

THE THERMAL ENERGY OF THE EARTH AND ITS GEOLOGICAL MANIFESTATIONS

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Abstract**Full Text**

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*Geophysics***Ya. B. Smirnov****THE THERMAL ENERGY OF THE EARTH
AND ITS GEOLOGICAL MANIFESTATIONS***(Presented by Academician A. V. Peive, March 15, 1967)*

The thermal energy of the Earth, recorded at the surface in the form of a deep heat flow, is considered the principal type of energy determining the geological development of our planet. This energy is an order of magnitude greater than other energy losses; in particular, it is tens of times greater than the total energy of volcanism, hundreds of times greater than the energy of earthquakes, etc. Consequently, the deep thermal energy lost by the Earth is quite sufficient to provide for the diverse geological processes taking place in the Earth's crust and in the upper mantle.

The present investigations are based on an analysis of the spatial distribution, established by us, of the deep heat flow over the terrestrial globe ^(6,8,9).

In doing so, we analyzed the genetic meaning of the laws of probability distribution of the heat flow. Thus, a normal distribution of the attribute indicates equilibrium of systems, which is also applicable to natural systems with slow changes in thermodynamic parameters. Proof of this, according to the theory of statistical fluctuations, follows from the Boltzmann distribution, which substantiates the statistical character of the second law of thermodynamics,

$$S = k \ln W; \quad w(x) = \text{const} \exp\{S(x)/k\}.$$

Transformations of this equation show that the probability of fluctuations of the state of equilibrium obeys the normal law, and their intensity increases with temperature. The very character of statistical fluctuations satisfies Lyapunov's theorem.

As applied to the analysis of the thermal field, the distribution laws may indicate thermodynamic or partial dynamic equilibrium of systems, as well as the absence of equilibrium; i.e., they make it possible to draw conclusions both about the stationarity of the thermal field and about the dynamics of its development in time.

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Let us consider a number of applications of the joint interpretation of the distribution laws of deep heat flow and geological and geophysical parameters in various tectonic regions of the Earth's crust (the latter according to data ^(2-5,10), etc.).

Regularities in the distribution of the thermal field. The present-day distribution of the thermal field has been studied on the basis of an analysis of about 2000 heat-flow measurements and is shown on the corresponding schematic map ⁽⁹⁾, as well as in Fig. 2. These data make it possible to conclude that the main geological regions of the Earth's crust are characterized by specific values of the deep heat flow, which increase regularly, according to the age of tectogenesis, from ancient structures to young ones. In stable regions they reflect the age of consolidation, and in rejuvenated regions, the age of activation of the crust.

In tectonically active belts, a characteristic feature of the distribution of the thermal field is the inevitable alternation of zones of high and low heat flows, indicating redistribution of deep energy. These zones generally correspond to eu- and miogeosynclinal-

ly active belts, and the heat flow in them changes with time. Such a change constitutes the essence of the thermal history of a geosyncline, which in general terms may be described by energy curves passing through a maximum and a minimum, respectively, for eu- and miogeosynclinal zones at certain stages of their development.

Fig. 1. Estimate of the distribution of deep temperatures in the tectonosphere. 1 –areas of Precambrian folding, 2 –areas of Paleozoic folding, 3 –areas of Cenozoic volcanism, 4 –oceanic basins (plates), uniform distribution of radioactive elements in the upper 1000 km, 5 –the same as the preceding, uniform distribution of radioactive elements in the upper 400 km, 6 –marginal oceanic troughs, 7 –rift zone of mid-ocean ridges, 8 –adiabatic temperature distribution in the upper mantle, 9 –temperature field for the most probable melting systems in the upper mantle, 10 –line of geostatic pressure.

Estimate of the age of structures from heat-flow data. The possibility of such an estimate follows logically from the regularities set forth above and is implemented in practice by comparing the laws of heat-flow distribution for different tectonic structures by the Fisher–Student method. The established energetic identity of structures is undoubtedly a consequence of the commonality and simultaneity of the deep processes that led to the same distribution of heat flow. From these positions, for example, the age of tectonically stable block ridges in the oceans proved to be predominantly Mesozoic–Early Ceno-

Fig. 2. Diagram of the relationships of the deep heat flow with other geological and geophysical parameters.

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zoic, which is also confirmed by geological data. An analogous comparison also showed that the tectonic regions of oceanic basins (plates) in all oceans have an age no older than Precambrian–Lower Paleozoic, since otherwise higher heat flows would be expected in them. The magnitudes of heat flow make it possible to establish the age of activation of structures and to refine tectonic boundaries.

Distribution of deep temperatures in the upper shells of the Earth.

This question has been considered by many investigators ((2, 4, 7) and others), but in their estimates they used the mean value of heat flow for the Earth, which averaged the deep temperatures for all tectonic zones. Establishing the spatial differences of the thermal field has made it possible to reconsider these data. An estimate of the distribution of deep temperatures in the Earth's crust and upper mantle for various tectonic regions down to depths of 500 km is given in Fig. 1.

The course of temperatures beneath tectonically stable and tectonically active regions satisfactorily explains the horizontal and vertical heterogeneities in the upper mantle, in particular the differences in the depths of occurrence and in the thickness of the layer of reduced velocities. Analysis of the temperature curves makes it possible to outline the conditions of phase transitions, and comparison of the course of temperatures in regions where zones with different heat flows meet makes it possible to identify horizontal temperature gradients at different depths.

Relation of the thermal field to geological and geophysical parameters. A schematic diagram reflecting the relation of the deep heat flow to other geological and geophysical parameters is given in Fig. 2.

From a preliminary analysis of these data it is evident, in particular, that in the miogeosynclinal zones of tectonically active belts there is observed

there is a direct correlation between the magnitudes of the deep heat flow and almost all other indicators (low values of heat flow correspond to negative landforms, reduced crustal thickness, high negative gradients of vertical movements, negative isostatic anomalies, etc.; high values of heat flow correspond to positive values of these characteristics). In eugeosynclinal zones such relationships are ambiguous, and in a number of cases an inverse correlation is also observed between the quantities being compared. Further interpretation of the observed correspondences requires additional studies; however, even preliminary comparisons make it clear that all

Fig. 2. Diagram of the relationships of the deep heat flow with other geo-

logical and geophysical parameters. z –thickness of the Earth’s crust in km; shown are: relief, thickness of the sedimentary layer, thickness of the consolidated crust, with the most typical velocities of elastic waves in the “granitic” and “basaltic” layers and in the upper mantle. Harmonics show the nature of variation of the parameters around mean values. Δg –gravitational anomalies in the Bouguer reduction, mgal; $\Delta g'$ –isostatic anomalies, mgal; φ –nature of magnetic anomalies; v –mean velocities of vertical tectonic movements over the Neogene-Quaternary period (cm per year), v' –mean velocities of recent vertical movements of the Earth’s surface (cm per year), q –magnitudes of the deep heat flow in $\mu\text{cal}/\text{cm}^2 \text{ sec}$; $\text{grad } T_x$ –estimate of horizontal temperature gradients at depths of 10-20 km ($^{\circ}\text{C}$ per 100 m). Harmonics show the limits of variation of heat-flow values around mean values; dotted curves show the change in heat flow perpendicular to the strike of particular structures.

Regions with crust of ancient continental type. Regions of Precambrian folding: **1** –shields, **2** –platforms; **3** –outputs of the Toscanan orogenies, **4** –plates; regions of Cenozoic folding: **5** –marginal troughs, **6** –mountain-folded structures of miogeosynclinal zones, **7** –intermontane depressions, **8** –eugeosynclinal zones, **9** –intermontane depressions in eugeosynclinal zones.

Regions with crust of transitional type. **10** –geosynclinal depressions of marginal and inland seas, **11** –island arcs, eugeosynclinal zones, **12** –island arcs, folded structures of miogeosynclinal zones, **13** –fore-arc depressions, **14** –marginal oceanic trenches.

Regions with crust of oceanic type. **15** –oceanic basins (plates); mid-ocean ridges; **16** –slope parts; **17** –rift mountain ranges; **18** –rift valley; **19** –deep-sea ridges and swells.

the parameters shown in Fig. 2 are genetically linked with one another; moreover, the magnitudes and dynamics of change of most of them may be related to the characteristics of the thermal field.

Magnitudes of the mean heat flows and the total heat loss by the Earth in the present epoch. Since different regions of the Earth are characterized by different heat losses, taking their area into account, the mean heat flow for the Earth as a whole was obtained, as well as the mean values of heat flows for crust of the continental and oceanic types, respectively equal to 1.18; 1.19 and $1.17 \pm 10\% \mu\text{cal}/\text{cm}^2 \cdot \text{sec}$ (⁸). Repetition of these calculations fully confirmed the values obtained, as well as the magnitude of the total heat loss by the Earth in the present epoch, equal to $(6.0 \pm 0.6) \cdot 10^{18} \mu\text{cal}/\text{sec}$ or $(2.5 \pm 0.25) \cdot 10^{20} \text{ erg}/\text{sec}$ with a probability of 99%. It should be emphasized that the application of methods of harmonic analysis to the calculation of mean heat flows from inhomogeneous and unevenly distributed data cannot be recognized as correct, just as the numbers obtained in this way cannot be accepted (¹¹).

The total heat losses through the areas of tectonically active belts, which can be expressed through the weighted mean heat flow, proved to be very close–of the

order of $1.65 \pm 20\% \mu\text{cal}/\text{cm}^2 \cdot \text{sec}$ (regions of Cenozoic folding ≈ 1.60 , regions activated in the Cenozoic ≈ 1.70 , regions with transitional-type crust ≈ 1.65 , mid-ocean ridges ≈ 1.60), which is somewhat higher than the world average.

In conclusion, we note that the total energy losses by the Earth in the present epoch, as well as the integral heat losses, are fully accounted for by heat generation during the decay of radioactive elements. Other sources are of subordinate importance. The revealed differences in thermal regime and the associated features of the geological-tectonic development of particular regions can be satisfactorily explained by the redistribution of this energy in tectonically active belts as a result of phase transitions. The initial trigger is probably fluctuations in composition, temperature, pressure, etc. Subsequently, the processes become localized in concentric zones (the world rift system, belts of Cenozoic folding, etc.) and undergo regular polycyclic development.

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