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Crustal heat flow in Ukraine

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Information on the network density of heat flow measurements with the authors' participation in Ukraine's territory and beyond is presented. Data of such quality can be effectively used to control the schemes of deep processes in the tectonosphere and the origin of mineral deposits. We provide maps of heat flow distribution and concentration of geothermal resources. Combined geological and geophysical knowledge of Ukraine's territory allows us to proceed to a more in-depth study of the thermal field. The main objective was to calculate the crustal heat flow due to radiogenic heat generation throughout the country, which has not been done before. We used information on the distribution of *P*-wave seismic velocities along the DSS (deep seismic study) profiles of about 12,000 km total length. The error in determining the seismic wave velocity was calculated by the velocity difference at the profiles' intersections or overlaps. On average, the velocity difference is about 0.2 km/s. Accordingly, the error of velocity determination is about 1.4 km/s. Such an error allows us to draw isolines of the crust heat flow through 4 mW/m^2. Variants of velocity and heat generation correlation for different crustal rocks are presented. Together with mapping crustal heat flow distribution based on the DSS data, the Moho depth was also plotted considering the error in determining this parameter. Regional crustal heat flow anomalies were identified as being associated with the geological evolution of individual regions. In the platform part of Ukraine, we detected heat generation anomalies related to the anomalies in the upper mantle. The results allow us to proceed with determining the heat flow from the mantle on the territory of Ukraine.

Key words: seismic wave velocities, radiogenic heat generation, crustal heat flow.

Introduction. The latest edition of Earth Heat Flow (HF) Catalogue [Global..., 2024] allows us to estimate the density of the planet's HF measurement network and the fraction of data obtained with contributions from the authors. The total number of HF determinations in the Catalogue is about 91 thousand. Of these, about 56 thousand are on the continents. Within Ukraine, 13 thousand heat flow values were determined with the participation of the authors. Also, approximately more than 1 thousand HF values were determined on the territories of Russia, Poland, Belarus, Moldova, Armenia, Uzbekistan, the southern part of Kazakhstan, Kyrgyzstan, and Tajikistan [Gordienko, Talvirskiy, 1990; Sergeev et al., 1992; Gordienko et al., 2002, 2005, 2006, 2011, 2012, 2015, 2017; Varentsovet al., 2013, etc.]. That is, the authors' contribution to the study of continental heat flow is about 25 %. The number of HF records in Ukraine is comparable within the USA; the average density of HF measurement in Ukraine is thus many times higher. Detailed data on the number of HF values for many countries are not yet available, but it is quite possible to assume that the network density in Ukraine is maximum. Of course, it is very uneven. For example, in the Donbas, about 6 thousand single HF values have been established, yet there are many «white

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spots» on the Ukrainian Shield and its slopes.

One should note the advantageously high accuracy of the Ukrainian HF values. The authors participated in estimating the errors in temperature records (*T*) in wells using different methods under different conditions in the USSR and some other countries. The same procedure was applied to determine the thermal conductivity of rocks. Finally, it was possible to select the most reliable results, which were used for HF calculating. Other data obtained on the territory of Ukraine (without the authors' participation) were not taken into account in heat flow mapping. The reliability of the HF values should also be noted. It was achieved by introducing numerous corrections considering the influence of many factors that distort the heat flow value at different depths in the near-surface zone. Differences in the heat flow material quality were revealed, particularly when considering the data on long seismic profiles encircled the northern hemisphere [Gordienko, Gordienko, 2023, 2024, etc.]. In different regions of continents and oceans, calculated HF (corresponding to the author's geological theory [Gordienko, 2022, etc.]) and experimental HF were compared. The current Catalogue [Global…, 2024] does not yet present the HF data for all the necessary regions in a user-friendly form, and its use is technically difficult. Therefore, outside of Ukraine, information fromthe previous Catalogue (released in 2020) was used to compare with the calculations. The results of such comparison for the EUROBRIDGE and VI geotraverses are presented in Fig. 1.

The combined profile crosses the northern border of Ukraine at km ~1040. The histograms of differences between calculated and observed HF clearly illustrate the difference in the intensity of arbitrary heat flow variations. Within Ukraine, it corresponds to an error of 4—5 mW/m^2. This value differs slightly from the TP variations at practically coinciding points in Ukraine. Outside of Ukraine, it increases so much (30 mW/m^2) that there is no point in using the observed HF to verify the calculated values. A similar situation is also found in other regions of the continents and, in particular, oceans [Gordienko, Gordienko,

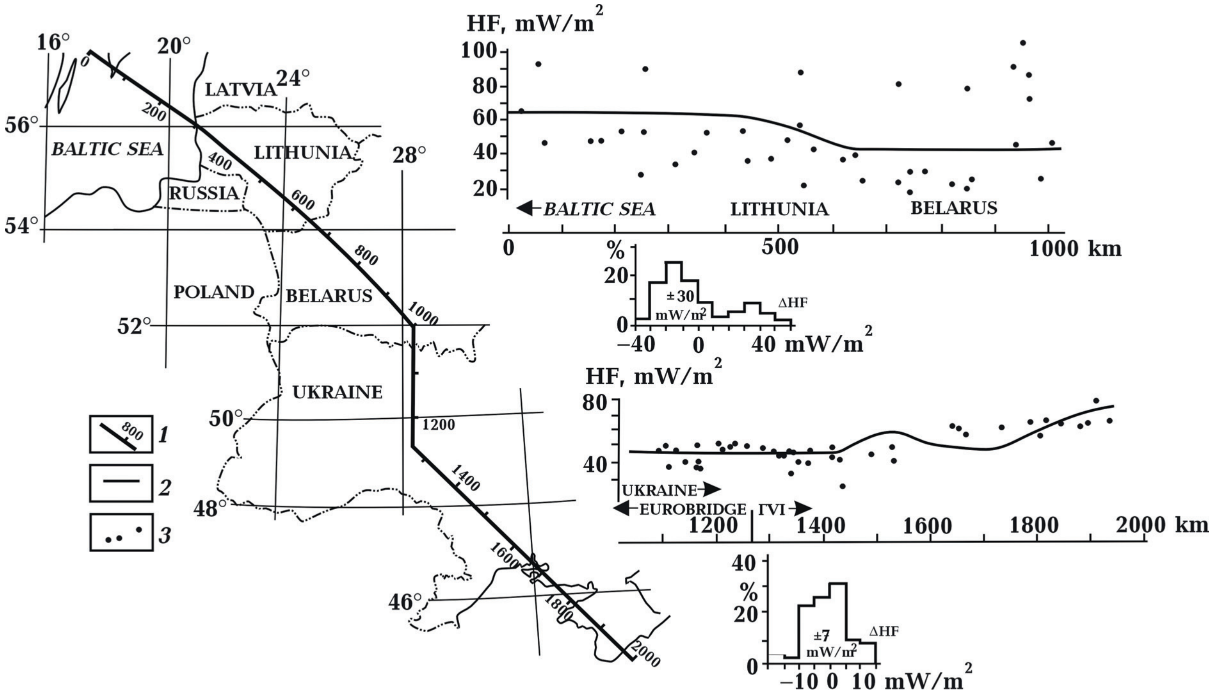

Fig. 1. A comparison of calculated and observed HF values along the EUROBRIDGE (pc 0—1270) and GVI (pc 1270—2000) DSS profiles [Gordienko, Gordienko, 2024]: *1* — profile locations, *2* — calculated HF values, *3* — observed HF values.

2024, etc.], so on average the agreement is much better than in the northern part of the profile in Fig. 1. It can be expected that in the territory of Ukraine, the distribution of experimental HF values in many cases is applicable to verify the schemes of deep processes, to determine the mechanisms of formation of various minerals deposits, and to develop criteria for their prospecting.

To use the available data in such a way, it makes sense to consider the entire data array, first at the regional level, and to determine its background parameters with their constituent characteristics. The distribution of the total HF value at this level has already been described [Gordienko et al., 2002, etc.]. This paper considers the HF produced by the crust as a stationary radiogenic heat source. Using this parameter, we can calculate its mantle component, i.e., the difference between the observed and crustal heat flows. In this case, the term «mantle component» is assumed as conditional. It is obvious that by using this method, the effects of HF sources in the crust, different from those caused by radiogenic heat generation (HG) in the given depth interval, will also be included in its value. This implies the long-term cooling of the planet and relatively young intrusions of overheated matter from the mantle into the crust. Besides, the youngest of them may not manifest themselves in the heat flow at the surface. Such features must be taken into account when considering the value of the mantle component of the HF at the next stage — comparing it with the results of heat and mass transfer in the tectonosphere of tectonically active regions [Gordienko, 2017, 2022, etc.]. Such a comparison will allow the errors of both parameters to be determined. As a result, it would be possible to construct the distribution of regional (background) temperature in the crust and upper mantle with error estimation and to robustly model local thermal anomalies, which could be associated with some mineral deposits, or to abandon the idea if the data are of insufficient quality.

Thus, we plan the following work order: 1) (the current paper) calculation of the crustal HF for the entire territory of Ukraine for all DSS profiles. Such calculations used to be done for selected profiles within individual regions. The velocities were converted into heat generation values using formulas established for the Ukrainian data [Gordienko et al., 2002, etc.]; 2) calculation of the mantle HF by subtracting the crustal HF from the experimental data and determination of the resulting error; 3) calculation of mantle HF following the geological theory and history of deep processes in Ukraine, comparison of two variants of the mantle HF calculation results (results in the next article); 4) if the error of mantle HF is acceptable — construction of a thermal model for the entire territory of Ukraine for the whole depth of the tectonosphere (the final article).

Materials. To calculate the heat generation of crustal rocks required for calculating the crustal HF, we used data on the distribution of *P*-wave velocities (V_P) along the deep seismic sounding profiles on the territory of Ukraine. Information on the velocity cross-sections and references to them are given mainly in the same monographs written with the authors' participation as the heat flow data [Gordienko et al., 2005, 2006, 2011, 2012, 2015, 2017; Varentsov et al., 2013, etc.]. Additional information related to the results of recent years is taken from publications [Yegorova et al., 2006; Grad et al., 2006; Baranova et al., 2011; Starostenko et al., 2013, 2015, 2017; Janik et al., 2020, 2024, etc.]. In addition, we used the data on the CEL 05 profile [Grad et al., 2006] (outside but close to the border of Ukraine), as well as some information along the profiles in Russia close to the border near the Voronezh massif. One of the Ukrainian seismic profiles (XXII), passing through the Crimean Mountains and Kerch Peninsula, was excluded from the consideration since its velocity model was constructed mainly using data on the intersecting profiles. The DSS profiles used are presented in Fig. 2. Their total length is about 12 thousand km.

For the convenience of further processing, the V_P distributions on the seismic cross-sections were presented by velocity isolines with the steps given in the author's sections. In several cases, notable gaps were found, such

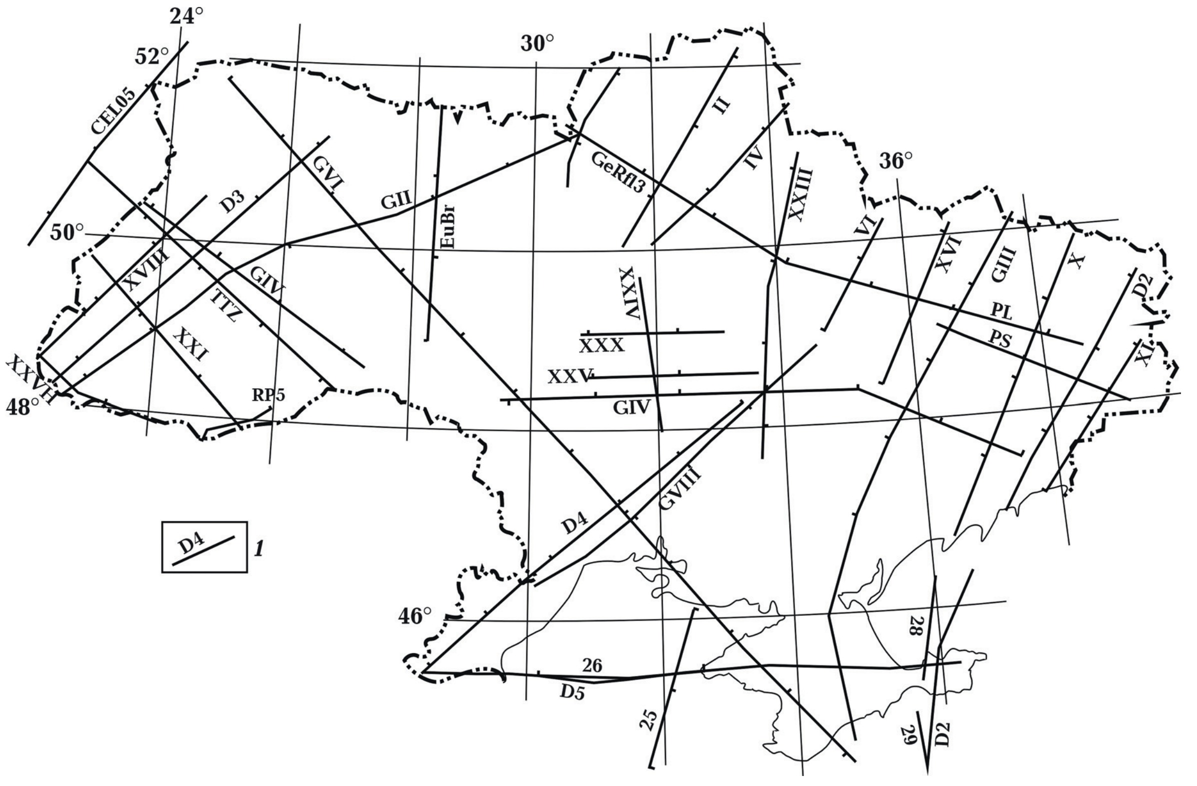

Fig. 2. Location of the DSS profiles on the territory of Ukraine [Gordienko et al., 2004; Tripolsky, Sharov, 2004; Starostenko et al., 2013, 2015, 2017; Janik et al., 2020, 2024 etc.]: *1* — profiles, their numbers, pickets (in km). Profiles PL — Poltava—Luhansk, PS — Poltava—Sverdlovsk.

as insufficient or absent information on sediments. In the calculations, such «blank spots» were filled with information from neighboring profiles. The distortions introduced in this case are insignificant.

Determination of the typical error in calculating V_P seems interesting. According to the assessment [Gordienko et al., 2005, 2006, etc.], based on the comparison of the intersecting profiles and those obtained on the same profile by different authors, in the crystalline crust (without a thick sedimentary layer), the error in the upper part (up to ~10—15 km) is about 0.1 km/s; below these depths, the value is greater, but its quantitative determination seemed unclear. According to the available data, the differences in magnitudes on intersecting profiles with thick sedimentary layers are higher than the mentioned value.

It makes sense to consider the entire data set to compare all the velocity cross-sections at the intersection and overlapping parts of the profiles. The velocity values are then compared within a vertical step of 5 km. In places where profiles were very close or coincided, velocity differences at isovelocity intersection points were considered. In total, more than 450 ΔV_P values were obtained, and the results are shown in Fig. 3, *a*.

At one point at the intersection of the CEL05 and TTZ-South profiles, the comparison of velocity distribution was made outside Ukraine, near its border. The resulting difference shows a rather significant error — up to 0.14 km/s. At each depth section, only velocity isolines with a step of 0.4 km/s are considered reliable, which makes such a picture rather uninformative.

Calculating velocity distributions along the new DSS profiles resulted in smaller errors. Comparison of the models on profiles done after 2000 at their intersections encounters insignificance of information. There are few intersections. It is possible to use DOBRE3-TTZ-South, DOBRE4-DOBRE5, CEL05-TTZ-South, DOBRE5-DOBRE2, DOBRE5-28,

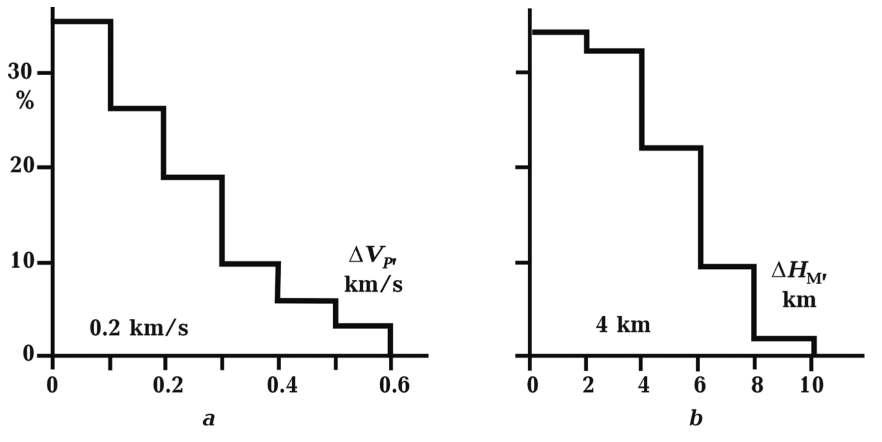

Fig. 3. Histograms of differences distribution: *a* — seismic wave velocities, *b* — M discontinuity depths (*H*, m), obtained on intersecting or overlapping profiles within Ukraine.

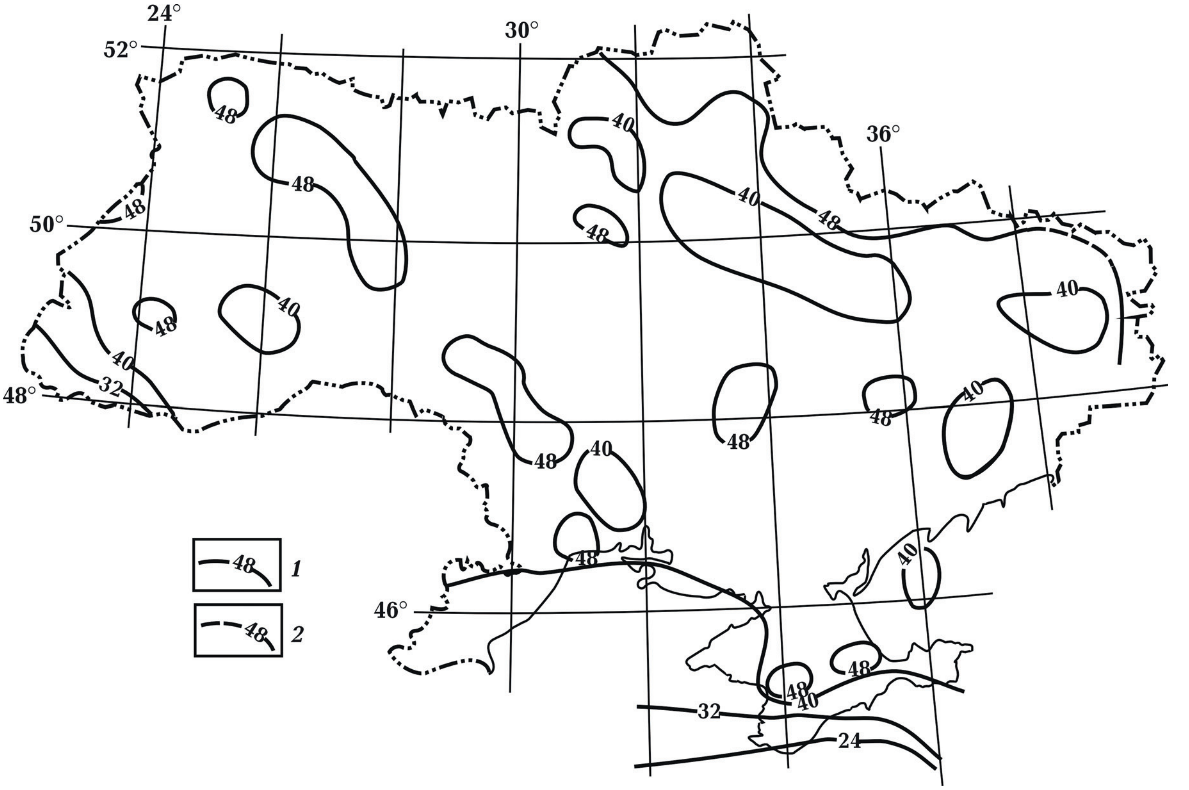

Fig. 4. Moho discontinuity depths in Ukraine: *1* — isolines of the Moho depths, km, *2* — an insufficiently reliable fragment of the isoline.

DOBRE2-29, but the number of velocity comparisons is order of magnitude higher when using data on all profiles, and the matching is at least not better. Adding information on the coinciding profiles DOBRE-5 and profile 26 does not noticeably change the situation. Thus, the material for calculating heat generation was obtained with a significant error. However, its value does not make sense to directly transfer to the error of the subsequent calculation. That is precisely what is happening in this case, so with a methodology adequate to the calculation situation, one can fully expect an acceptable result.

The crustal thickness of Ukraine and typical errors in its determination on the DSS profiles are essential for assessing crustal heat generation. They are presented in Figs 3, *b* and 4. In addition to the profiles in Fig. 3, the variants of constructing velocity models from [Zverev, Kosminskaya, 1980] were used for comparison.

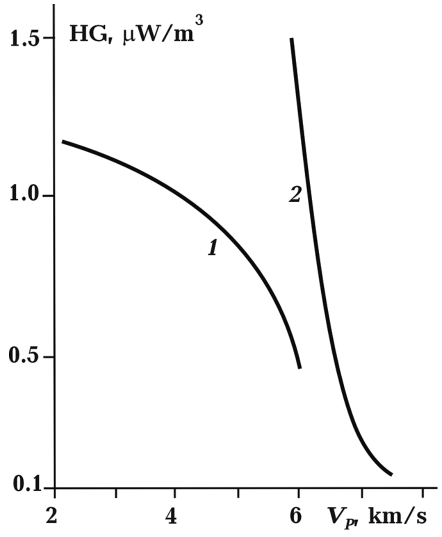

Fig. 5. Relationship between seismic wave velocity and heat generation for crustal rocks [Gordienko et al., 2002 etc.]: *1* — sediments, products of epi- and catagenesis, *2* — crystalline rocks.

The depth discrepancies at the points of intersection (or coincidence) of the profiles are rather significant — 4 km, corresponding to the error of 2.5—3.0 km for each model and determining the cross-section of reliable isolines not less than 8 km. Therefore, placing the depth anomalies of Moho depths on the local mosaic scheme does not make sense. Only large structural elements are reliable. A clear reduction of crustal thickness in the regions of recent activation of the Alpine and Cimmerian geosynclines is obvious. Unlike similar processes on the platform, here they are accompanied by crustal thickness reductions comparable to rifting or even oceanization. V.V. Belousov called such development in the geological past «failed oceanization» [Belousov, 1982]. More ancient traces of the Hercynian rifting are traced by the reduced crustal thickness in the Dnieper-Donets Basin and part of the Donbas parageosyncline.

Some crustal thickening on the periphery of the Dnieper-Donets Basin reflects a noticeable horizontal overflow of crustal matter within the rift advection zone [Gordienko et al., 2006, 2015; Gordienko, 2017].

The strip of crustal thickening of the northeastern strike in the western part of the Ukrainian Shield and the Volyn-Podolsk Plate is associated with more ancient (at least pre-Riphean) events. It is considered below as an argument for anomalous heat generation in the crust of the East European Platform.

Calculation of heat flow from the crust of Ukraine. The relationship between the *P*-wave seismic velocity and radiogenic heat generation for the rocks of the Earth's crust of Ukraine has been studied in detail and undergone multiple checks and refinements by our research in all regions of the country [Gordienko et al., 2002, 2005, 2006, etc.].

The values of the parameters in Table and Fig. 5 are given for platform *PT*-conditions. Information for a recalculation that considers the effects of abnormal temperatures compared to platform ones can be obtained relatively easily for velocities (approximately 0.06 km/s per 100 °C) in crystalline crustal rocks. They are the ones that underwent

Longitudinal seismic wave velocities and crustal rock's heat generation

V_P, km/s	HG, mkW/m^3	V_P, km/s	HG, mkW/m^3	V_P, km/s	HG, mkW/m^3
Sediments, products of epi- and catagenesis					
2.0	1.18	3.5	1.05	5.0	0.87
2.5	1.15	4.0	1.01	5.5	0.73
3.0	1.10	4.5	0.95	6	0.48
Crystalline basement rocks					
5.8	1.54	6.4	0.66	6.9	0.28
6.0	1.22	6.5	0.60	7.0	0.23
6.1	1.08	6.6	0.54	7.1	0.23
6.2	0.90	6.7	0.43	7.2	0.20
6.3	0.80	6.8	0.34	7.4	0.16

the most significant impacts of anomalous temperatures [Gordienko et al., 2002, etc.]. Naturally, their impact led to the rock density change (U, Th, and K concentrations, i.e., to a change in heat generation), to which corrections in the calculated HG (of a different sign) should correspond. However, they are insignificant (less than 10 % of corrections related to the account of temperature anomalies of velocity).

As calculating the HG value using the velocity models of the crust requires a sufficiently detailed idea of the composition and *PT*-conditions incrust, we used geological and geophysical data covering the entire Ukraine area [Gordienko et al., 2005, 2006, 2011, 2012, 2015, 2017; Varentsov et al., 2013, etc.].

For calculations, we used the program for estimation temperatures (T) produced by stationary three-dimensional sources used in many publications mentioned above. The program calculates the parameters of objects with anomalous ΔT and volumetric heat capacity (cv) over short periods of time (Δt) — ΔT=HG$\Delta t/cv$. Successive inclusions of such sources occurred until complete stabilization of T was achieved in the depth range of about 70 km. At a greater distance from the sources, it is necessary to consider the change in heat generation over time. In this case, we used the results of the upper 5-km section, for which regional thermal conductivity values could be applied (as, for example, has been done by calculating the geothermal energy reserves of Ukraine [Gordienko et al., 2002, etc.]). The check demonstrated sufficient accuracy of the calculations — within 1 mW/m^2 level. It was performed for a pack of layers of practically infinite length and width with a total thickness of 40 km (the reference block). Precise knowledge of heat generation in the strata was assumed.

For almost all regions of Ukraine, the characteristics of the HG models were studied in terms of the influence of the sizes of the crustal sources on the results of the calculated total effect of HF [Gordienko, 2005, etc.]. For typical cases, for a block width of 30—40 km, the effect of the upper 15 km of the crust is 15 mW/m^2; its difference from the reference block reaches a few percent. The effect of the block at a depth of 15—30 km is about 7 mW/m^2, constitutes a difference from the reference block of about 10 %, and for the block in the depth range of 30—45 km, it reaches 3 mW/m^2 with a difference up to 20 %.

Such peculiarity of the radiogenic HF from the crust of calculation in comparison with calculations of the gravity effect of the density model is associated with a sharp change in heat generation with depth (basicity) and metamorphic stage of the crustal rocks. From the top of the basement, the rock density increases by about 50 %, whereas heat generation decreases by an order of magnitude.

Results, discussion, and conclusions. Acomparison of the calculated HF at the intersection and coincident regions of the DSS profiles was made (Fig. 6). The difference between them is 10 % of the medium HF value on average — about 2.5 mW/m^2. The error of the separate value is about 1.8 mW/m^2. Reliable isolines can be drawn with a 5 mW/m^2 interval (a 4 mW/m^2 seems more convenient for representing the real field).

As in the case of the Moho depths scheme (see Fig. 4), the compiled scheme (Fig. 7) characterizes only the regional features of radiogenic heat generation of crustal rocks.

The observed crustal heat flow values range from 15 to 30 mW/m^2. Almost the same values occur in all fairly large and tectonically heterogeneous continental regions of the Earth.

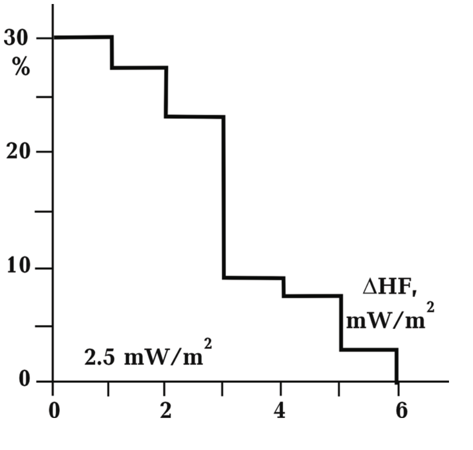

Fig. 6. Distribution histogram of differences in the calculated crustal heat flow values obtained at intersecting or overlapping profiles within Ukraine.

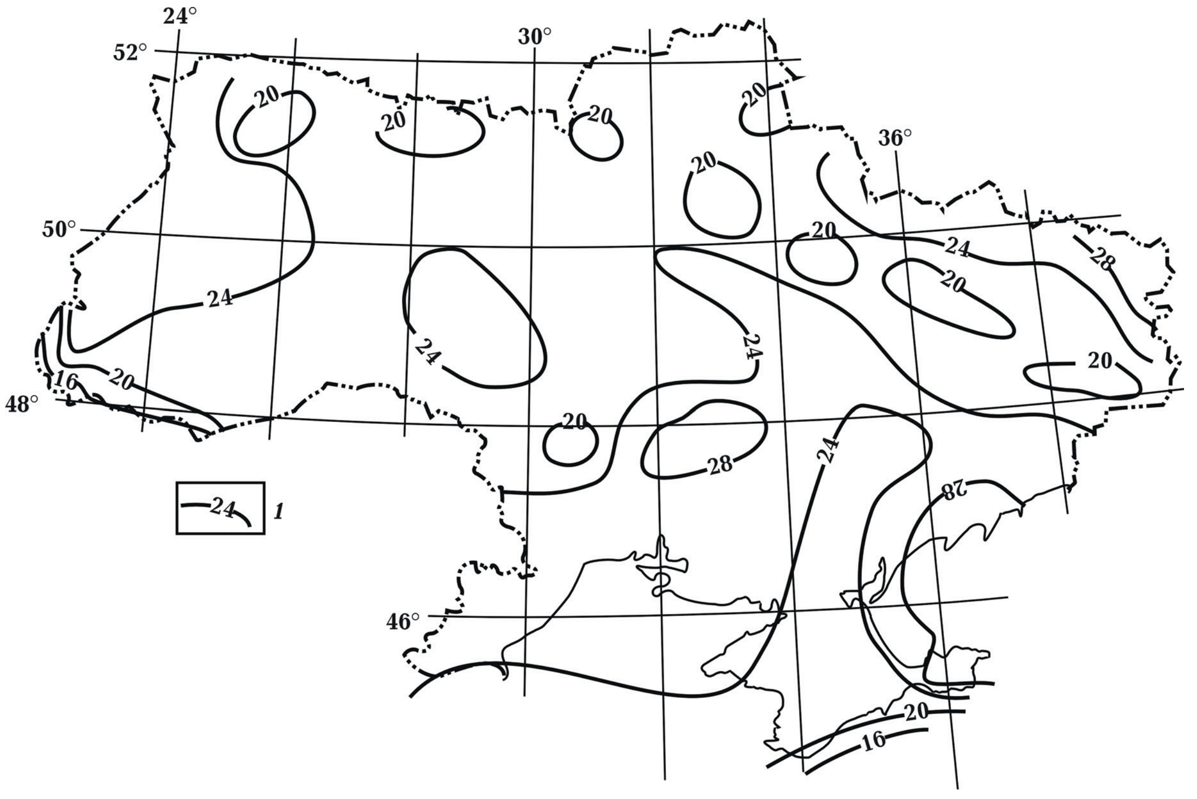

Fig. 7. Heat flow distribution formed by radiogenic heat generation of crustal rocks in Ukraine: *1* — HF isolines, mW/m^2.

Natural minima on the HF scheme are visible in the areas of reduced crustal thickness on the margins of the Pannonian massif, which belongs to the Alpine geosyncline of the Carpathians and the Black Sea Basin.

A smaller decrease in crustal HF has been recorded in the Dnieper-Donets Basin and Donbas. In these regions, it is associated with the cumulative effect of some reduction in the thickness of the crust, and its notable basification occurred during rifting (including the Riphean stage of this process).

It is possible to obtain fundamentally new information by considering the nature of the above-mentioned band of abnormal crustal thickness and heat generation over the northwestern margin of the Ukrainian Shield and the Volyn-Podolian Plate. Large parts of this band show simultaneous crustal thickening at 10—15 % and a reduction in crustal HF by approximately the same value (to 18—20 mW/m^2). Such variations in heat generation in the rocks of the upper mantle beneath the platform seem quite probable based on the experimental data. In the central part of the Ukrainian Shield, the background value of crustal heat flow is 20—24 mW/m^2 [Tsymbal et al., 1999]. By combining the anomalous HG in the crust and upper mantle of the platform, it turns out that calculated temperatures in the tectonosphere of these areas are noticeably different (up to 200 °C). Naturally, such calculations consider the formation of temperatures during the complete (in time and depth) thermal history of the tectonosphere [Gordienko, 2017, etc.].

The results allow independent verification by geological data. Moreover, it turns out that similar anomalies are known not only in the Ukrainian Shield but also in the eastern part of the Baltic Shield (Karelian and Belomorian blocks) [Tsymbal et al., 1999; Panov et al., 2000; Tsymbal, Tsymbal, 2003; Svetov, Smolkin, 2003; Shcherbakov, 2005, etc.] (Fig. 8). In Ukraine, this information was obtained by studying xenoliths taken

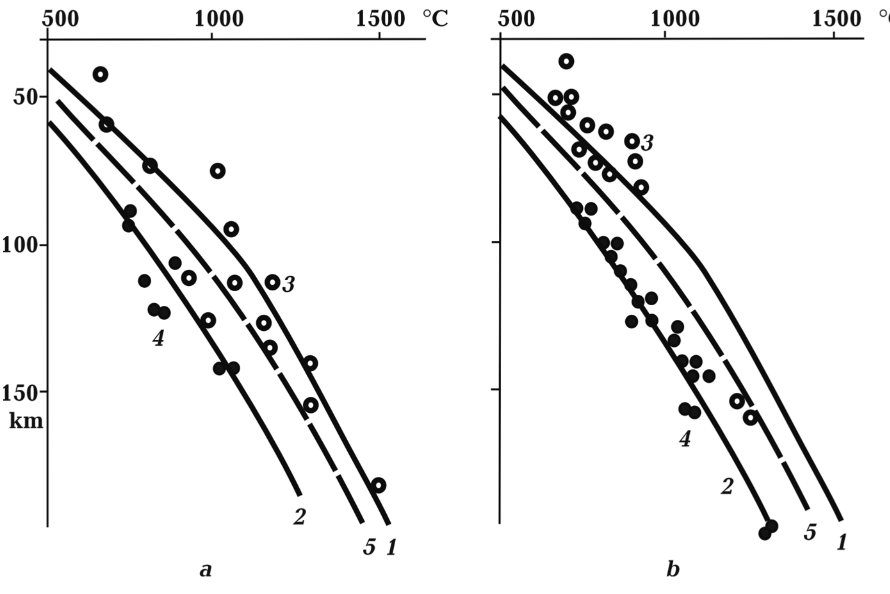

Fig. 8. Calculated (*1*, *2*) and experimental (*3*, *4*) temperatures (*a* — Ukrainian Shield, *b* — Baltic Shield) in zones of background (*1*, *3*) and reduced (*2*, *4*) heat generation in the crust and upper mantle [Tsymbal et al., 1999; Panov et al., 2000; Svetov et al., 2003; Tsymbal, Tsymbal, 2003; Gordienko et al., 2005; Shcherbakov, 2005; Gordienko, 2017, 2022, etc.]; *5* — mid-platform modern *T* distribution.

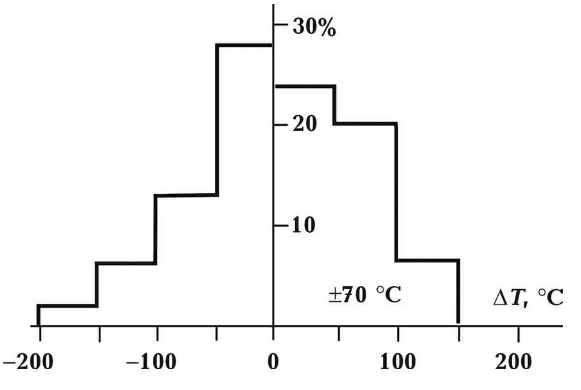

Fig. 9. Histogram of differences between calculated and experimental temperatures in the mantle of the Ukrainian and Baltic Shield blocks.

out from the mantle by kimberlites. In some places, their concentration reaches 40—50 % of the volume of kimberlite dikes. They are practically lacking crustal xenoliths. On the Baltic Shield, proper igneous rocks of mantle origin were studied. From the available data, two rock groups originated approximately at the same time range (middle Proterozoic) as kimberlites and had different calculated temperatures.

A comparison of calculated and experimental data (temperatures calculated from rock compositions [Gordienko, 2022, etc.]) demonstrates their complete consistency (Fig. 9).

The average discrepancy is 70 °C. The error in determining the temperature from the composition of mantle rocks is 50 °C. That is, ΔT corresponds to the same calculation error.

The findings allow us to draw the following conclusions.

1. The density of the DSS profiles network and the error in determining the values of *P*-wave seismic velocity on the velocity models for the Ukrainian crust allow us to calculate the total radiogenic heat generation of crustal rocks with the revealing regional crustal heat flow anomalies.

2. The main differences in HF from its average value for the Precambrian platform could be explained by active deep processes of the Alpine (Carpathians, Black Sea) or Hercynian (Dnieper-Donets Basin) age.

3. HF anomalies of both signs are revealed on the platform territory.

4. These heat generation anomalies coincide with the anomalies of the same sign from the upper mantle.

5. Similar anomalies were found in the Baltic Shield mantle. However, the source of information differs significantly from that of the Ukrainian one. Moreover, based on the available data, it is impossible to assume the existence of uniform anomalous zones extending across the entire platform.

6. The coincidence of mantle and crustal HG anomalies is preserved to depths of about 150—200 km during >1800 Ma. Hence, the crust and upper mantle of the Ukrainian part

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of the platform did not experience mutual displacements during this period.

7. The calculation shows that the temperatures under the zones of anomalous heat generation of different signs smooth out towards the base of the upper mantle [Gordienko, 2017, etc.], which allows the ubiquitous passage of the process of recent activation.

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Коровий тепловий потік на території України

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Наведено інформацію про вивченість теплового потоку на території України та за її межами за участю авторів. Показано, що за досягнутої якості отриманих даних вони можуть бути ефективно використані для контролю схем глибинних процесів у тектоносфері та походження родовищ корисних копалин. Побудовано карти розподілу теплового потоку і концентрації геотермальних ресурсів. Геолого-геофізична вивченість України дає змогу перейти до більш поглибленого вивчення теплового поля. Поставлено завдання розрахунку корового теплового потоку з огляду на радіогенну теплогенерацію на всій території країни. Для цього використано відомості про розподіл швидкості поширення поздовжніх сейсмічних хвиль уздовж профілів ГСЗ. Їх загальна протяжність становить близько 12 000 км. Виявлено похибку визначення швидкості поширення сейсмічних хвиль на профілях за величиною різниці в точках їх перетинів або накладень. У середньому різниця швидкостей становить близько 0,2 км/с. Відповідно, похибка визначення швидкості дорівнює близько 1,4 км/с. Така похибка дає змогу проводити ізолінії теплового потоку земної кори через 4 мВт/м^2. Наведено види зв'язку сейсмічної швидкості та теплогенерації для різних порід кори, дані щодо врахування аномальних (порівняно з платформними) температур. Разом із побудовою схеми корового теплового потоку за даними ГСЗ побудовано схему глибини поділу Мохо, що враховує похибку визначення цього параметра. Виділено регіональні аномалії корового потоку, пов'язані з геологічною історією окремих регіонів. Виявлено аномалії теплогенерації у платформній частині території України. Показано їх зв'язок з аналогічними аномаліями у верхній мантії. Отримані результати дають можливість перейти до визначення мантійного теплового потоку на території України.

Ключові слова: швидкості сейсмічних хвиль, радіогенна теплогенерація, коровий тепловий потік.