on the western flank of the Mid-Atlantic Ridge and the East Pacific Rise [2, 3].

In this work, we analyzed, for the first time, the distribution of the heat flow on the flanks of the West Indian Ridge (Fig. 1). The West Indian Ridge is a branch of a larger structure—the Southwest Indian Ridge, which is morphologically divided into the West Indian and African-Antarctic Ridges joining in the zone of the Prince Edward transform fault at 37°E. The West Indian Ridge is characterized by an extremely dissected relief with a difference in elevation of up to 4 km. Numerous transform faults intersect the ridge and, sometimes, displace the current axis of spreading over tens of miles [8].

The Southwest Indian Ridge relates to slowly spreading ridges. The spreading rate here is no more than 14 km/Myr (1.4 cm/year)[1] on average; on the opposite side of the ridge, the crust accretion is dramatically asymmetrical. Therefore, on the "antarctic" side, the accretion is 8/5 km/Ma, and on the "african" side, it is 5.5 km/Ma [9]. Along the ridge strike, structural asymmetry is also observed. The segments stretching west of the Andrew–Bain transform fault (30°E) and east of the Melville transform fault (61°E) are characterized by the anomaly of a deep axial valley, oblique spreading, an insignificant value of the central magnetic anomaly, and unstable manifestation of the passive parts of the transform faults on the ocean floor [8]. These features of the peripheral parts of the

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[1] As a comparison, the mean spreading rate is 2.5 cm/year in the Mid-Atlantic Ridge.

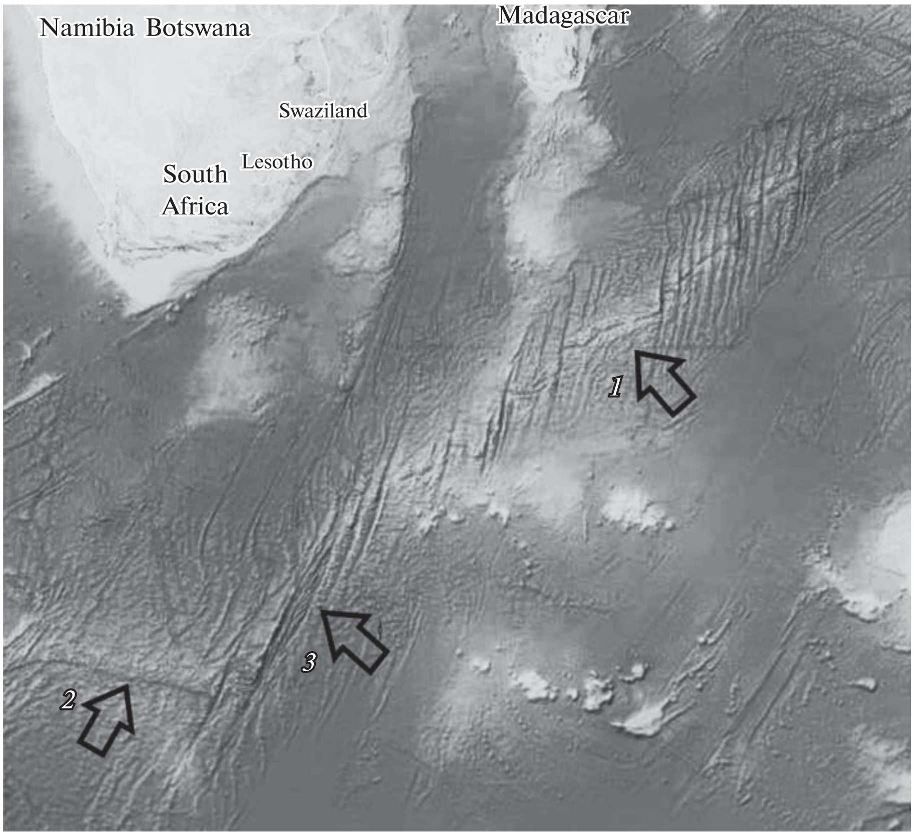

Fig. 1. The morphological scheme of the Southwest Indian Ridge. Arrows show: (*1*) West Indian Ridge, (*2*) African Antarctic Ridge, (*3*) Prince Edward transform fault.

Southwest Indian Ridge allow us to assume that they have a relatively "cold" mantle, solid and thick lithosphere, and scarcity of magma reserves. On the contrary, the central part of the Southwest Indian Ridge between 30°E and 61°E is characterized by transform faults, which are perfectly manifested on the Earth's crust, orthogonal spreading, and a clear central magnetic anomaly [8, 9]. In the West Indian Ridge, between the Atlantis II (56°45′ E) and Navara (58°40′ E) transform faults, there is a segment that, judging by the spreading rate, can be compared with most segments of the Mid-Atlantic Ridge.

Table 1. Statistical characteristics for the values of the heat flow (mW/m^2) on geotraverses 1 and 2

Geotraverse no.	1		2	
Westward/eastward of the axis of the West Indian Ridge	З.	В.	З.	В.
Mean value of the heat flow	76	48	124	77
Mean square deviation	59	30	79	40
Number of measurements	65	28	12	48
Value of the Cramer–Welch criterion	2.38		2.9	
Confidence coefficient	99%		99%	

Therefore, the Southwest Indian Ridge and its fragment, the West Indian Ridge, are characterized by structural and morphological asymmetry not only across but also along the strike.

Since the 1960s, in the southwestern part of the ocean, expedition works, including heat flow measurements, have repeatedly been carried out on board of American, French, and Japanese research vessels [10–12]. Compilation of the measured values is reflected in the global database [13–15]. Figure 2 shows all the current measurement stations located in this part of the Indian Ocean and in the adjacent area of the African continent.

To establish the existence of the geothermal asymmetry on the flanks of the West Indian Ridge, we compared the heat flow samples along the two long profiles (geotraverses) intersecting the ridge (Fig. 2). The statistical samples for each geotraverse are absolutely representative (Table 1) to carry out the comparative analysis.

The evidence of the possible geothermal asymmetry of the transform faults is based on the statistical comparison of the empirical data samples related to

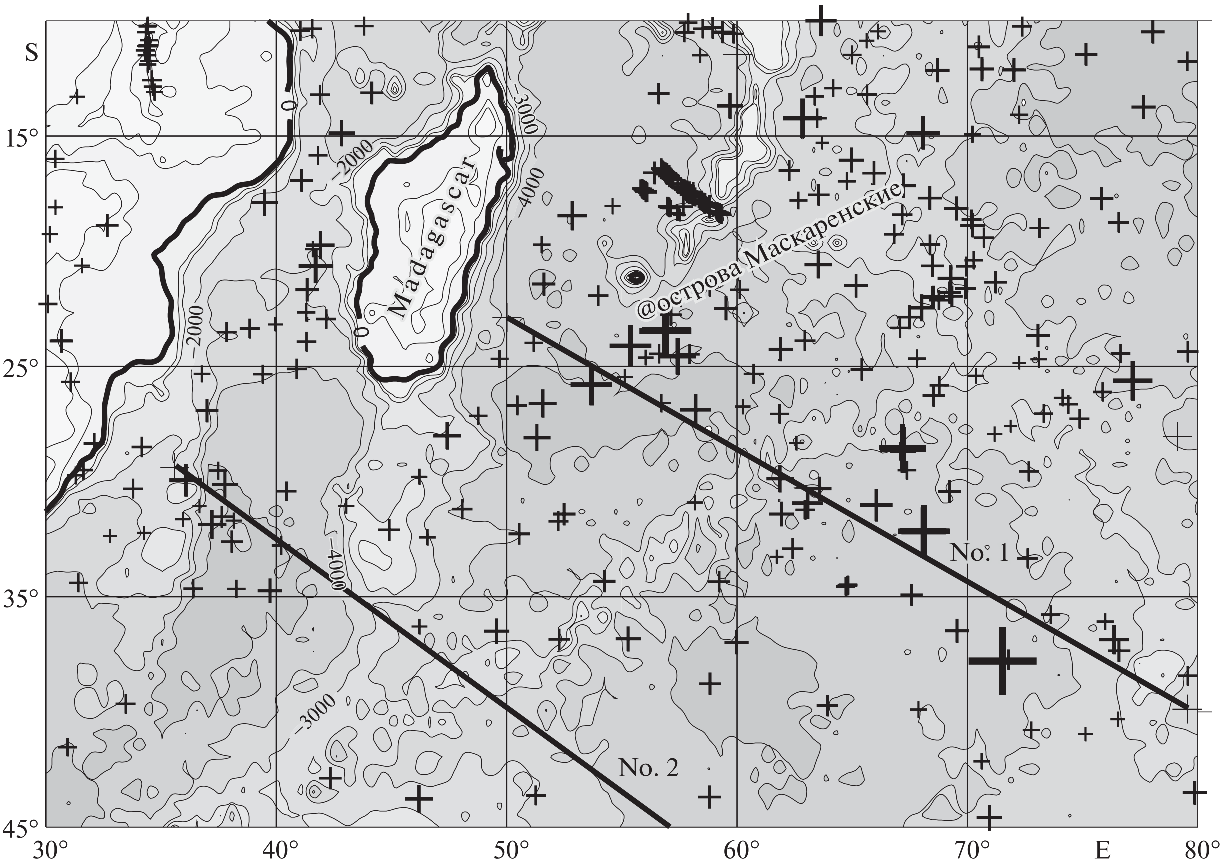

Fig. 2. The bathymetrical map of the southwestern part of the Indian Ocean (the isobath interval is 1000 m); position of the stations for the heat flow measurements (crosses). A cross size is proportional to the heat flow value. (1, 2) Geotraverses along which the geothermal data were statistically processed.

the different parts, in our case, to the western and eastern strike of the fault.

To estimate the statistically significant difference of the mean values of the heat flow in the studying samples, the Cramer–Welch criterion (T) was used; the value of this criterion is found by the formula

$$T = \frac{\sqrt{mn}(\bar{x} - \bar{y})}{\sqrt{ns_x^2 + ms_y^2}},$$

where $\bar{x}$, s_x^2, n, and $\bar{y}$, s_y^2, and m are the sample mean, dispersions, and amount of data for the two compared samples, respectively. If $T < \varphi(1 - \alpha/2)$, where $\varphi(1 - \alpha/2)$ is the value of the inverse function of the normal distribution from a significance level α, where $\alpha = 1 - P$ and P is the confidence coefficient, one accepts the hypothesis that the mean values of the heat flow are homogenous; i.e., the existence of the asymmetry is not confirmed. Conversely, if $T \geq \varphi(1 - \alpha/2)$, one accepts the hypothesis that the mean values for the characteristic considered are heterogeneous and the asymmetry is confirmed. At the significance level of $\alpha = 0.05$ (where $P = 95\%$), the critical value of the Cramer–Welch criterion $T = 1.96$. Therefore, if the criterion does not exceed this value, the hypothesis for the homogeneity of the samples on the mean value should be excepted. If the criterion is greater than or equal to the critical value, the samples on the mean value are accepted as different. The confidence coefficients of the result of the differences of the heat flow mean values for the western and eastern parts (geotraverse 1 and geotraverse 2) are 99%. Table 1 and Fig. 3 show the main characteristics of the samples considered and the values of the Cramer–Welch criterion.

Therefore, in the southwestern part of the Indian Ocean, we confirm the presence of not only structural but also geothermal asymmetry of the West Indian Ridge relative to the ridge axis. Without disregarding all the above-mentioned reasons for the asymmetry phenomena, we will consider another, in our view, reasonable explanation.

The Coriolis force $F_{\mathbf{k}} = 2mv\omega\sin\varphi$ will act on any material point of the Earth (m) due to its counterclockwise rotation with the rate (ω); in the southern hemisphere, the Coriolis force will deflect the mass to the left relative to the radius (Fig. 4). In the divergent zones, such a mass appears to be magma ascending from the asthenosphere mantle reservoir with a rate v

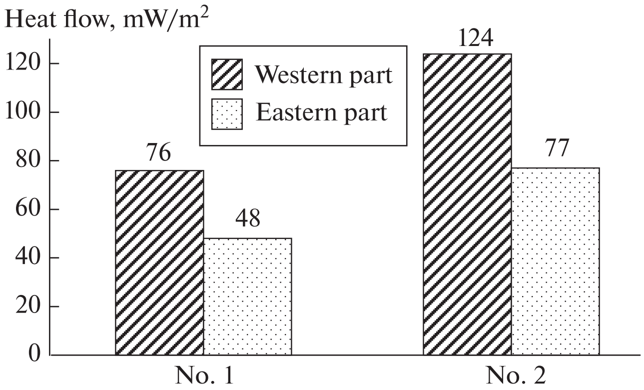

Fig. 3. The diagram of comparison of the mean values of the heat flow westward and eastward of the axis of the West Indian Ridge along the geotraverses.

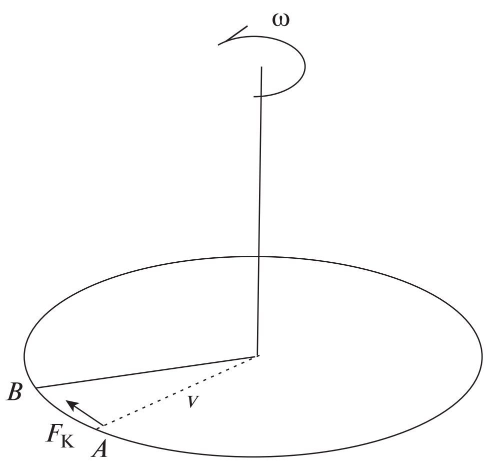

Fig. 4. Action of the Coriolis Force.

and providing the spreading of the oceanic plates. Under the action of the Coriolis force, which is directed perpendicularly to the trajectory of the magma ascent, the velocity vector is not orthogonal to the floor surface, but deviated to the west. Mass *m* will displace from point *A* to point *B* (Fig. 4). The displacement amplitude of the magma flux will be more in higher latitudes (φ) than near the equator.

Geotraverses 1 and 2 are situated in the southern hemisphere; therefore, the ascending magma flux invariably deviates to the west. This fact explains the observed asymmetry in the Indian Ocean. We recall that the similar asymmetry of the heat flow was observed in the Angola–Brazil Geotraverse in the Atlantic [1], which is also situated in the southern hemisphere.

ACKNOWLEDGMENTS

This work was supported by the state budget, project no. 0135-2015-0021, and the Executive Committee of the Russian Academy of Sciences, project no. 49.

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Translated by V. Krutikova

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