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# Mantle heat flow in the territory of Ukraine

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The article describes the second stage of studying the thermal field of Ukraine. We considered two options for calculating the mantle heat flow. The first variant ($HF_{m1}$) was a calculation of the difference between the observed heat flow and the heat flow determined at the first study stage caused by radiogenic heat generation in the crustal rocks. In the second variant, we calculated the mantle heat flow ($HF_{m2}$) as the sum of several effects. We considered the general cooling of the Earth, heat generation in immobile rocks of the upper mantle, and the reflection of heat and mass transfer processes in the tectonosphere (practically — only in the Phanerozoic). The latter also includes recent activation. Calculations have shown that a significant difference between the platform and geosyncline existed in the last approximately 2.5 billion years, and the contribution to the present-day conductive heat flow from the mantle in these regions does not differ significantly. The difference in the released energy is compensated by a different number of convective heat and mass transfer events. The effects of recent events are considered for cases when they are still noticeable in the modern mantle heat flow. In practice, this applies to the Hercynian and younger geosynclines. These effects were calculated for the Donbas, the Lublin-Lviv Trough, the Scythian Plate, and the Carpathians. Particular attention is paid to recent activation, the deep process of which is not fully understood. The calculations of both variants coincide on the territory of Ukraine with acceptable accuracy. Thus, the heat and mass transfer schemes adopted by the authors have been controlled by independent data. The results allow us to proceed to the third stage of the study — the construction of a complete thermal model of the tectonosphere of Ukraine.

**Key words:** mantle heat flow, heat-mass transfer schemes, recent activation.

**Introduction.** The study of the crustal heat flow (HF) distribution conducted by the authors [Gordienko, Gordienko, 2025] was the first stage of the work on creating a thermal model of the tectonosphere for the entire territory of Ukraine. Its results allow us to move on to the second stage — determining the mantle HF over the same area. Regarding calculating this thermal field parameter, it is necessary to mention that we are not talking about the magnitude of the heat flow from below to the Moho discontinuity, but about the amount of heat supplied by mantle sources to the Earth's surface. The difference, in particular, is that the energy of magmatic intrusions into the crust is convectively removed from the mantle, creating an additional part of the observed heat loss through the surface. The crustal HF calculation method also does not consider the effect of long-term crustal cooling as part of the entire tectonosphere, and this effect is thus formally included in the mantle heat flow.

Given sufficient geothermal exploration of the area and satisfactory data quality, determining the mantle heat flow ($HF_m$) can be outlined in two ways. The first is relatively simple: subtracting the crustal heat flow

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from the total observed heat flow. The result ($HF_{m1}$) is of some interest in itself as a source of information to search for the nature of the flow. In our work, we calculated it to verify the mantle HF ($HF_{m2}$), defined as the result of the heat-mass transfer history in the tectonosphere for the entire formation period of the modern value. Heat and mass transfer schemes in regions with different endogenous regimes followed the geological theory outlined in [Gordienko, 2022]. Before being applied in Ukraine, such a technique was tested by modeling along a system of deep seismic sounding (DSS) profiles encircling the northern hemisphere of the Earth with a total length of about 50,000 km (Fig. 1). We compared the sums of the calculated crustal and mantle heat flows with the observed HF. Our study explored inactive and activated platforms, Alpine (including island arcs), Cimmerian and Hercynian geosynclines, Alpine and Hercynian rifts, ocean basins and mid-ocean ridges, deep-sea trenches, and back-arc seas.

Over most of the profiles' lengths, agreement between the calculated and experimental HF is at a level explainable by the errors. Discrepancies (totaling several thousands km of profile length) of a much larger size, virtually excluding the use of heat flow data for solving the problem, are always associated with large errors in the observed field. On the continents, one such example is given by [Gordienko, Gordienko, 2024, 2025]. In the northern part of the Siberian Platform, HF had to be excluded from consideration over a large area due to errors in accounting for the permafrost effect. In the oceans, the maximum distortion is associated with the Mid-Ocean Ridge. One of the limiting cases is shown in the inset in Fig. 1. It is pointless to talk about the correspondence of the HF distribution to the Slater curve. The formation of strip magnetic anomalies alternating in time due to the change in the polarity of the magnetizing field is also unrealistic. This situation was described long ago by Matthews and Bath [1967].

Nevertheless, over large areas of the oceans, it is possible to demonstrate the agreement of the models of deep processes and heat flows in the Pacific and Atlantic basins with and without recent activation, and

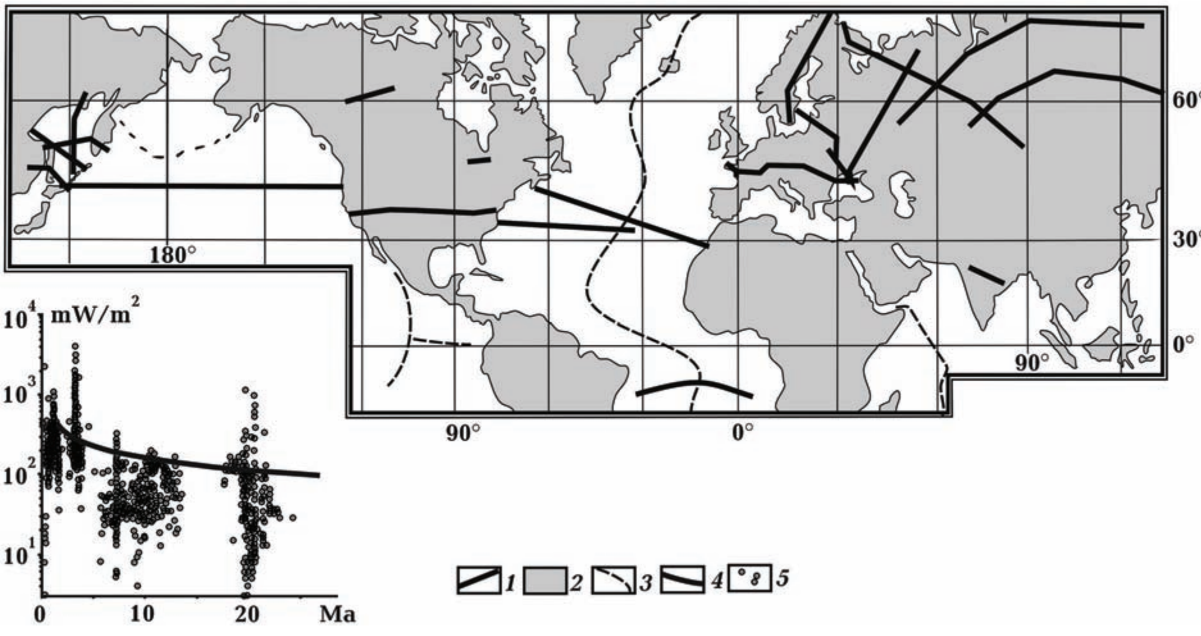


Fig. 1. The location of the DSS profiles along which the observed and calculated heat flow data were compared [Gordienko, Gordienko, 2023a, 2024]. In the inset, the heat flow distribution in the region of the Mid-Atlantic Ridge is near 40 °N [Le Gal et al., 2018]: *1* — DSS profiles lines, *2* — continents, *3* — Mid-Ocean Ridge axes, *4* — the calculated distribution of heat flow as distance from the spreading axis, from crustal age growth, and from bottom dipping (by Slater's rule in the concept of plate tectonics), *5* — observed heat flow values.

to note the effects associated with marginal troughs, flank plateaus, areas of ongoing modern oceanization, and island arcs. Unfortunately, we cannot speak on the impact inherent in the deep process itself in the Mid-Ocean Ridge: it is too «noisy». The results in matching empirical and model data so far should be recognized as «semi-qualitative».

On the continents, the situation is much better; here, we managed to confidently show the correspondence of thermal models of deep processes to the observed HF within the limits of activated and inactive platforms of different ages, young geosynclines, and rifts of Eurasia and North America. On profiles with a total length of about 20,000 km (out of 25,000 km of the total length of continental profiles), an average discrepancy between the calculated and experimental HF was obtained at a level of 7—8 mW/m$^2$, which differs little from that shown in [Gordienko, Gordienko, 2025] for the territory of Ukraine.

For further progress in the use of geothermal information in the framework of regional studies of the geodynamics of the present and past, in addition to a significant increase in the density of the HF observation network, it is necessary to pay much more attention to the conditions of heat and mass transfer at shallow depths, where sources of interference are formed that prevent reliable diagnostics of the components of the heat flow from the crust and upper mantle of the Earth. For Ukraine, the required level of experimental quality has been achieved (see below).

**Heat flow from the mantle of Ukraine as the difference between the observed and crustal one.** The distribution of the heat flow generated by radioactive decay in crustal rocks over Ukraine's territory at present and in the recent geological past is given in [Gordienko, Gordienko, 2024]. The error of the presented parameter does not exceed a few mW/m$^2$. The authors have repeatedly published information on the second parameter necessary for calculating the mantle component — the distribution of observed HF passing through the surface over Ukraine's territory. It is possible to use the variant of the HF map obtained by applying kriging to

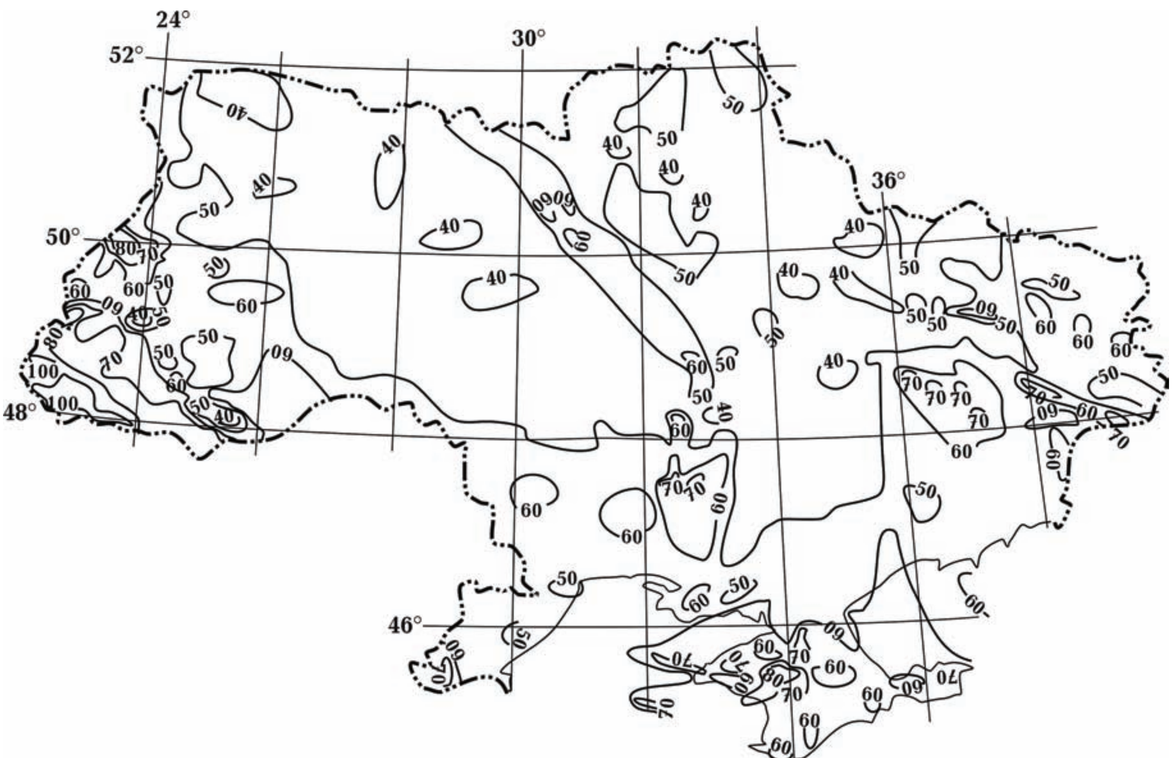


Fig. 2. Distribution of the Earth's heat flow in Ukraine's territory (in mW/m$^2$).

the experimental data, which allows for filling the gaps in the study with a high degree of probability [Gordienko, Gordienko, 2022]. Of course, it is impossible to reconstruct local HF anomalies using this technique; however, in any case, they will not be analyzed at the achieved regional level of work (see below). The HF distribution in Ukraine is given in Fig. 2. The figure does not include tectonic regionalization, since the subtraction procedure used does not provide any features for calculating the differences in the compared parameters in different places of the territory.

The HF distribution scheme has some simplifications. The most intense local anomalies are absent. Some of them cannot be depicted in the figure (for example, disturbances of about 1 km wide in the oil-and gas-bearing part of the Dnieper-Donets Basin). Others, of slightly larger sizes (for example, an anomaly with an intensity higher than 120 mW/m$^2$ in the Transcarpathian Trough or many negative disturbances in the Dnieper-Donets Basin) are also associated with heat distribution at relatively shallow depths; they are not interesting for the analysis.

The error of single HF determination in typical cases is about 3 mW/m$^2$. It is established by the spread of values obtained from the neighboring wells. When constructing the heat flow distribution scheme, the results were averaged over several points within the areas of trapezoids with sides of one minute of geographic coordinates. Naturally, this method was used only in the most — detailed studied areas (Donbas, Dnieper-Donets Basin, the Fore-Carpathian Trough, and local areas of other regions). Therefore, the adopted step of digitizing isolines (10 mW/m$^2$) may be insufficient in places with high and sharply changing HF. For values over 80 mW/m$^2$, the step was 20 mW/m$^2$.

Comparison with the distribution of crustal HF was performed first by fixing the obtained values of mantle heat flow at the intersection points of the isolines. Then, based on the obtained results, a slightly smoothed version was constructed. For each trapezoid with an

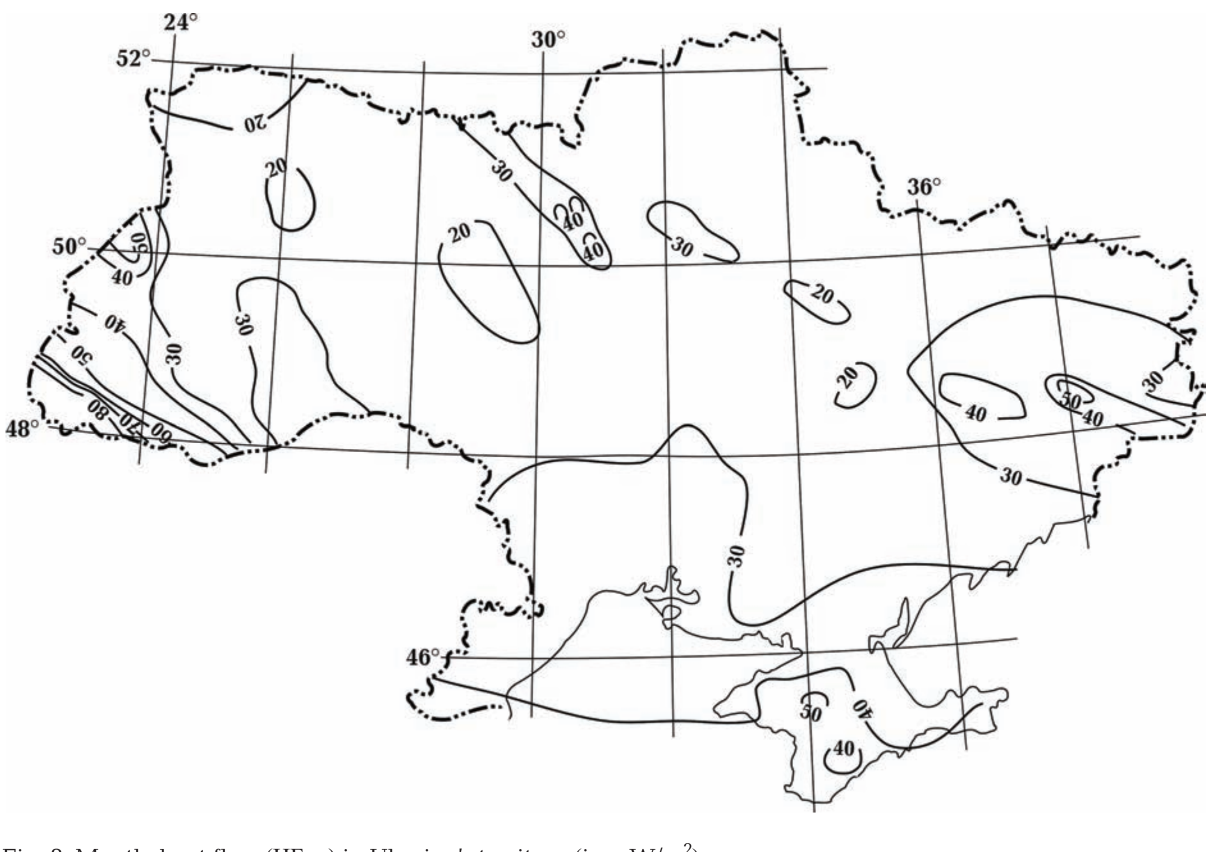


Fig. 3. Mantle heat flow ($HF_{m1}$) in Ukraine's territory (in mW/m$^2$).

area of 0.5×0.5° geographic coordinates, the average values of $HF_{m1}$ were calculated. It significantly reduced the contribution to the overall picture of local anomalies, the sources of which are knowingly absent in the $HF_{m2}$ calculation model.

The error estimate for the mantle flow ($HF_{m1}$), considering the errors of both parameters used [Gordienko, Gordienko, 2025], can be taken to be approximately 4 mW/m$^2$, although the reliability of the error obtained in calculating mantle HF cannot be considered fully proven based on the relatively small amount of data involved.

Fig. 3 shows the distribution of the calculated parameter on the territory of Ukraine.

The resulting picture mainly contains the expected elements. Mantle HF sharply increases in the Carpathian geosyncline, less significantly on the Scythian Plate, and in the Donbas. Moderate values (except for the activation zones of the Dnieper and, partly, Kirovohrad HF anomalies) are widespread on the East European platform. Some decrease is noticeable in the Dnieper-Donets Basin, where the effect of recent activation is weaker. However, a similar lowering in the western part of the Ukrainian Shield is spread significantly further south than could be assumed from the crustal heat flow data and geological information [Gordienko, Gordienko, 2025].

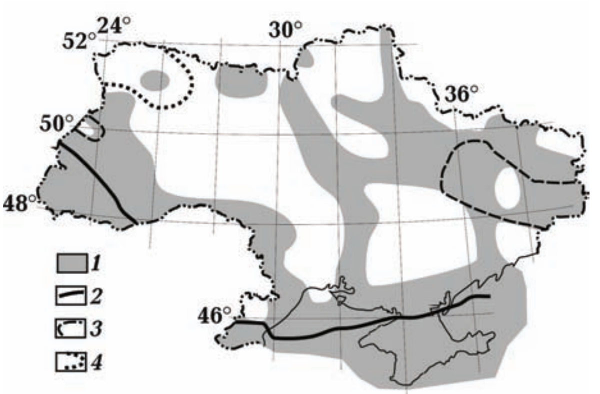


Fig. 4. Sources creating mantle heat flow, supplementing the one widespread on the unactivated Precambrian platform: *1* — areas of recent activation, *2* — the boundary of the East European Platform, *3* — parageosynclinal zones of Donbas and the Lublin-Lviv Trough, *4* — zone of reduced heat generation of upper mantle rocks.

**Direct calculation of mantle's heat flow ($HF_{m2}$).** The $HF_{m2}$ calculation scheme includes three main elements: general cooling of the Earth, heat generation (HG) in immobile rocks of the upper mantle, and reflection of heat and mass transfer processes in the tectonosphere (practically only in the Phanerozoic). The latter, of course, contains recent activation. In Ukrainian territory, this list can be supplemented by the deviation of mantle heat generation from the average (towards a decrease), discovered here, identified on the northeastern margin.

The calculation of the first element of the described scheme has been repeatedly considered. It is not of particular interest, since it assumes the same addition to the effects of all other sources everywhere [Gordienko, 2017]. Fig. 4 shows the location of other heat flow sources within Ukraine.

The division of Ukraine's territory shown in Fig. 4 does not strictly follow the accepted terminology for the convenience of describing heat sources. In particular, this applies to the allocation of Hercynian parageosyncline zones (according to V.V. Belousov) [Belousov, 1975] in the body of the East European Platform.

The heat flow caused by the general cooling of the Earth has been considered for 4.2 billion years. The initial temperature distribution corresponded to the solidus temperature of mantle rocks $T_{sol}$=1013+3.914$H$–0.0037$H^2$, where $H$ is the depth in km. Fig. 5 shows the magnitude of the modern effect.

Heat generation in the upper mantle of Phanerozoic geosynclines during the Earth's early history (up to about 2.5 billion years ago) differed little from the platform HG. At this time, convective heat removals (and, accordingly, the frequency of active heat transfer episodes) coincided [Gordienko, 2023]. In the subsequent period, more acts of convective heat transfer in the mantle of geosynclines caused the levels of heat flow due to HG and on the platform to approximately equalize. The calculated values differ by the first mW/m$^2$, which is comparable with the calculation error. Thus, the sum of the two components studied can be considered the same and equal approximately 20 mW/m$^2$.

We monitored the value in a variety of ways. One of the ways is by the HF level at the continental platform sections of the profiles around the northern hemisphere outside the zones of recent activation. The total length of such sections (with high-quality data on the heat flow) is 5500 km. In all cases, the mantle heat flow at 20 mW/m$^2$ level allows us to explain the observed values with acceptable deviations.

In the activated areas of the platforms, gravity modeling showed that the heat and mass transfer scheme adopted in geological theory corresponds to reality [Gordienko, Gordienko, 2023b,c]. The scheme is the rise of superheated and partially molten matter of the lower part of the upper mantle under the crust to a depth interval of 50—100 km without an intermediate stop. In such areas (at the total length of the DSS profiles of about 5000 km), increased values of heat flows are also observed (if the material quality is sufficient). The calculation shows they should exceed the HF on a quiet platform by 12—15 mW/m$^2$. The age of the onset of recent activation remains an unresolved problem. In cases where it is accompanied by magmatism, dates have been established in the range of approximately 5—25 million years. However, such direct dating is relatively rare. Therefore, an average value of 15 million years was often used (including in the territory of Ukraine). Naturally, this situation creates an additional source of error in the calculation of HF$_{m2}$.

Many signs indicate a complex nature of the recent activation, probably including several acts of matter movement in the crust and mantle. The simplified model needs to be complicated, bringing it closer to reality. In any case, there is no doubt that the formation process of hydrocarbon deposits is much younger. Here, we are talking about hundreds of thousands of years and mass transfer to the upper part of the crust from an intermediate center of partial melting and fluidization in the middle part.

Uncertainties in the age of the studied rocks also create a problem when assessing the modern decrease in mantle heat flow in the northeastern part of the Ukrainian Shield [Gordienko, Gordienko, 2024]. According to the available data, the anomaly can be estimated at minus 5±2 mW/m$^2$.

In general, the distribution pattern of HF$_{m2}$ on the platform part of Ukraine's territory looks like this. Outside the activation zones (see Fig. 4), the mantle heat flow is 20 mW/m$^2$, decreasing to 15 mW/m$^2$ in the area with reduced mantle rock heat generation. At the boundary of the recent activation zone, it increases to 27 mW/m$^2$ (except for the area with reduced HG, where it reaches 22 mW/m$^2$),

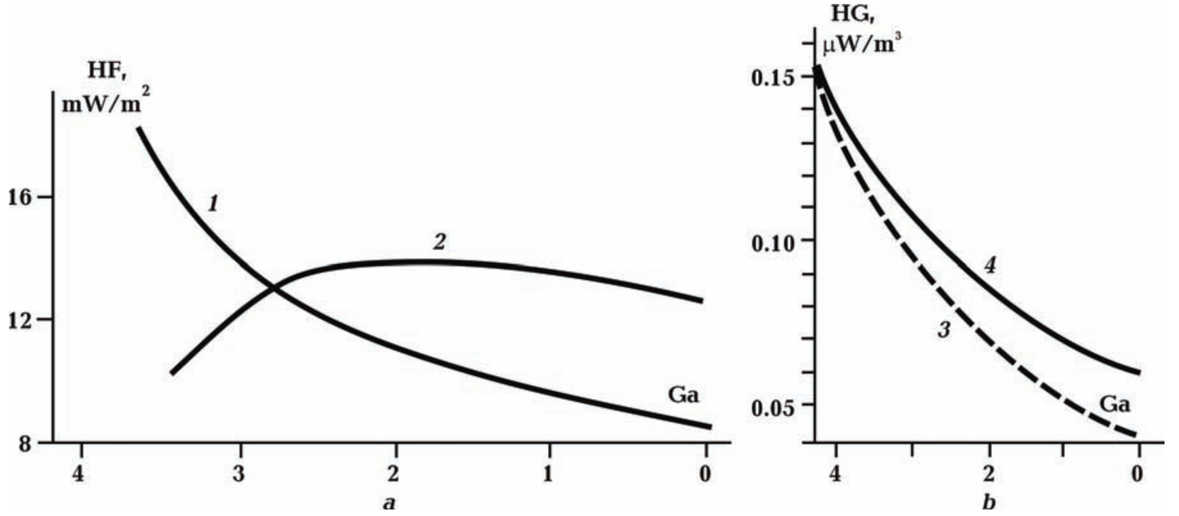


Fig. 5. Time variation of heat flow (*a*) associated with the tectonospheric cooling (*1*) and heat generation in the upper mantle of the platform (*2*); *b* — heat generation of the upper mantle rocks of the platform (*3*) and geosyncline (*4*).

and in fairly large activated areas it grows to 32—35 mW/m$^2$.

The heat and mass transfer processes in the mantle of the Hercynian rift regions of Ukraine are currently no longer manifested in an anomalous (compared to the platform) heat flow value.

In contrast, the influence of geosynclinal events in the Donbas and Lublin-Lviv regions is still noticeable. To take it into account, calculations were performed for three acts of heat and mass transfer corresponding to deep processes.

1. The first quantum of tectonic action rose 380 million years ago from the asthenosphere (260—480 km) into the depth interval of 160—220 km. Anomalies reach +400 °C and –110 °C.

2. About 330 million years ago, overheated and partially molten matter rose from the depth interval of 350—470 km to 100—160 km. The resulting anomalies are –320 and +640 °C.

3. The removal of matter (260 Ma) occurred from the depth interval of 130—270 km into the 40—100 km depth interval. After a short time, mantle melts were introduced from the formed subcrustal asthenosphere into the crust, to depths of 20—40 km. Some cooling of the subcrustal depth interval occurred. The calculated parameters are in full agreement with geological data on the sources of magmatism in Donbas [Gordienko et al., 2015]: 190 km and 1650 °C, 150 km and 1500 °C, 90 km and 1300 °C, and 50 km and 1200 °C (Table 1).

After the geosynclinal process completion, two more one-act activations occurred in the Donbas, the consequences of which are almost imperceptible in the mantle heat flow. By now, the overall effect is about 10 mW/m$^2$, supplemented across most of the region by the influence of recent activation with 12 mW/m$^2$. In the Carpathians, the Transcarpathian (TrC) and Folded-Carpathian (FC) zones are important for calculating the mantle flow of Ukraine. The Alpine process began in the TrC zone 190 Ma ago by the uplift of rocks from the 230—480 km interval to the 180—230 km interval (anomalous *T*=+200 °C). The rock subsidence from the upper interval led to the cooling of the lower one by 40 °C. At the second stage (150 Ma ago), the rocks rose from the interval of 180—490 km (anomalous *T*=–60 °C) to the interval of 120—170 km (anomalous *T*=+ 360 °C). At the third stage 100 Ma ago — from depths of 180—480 km (anomalous *T*=–140 °C) to 40—90 km (anomalous *T*=+870 °C).

In the FC zone, the process began 150 Ma ago with the rise of matter from the depth interval of 220—480 km to the interval of 170—220 km (anomalous *T*=+200 °C). The lower interval cooled by 40 °C. In the second stage, 100 Ma ago, from depths of 180—480 km (anomalous *T*=–80 °C) the substance was carried to the depths of 120—170 km (anomalous *T*=+400 °C). At the last stage (50 million years ago) — from the 140—260 km (anomalous *T*=–240 °C) to the 40—90 km interval (anomalous *T*=+580 °C). The calculated depths of magmatic chambers in the Ukrainian Carpathians agree with those established by the

**Table 1. Comparison of experimental (1) and calculated (2) depths (km) of magmatic chambers in Donbas**

| Age, million years | 1 | 2 |
|---|---|---|
| 370 | 150 | 160 |
| 370 | 180 | 210 |
| 320 | 100 | 100 |
| 240 | 50 | 65 |
| 240 | 90 | 100 |

**Table 2. Comparison of experimental (1) and calculated (2) depths (km) of magmatic chambers in Carpathians**

| Age, Ma | TrC | | FC | |
|---|---|---|---|---|
| | 1 | 2 | 1 | 2 |
| 190 | 200 | 220 | — | — |
| 140 | 125 | 130 | — | — |
| 90 | 200 | 220 | 150 | 160 |
| 90 | 50 | 60 | 100 | 110 |
| 50 | — | — | 50—100 | 50 |
| 2—15 | 75 | 45—90 | 20 | 25 |
| 2—15 | 20—25 | 20—25 | — | — |

composition of the region's igneous rocks (Table 2), as are the sedimentation rates, the anomalous densities' distribution corresponding to the calculated gravitational field, etc. [Gordienko et al., 2011].

The calculated values of $HF_{m2}$ associated with the geosynclinal processes in the Carpathians and recent activation (assuming a different version of heat and mass transfer than the platform one) reach a maximum of 60 mW/m$^2$.

Similarly, calculations were for the territory of the Scythian Plate, including relatively narrow folded zones of the Hercynian and Cimmerian ages. Here, the obtained temperature data are also consistent with geological information, particularly by the composition of the Lomonosov Uplift's rocks [Gordienko et al., 2017]. The corresponding effect as an additional mantle anomaly is 15—20 mW/m$^2$.

Fig. 6 presents a summary scheme of the $HF_{m2}$ distribution as isolines of the parameter under consideration. They were constructed based on calculating results of the average values in the above-mentioned trapezoids of 0.5×0.5° geographic coordinates.

The scheme reflects the current development's state of deep processes' mechanisms in the tectonosphere. The above information on the problems due to the lack of geological data insufficiency shows that many more clarifications are needed. However, the scheme's achieved level of adequacy to the real situation already allows us to obtain a robust solution to the problem.

**Comparison of options of mantle heat flow calculation.** The above results of $HF_{m1}$ and $HF_{m2}$ calculations were obtained by fundamentally different methods using different initial information. They can be considered as established independently. Their coincidence means the reliability of the data used for the calculation and correctness of the calculation methodology. The differences indicate existing errors (Fig. 7).

Comparison of Figs. 3 and 6 in the text of the article reveals elements of similarity and difference in the presented distributions. The most intense anomalies (in the Carpathians, on the Scythian plate, and in the Donbas) are naturally present in both cases, although with some offsets. It is difficult to capture the

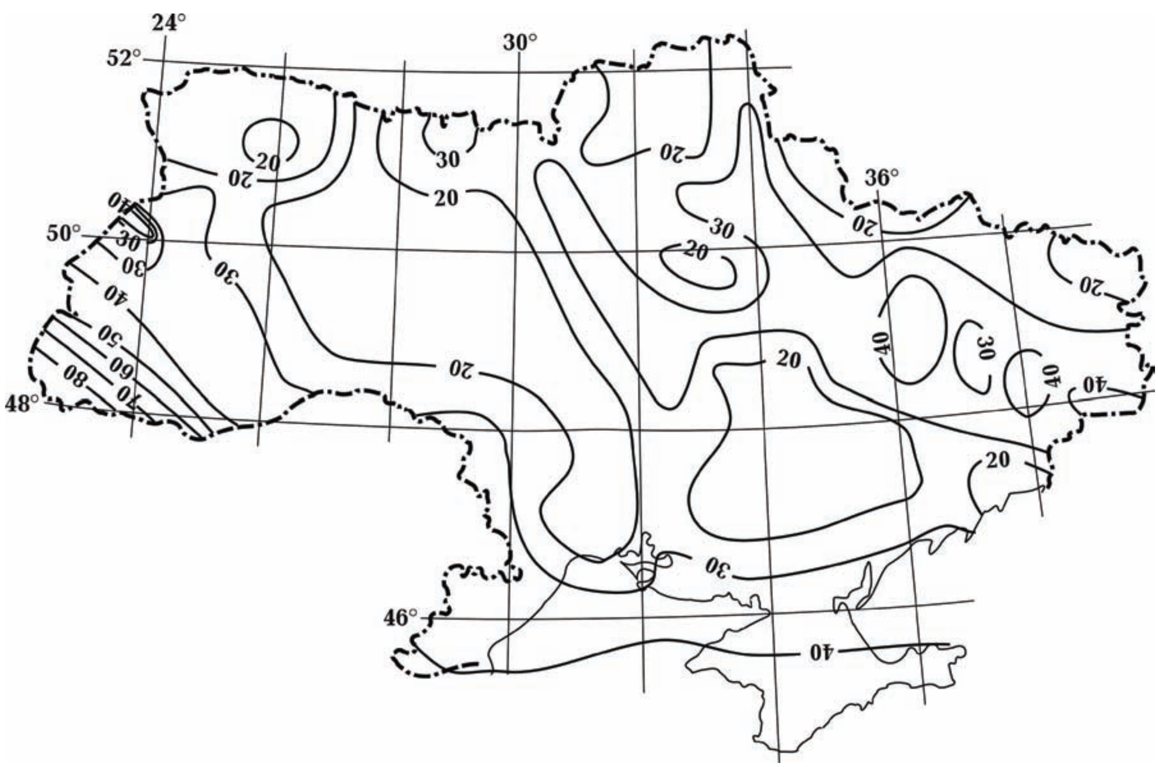


Fig. 6. Distribution of the calculated heat flow ($HF_{m2}$) from the mantle of Ukraine (in mW/m$^2$).

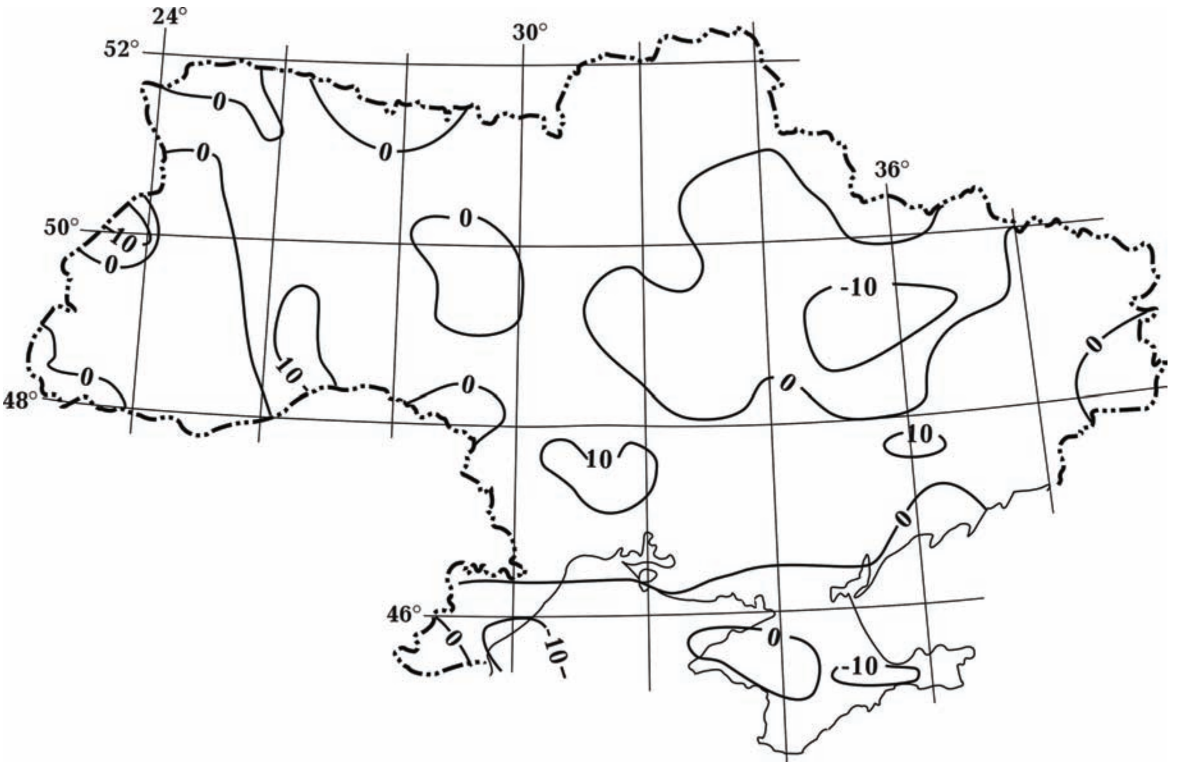


Fig. 7. Comparison of the results of two variants of mantle heat flow calculation in the territory of Ukraine ($HF_{m1}$–$HF_{m2}$ in $mW/m^2$).

prevailing trends in areas with less intense disturbances.

In this case, the comparison is for the entire study area based on the mantle HF values for the trapezoids mentioned above. Their total number was 320. Isolines with a step of 10 $mW/m^2$ are drawn based on the values of differences.

Obviously, over most of the territory, there are discrepancies of diverse signs, differing from 0 by several units of $mW/m^2$. Discrepancies of –10 or +10 or more $mW/m^2$ occupy 2—3 % of the area each. For a more complete quantitative characterization, it is convenient to consider a histogram of their distribution with a more detailed step than the step of the isolines (Fig. 8).

Judging by the histogram, the distribution of differences is close to normal. Two-thirds of them do not exceed 6 $mW/m^2$, which, with equal calculation errors of both options, gives an error estimate of each option at about 4 $mW/m^2$. The result of calculating $HF_{m1}$ using observed HF data with an error of 3 $mW/m^2$

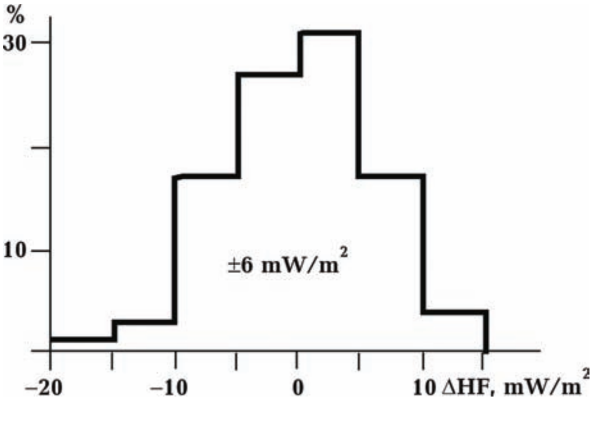


Fig. 8. Distribution of the $HF_{m1}$–$HF_{m2}$ differences on the territory of Ukraine.

and crustal HF data with a probable error of 2—3 $mW/m^2$ seems valid. Correspondingly, the $HF_{m2}$ error seems realistic as well.

The successful verification (likewise for other parameters of physical fields reflecting the character of deep processes in the tectonosphere) allows us to proceed to the next stage: the complete thermal model construction of Ukraine's tectonosphere. Naturally, we are talking about the creation of a model of a regional character.

**Conclusions.** Comparison with independent data allowed us to establish that the constructed scheme of heat generation and transfer in the tectonosphere is correct and as accurate as possible. Such a result is possible only with high-quality initial data — observed heat flow values, velocity sections of the Earth's crust, and methods for converting velocity values into heat generation values, and calculating HF by HG. These conditions are fully met for the territory of Ukraine; in other continental and (especially) oceanic spaces, such information is not always available.

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# Мантійний тепловий потік на території України

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Проведено другий етап вивчення теплового поля України — розглянуто два варіанти розрахунку мантійного теплового потоку. Перший варіант ($HF_{m1}$) був обчисленням різниці між спостереженим тепловим потоком і встановленим на першому етапі дослідження тепловим потоком, викликаним радіогенною теплогенерацією у породах земної кори. Другий варіант ($HF_{m2}$) розраховувався як сума кількох ефектів. Було враховано: загальне остигання Землі, теплогенерація в нерухомих породах верхньої мантії та відображення процесів тепломасоперенесення в тектоносфері (практично лише у фанерозої). До останніх віднесено і сучасну активізацію. Охолодження представлене як суто кондуктивний процес, що почався 4.2 млрд років тому з температури солідуса в породах верхньої мантії. Внесок у мантійний тепловий потік радіогенної теплогенерації розглянуто для її рівнів під докембрійською платформою та геосинкліналлю. Показано, що значна різниця між ними існує в останні приблизно 2,5 млрд років, а внесок у сучасний кондуктивний тепловий потік з мантії у цих регіонах помітно не відрізняється. Різниця в енергії, що виділилася, компенсується різною кількістю актів конвективного тепломасопереносу. Ефекти останніх подій розглянуто для випадків, коли вони помітні у сучасному мантійному тепловому потоці. Фактично це стосується герцинських і молодших геосинкліналей. Ефекти розраховані для Донбасу, Люблінсько-Львівського прогину, Скіфської плити та Карпат. Особливу увагу приділено сучасній активізації, глибинний процес якої повністю ще не вивчений. Результати обчислень обох варіантів $HF_m$ збігаються на території України із прийнятною розбіжністю. Таким чином, незалежними даними проконтрольовано прийняті авторами схеми тепломасоперенесення. Це дає можливість перейти до третього етапу дослідження — побудови повної теплової моделі тектоносфери України.

**Ключові слова:** мантійний тепловий потік, схеми тепломасоперенесення, сучасна активізація.