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GEOPHYSICS

Geothermal Asymmetry in Transform Faults of the Equatorial Atlantic Ocean

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Abstract—Statistical analysis of heat flow values measured in transform faults of the equatorial part of the Atlantic Ocean has been performed. Owing to the calculation using the Cramer–Welch criterion, it was established that not only is there an already known statistically significant difference between heat flow in active and passive zones of transform faults, but there is also an asymmetry in heat flow distribution between the western and eastern branches of passive zones of the fault zones. The western zones in all structures studied are characterized by higher average heat flow values. Two models are proposed to explain this phenomenon.

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Detailed studies of heat flow distribution on the slopes of the Mid-Ocean Ridge (MOR) and adjacent abyssal basins have shown that this distribution is not always symmetrical relative to the MOR axis, but rather follows a complex redistribution mechanism that depends on many geological causes associated with both tectonic processes and the structural features of the lithosphere of these zones. Thus, the geothermal asymmetry of the MOR flanks and adjacent abyssal basins was established in all oceans [4, 5, 8] and confirmed by statistical verification of the data samples of heat flow distribution on opposite sides of the MOR axis.

It was established that the parameters of the thermal field asymmetry (temperature and density of heat flow) are not a unique phenomenon for the MOR intersections. In addition, the asymmetry of the magnetic field [1] and the structure of the oceanic crust [6] relative to the Mid-Atlantic Ridge has been revealed by independent studies.

This work presents the results of comparison of heat flow values measured along the latitudinal transform faults of the equatorial Atlantic, which intersect the axis of the Mid-Atlantic Ridge. This makes it possible to conduct a statistical analysis of heat flow distribution constrained by the faults on opposite sides of the MOR axis. Among the targets of our research were the Vema, Doldrams, Sierra Leone, St. Paul, and Romanche faults, which are the most thoroughly studied in terms of geothermics (Fig. 1).

Transform faults are unique "test sites" to study and understand the geoenergetics of the oceanic lithosphere in the MOR zone. The fact is that measurements of heat flow in the MOR axial zone yield a very wide range of values: from outstanding high to zero and even negative ones. This is especially noticeable in areas with a low thickness of bottom muds that cover the rocks of the second layer of the oceanic crust. In this case, two main mechanisms of heat and mass transfer are manifested in varying proportions. In the case of only conductive heat transfer, as a rule, heat flow within the MOR zone is characterized by anomalously high values. However, if convective subaquatic fluid discharge occurs at the sea bottom, heat flow can vary from positive to negative values, depending on the trajectory of the fluid discharge. This does not mean at all that heat is not discharged from the lithosphere at the measurement point. One can assume that heat is simply entirely carried out by convection under nearly zero conductive heat flow (or not exceeding adiabatic (0.4 mW/m^2)) inside an ascending branch of the convective hydrothermal cell ("advective jet") [7]. The deepest trough part of all transform faults is always overlapped by a relatively thick layer of bottom sediments, which prevents advective discharge of deep heat and mass transfer or shields its convective compo-

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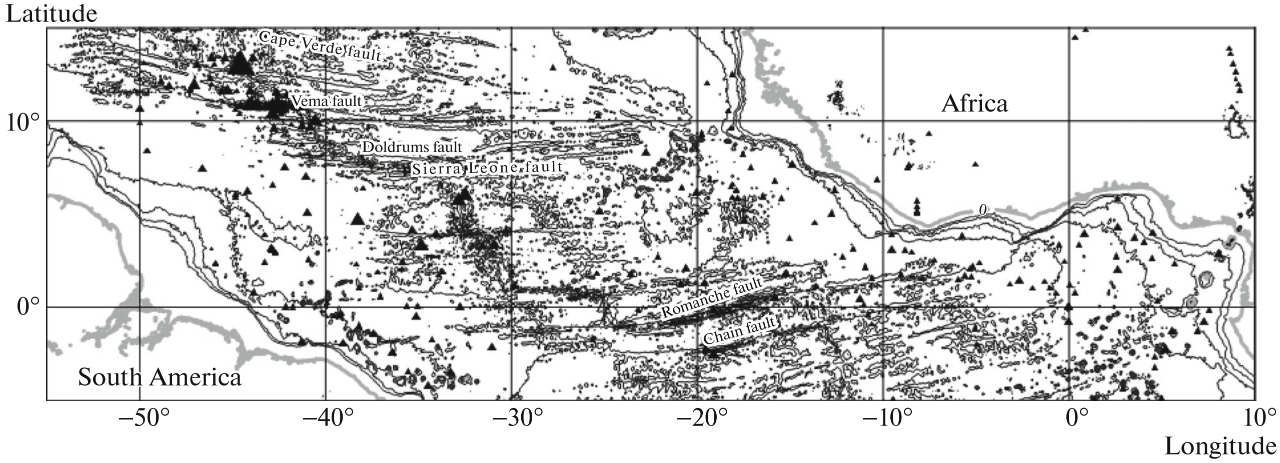

Fig. 1. Location of the transform faults in the equatorial Atlantic. Black triangles show the points of heat flow measurements (the size of triangles is proportional to the heat flow value).

nent. Accordingly, it is possible to use immersion probes for measuring the total heat transfer in the axial zones of the MOR. This is the reason why we have called transform faults zones "unique test sites."

Along the transform fault zone, between its intersection with the spreading axes in two segments adjacent to the MOR, sites that are subject to dynamic and thermal effects of shear deformations and related endogenous processes were identified. These areas are called active zones of a transform fault. As a rule, these active zones separate fragments of the MOR of the same age. On the other hand, the zones that are located on the outer sides of the MOR and not affected by recent shear deformations are called passive parts, or traces of transform faults [2, 13].

Geodynamic manifestations in the active and passive zones of transform faults vary greatly in their character. As was established by seismic monitoring [11],

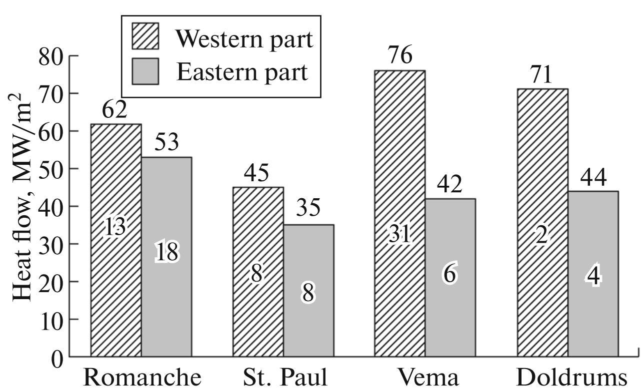

Fig. 2. Comparison of histograms of average values (the top of the columns) in the samples of heat flow values for the western and eastern peripheral parts of the transform faults. The numbers in columns are the number of measurements in the samples.

frequent weak earthquakes ($M \leq 4$), occurring along active zones of transform faults are quasi-synchronous and accompanied by manifestations of active volcanism in segments adjacent to the MOR. The stronger seismic events induced by the strike-slip displacements prevailing along the active fault zones lead to a discontinuity of the medium, creating here the prerequisites for magma upwelling. Thus, the magmatism within the MOR zone and the seismicity in transform fault zones are two conjugate geodynamic phenomena. Seismic activity of a strike-slip nature is also manifested in the passive zones of transform faults. In some cases, the magnitude of these seismic events is even greater than that in the active zones, which is associated with a lower temperature of the lithosphere and, correspondingly, a higher viscosity of the rocks beyond the MOR flanks [7].

The proposed geothermal asymmetry of transform faults is proved on the basis of a statistical comparison study of empirical data samples related to different parts of the MOR, in particular, in our case, to its western and eastern branches.

In order to estimate the statistically significant difference in the average heat flow values in the samples studied, the Cramer-Welch criterion (T) was used. To realize it, the following formula is used:

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

where $\bar{x}$, s_x^2, n, $\bar{y}$, s_y^2, and m are selected average values, dispersions, and data sets for two samples being compared, correspondingly. If $T < \varphi(1 - \alpha/2)$, where $\varphi(1 - \alpha/2)$ is an inverse normal distribution at a level of significance α, where $\alpha = 1 - P$ and P is the level of confidence, then the homogeneity hypothesis of average heat flow values is accepted. It means that the

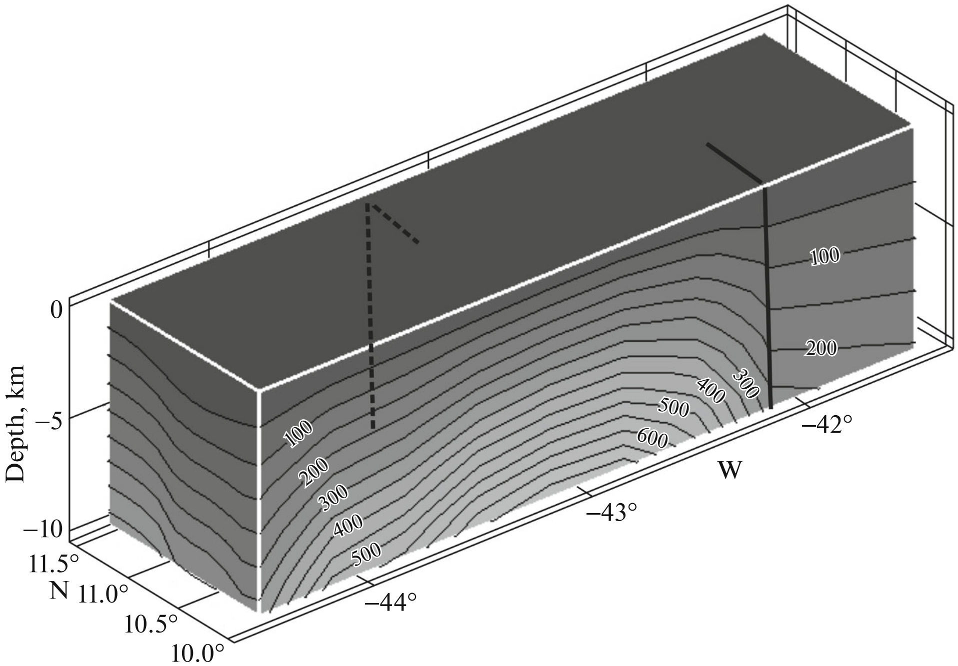

Fig. 3. Three-dimensional block diagram of temperature distribution (°C) along the Vema transform fault. Thick lines show the position of fragments of the Mid-Atlantic Ridge (solid line, to the south of the fault; dotted line, to the north of the fault).

occurrence of the asymmetry is not confirmed. In the case when $T \geq \varphi(1-\alpha/2)$, we accept the hypothesis that average heat flow values are heterogeneous and, accordingly, the occurrence of asymmetry is confirmed.

Figure 2 presents the compared histograms of the average heat flow values in the passive zones of four transform faults of the equatorial Atlantic. For all structures, the western ("Brazilian") branch of the transform fault is characterized by a higher heat flow than the eastern ("Guinean") branch. This difference is confirmed for all cases under test statistical verification. According to the average heat flow values, the data samples considered are statistically different at a confidence probability varying from 0.9 to 0.99.

During our previous investigations, the higher geothermal activity on the western flank of the Mid-Atlantic Ridge was confirmed by comparing the transatlantic geotraverses. As usual, the asymmetric distribution of geophysical fields on the MOR flanks is associated primarily with deep and crustal heterogeneities in the lithosphere, variations in its thickness, and, possibly, with the features of the tectonic evolution of these structural elements of the MOR [3, 10, 12]. However, transform faults are genetically related to the process of spreading of oceanic plates and, therefore, the established asymmetry of the thermal field can be explained either by asymmetric spreading occurring at a higher velocity on the western flank of the MOR than on the eastern flank or by displacement of a magma chamber in the westerly direction. Under either of these assumptions, the temperature gradient on the western flank will be higher than that on the eastern one. This leads to a decrease in the thickness of the thermal lithosphere[1] and a corresponding increase in heat flow.

As can be seen in the three-dimensional diagram of temperature distribution along the Vema transform fault (Fig. 3), the maximum temperatures are characteristic of the active part of this fault (from 42.2° to 43.6° W). The temperature decreases in both directions from the active part, but it becomes higher to the west. For example, the isotherm of 200°C on the western flank is located at a depth of 5 km, while on the eastern flank, it is found at a depth of 9.5 km. When extrapolating the temperatures to the lower half-space, we can estimate the thickness of the thermal lithosphere in the Vema fault zone: 13, 38, and 60 km under the active part, as well as the western and eastern passive zones of the fault, respectively.

Such a model is quite realistic and such contrast ratios of the lithosphere thickness are described for a number of oceanic structures [9]. However, it has not been confirmed for the Vema transform fault by independent geophysical results obtained by studying this and other transform faults, as well as by estimating the lithospheric thickness using the bottom bathymetry data [12].

[1] We call the geosphere, extending from the Earth's surface to the depth of the mantle substance solidus isotherm (1200–1250°C) the thermal lithosphere.

The assumption of the displacement of the magma chamber westward relative to the MOR axis is more realistic, because the structural heterogeneity, tectonic stratification of the crust, and inertness of the fractionally melted matter of the lithosphere inside its solid substance under the Earth's rotation create the prerequisites for deflecting the discharge channel of the deep heat–mass transfer to the west of the trajectory orthogonal relative to the bottom surface.

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