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Geotermal resources of Ukraine

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Геотермальні ресурси (W) — досить новий тип корисних копалин, але їх споживання — одне з найбільш швидкозростаючих галузей світової енергетики. Розрахунки величини W орієнтовано на ресурси, які можуть бути використані у теплопостачанні, видобутку води з температурою (T) не нижче 60 °C з використанням системи геоциркуляції та повернення води в надра з $T=20$ °C. Економічні оцінки передбачають досягнення рентабельності (за використання найбільш раціональних технологій) починаючи з геотермічного градієнта 0,02—0,025 °C/м ($W=2{,}5$ т ум. п. (тонна умовного палива)/м^2 до глибини 6 км). Розрахунки виконано не лише для глибини 6 км, а й для глибини буріння 3 і 4,5 км. Зазначимо, що обчислене значення W не повністю відображає теплові ресурси надр. Після видобутку енергії з глибини 5,5—6 км процес може бути продовжений на менших глибинах. Наприклад, у Дніпровсько-Донецькій западині (ДДЗ) ресурси, розраховані за формулою для глибини 6 км, можуть бути збільшені в 4,5 раза за рахунок екстракції з інших діапазонів глибин. Для розрахунку використано середні значення теплопровідності гірських порід (1,7—2,65 Вт/(м · °C)). Ресурси W розраховано на всіх 5500 точках, де визначено величину глибинного теплового потоку. Інтервал між ізолініями майже збігається з подвійною похибкою обчислення W. На картах показано, що рентабельні геотермальні ресурси розподілені у трьох великих басейнах — західному, східному і південному. У Центральній Україні вони трапляються лише на невеликих ділянках. Тепловий потік на цій території (головним чином, Український щит та його схили) вивчено щонайменше. В єдиній добре вивченій частині (центральній та у північно-східної межі щита) виявлено рентабельні ресурси. Найвище значення W отримано для західного басейну — Закарпаття (до 10 т ум.п./м^2), що перевищує ресурси великого нафтового або газового родовища, але середнє значення W (тут і далі для глибини буріння 6 км) становить близько 3,5—4 т ум.п./м^2. Загальна кількість енергії в басейні дорівнює близько 0,2 трлн т ум.п. У східному басейні високу величину W (5—7 т ум.п./м^2) зафіксовано лише в деяких районах Донбасу. Основна частина території має W близько 3 т ум.п./м^2, середнє значення в басейні — 3—3,5 т ум.п./м^2. Загальні ресурси становлять близько 0,3 трлн т ум.п. У південному бассейні, у центральній частині Криму, W дорівнює 7—8 т ум.п./м^2, але в більшій частині території — близько 3—4 т ум.п./м^2. Загальну кількість енергії басейну оцінено у $\approx 0{,}3$ трлн т ум.п. Загальні геотермічні ресурси України у діапазоні глибин 5,5—6 км (визначені до цього часу) перевищують у 20 разів запаси всіх горючих копалин на її території. Геотермальні ресурси, придатні для одержання пари (електричної енергії) без додаткового нагріву, проявляються у мінімальній кількості на глибині буріння 4,5 км лише в частині Закарпаття. У свердловинах на глибині 6 км ці ресурси досягають рентабельного рівня на Закарпатті й обмежених територіях Криму та Донбасу.

Ключові слова: глибинний тепловий потік Землі, геотермальна енергія, оцінювання геотермальних ресурсів.

Introduction. The share of the Earth's heat in the world's energy balance is insignificant, so far. It is, however, the fastest developing branch of power engineering [Zabarny et al., 1997; Lud, Mishchenko, 2001 and others]. The deployment in recent years of new technologies for heat extraction (thermal pumps and so on) [Tester, Herzog, 1990;

Lud, Mishchenko, 2001; Kohl et al., 2002 and others] speaks volumes about the potential geothermal power engineering advancing to occupy a leading position in residential energy consumption. In economically developed countries, over several recent years, about a million geothermal heating systems for households have been installed. The ecological aspect is also noteworthy here: The modern geothermal energy systems provide for complete return of the water, recovered from large depths, back into the ground. For that reason, analysis of geothermal evidence with a view to assessing the thermal energy resource potential appears to be important and topical.

This study is regional in character and aims specifically at an assessment of the concentration (density) of thermal resources (*W*). Actually, reserves in deposits can already be determined once relevant tasks are set for a number of Ukrainian regions. In accordance with requirements worked out for other mineral deposits, such an assessment can be performed in different versions [Dyadkin, 1985; Shpak et al., 1989; Dyadkin et al., 1991; Gordienko, 2001; Gordienko et al., 2002b and others] with dissimilar degrees of validity and proceeding from dissimilar heat-extraction technologies. The circulation technology for heat extraction from dry rocks [Armstead, Tester, 1987; Shpak et al., 1989 and others] appears to be the best as it fully reflects the region's energy potential. It is precisely for the case of circulation technology that calculations will be performed and, if necessary, the results can be re-examined in line with requirements of other technologies.

It is common practice to classify resources, in terms of the degree of validity, into the categories of promising (C_3) and forecast (P_1 and P_2). With regard to resources in category P_2, we are talking just about the probability of conditions prevailing in the region that might be favorable for the formation of geothermal energy fields. Information on temperature distribution at depth is based on geological and geophysical data (also, to a small extent, on geothermal data). The largest achievable drilling depth (10 km) is adopted in the calculations. It is assumed that the rock massif can be cooled down to a temperature prevailing at the surface. In fact, this approach can only result in a wishful appraisal, which is hardly suitable for identifying specific areas potentially promising for the extraction of the Earth's heat. The P_1 category is applicable to regions, for which energy extraction has already been rated as possible, in principle. The calculations use currently realistic drilling depths (down to 6 km) and take into account requirements from various energy consumers regarding the temperature at the input of the heat carrier to the heat-exchange unit and its subsequent discharge. Promising resources C_3 also take into account economic expediency of the Earth's heat utilization in terms of its confinement to densities at which the extracted energy can compete with that provided by conventional sources.

The borderline between P_1 and C_3 resources shifts with technological improvements and with the cost of energy from conventional sources. For that particular reason, the authors decided to perform calculations for the entire territory of Ukraine assuming the level of *W* that reflects the contemporary position of the borderline between P_1 and C_3. In doing so, we will focus on resources suitable for the use in heat supply systems, i. e., for hot fluid extraction from the geothermal circulation system (GCS) at the temperature of 60 °C and it's dumping out at 20 °C. These are the largest possible resources, considering that we need 100—40 °C and 210—70 °C, respectively, for heating and electricity production (steam for turbines). This approach enables us to adopt globally approved results of economic appraisals published by the Massachusetts Technological University (Fig. 1). They point to the economic feasibility of geothermal energy extraction from the GCS for the most up-to-day technologies at the level of the geothermal gradient γ equaling 20—25 °C/km. Ukraine also provides an example of using thermal energy in practice in an area with such a value of γ.

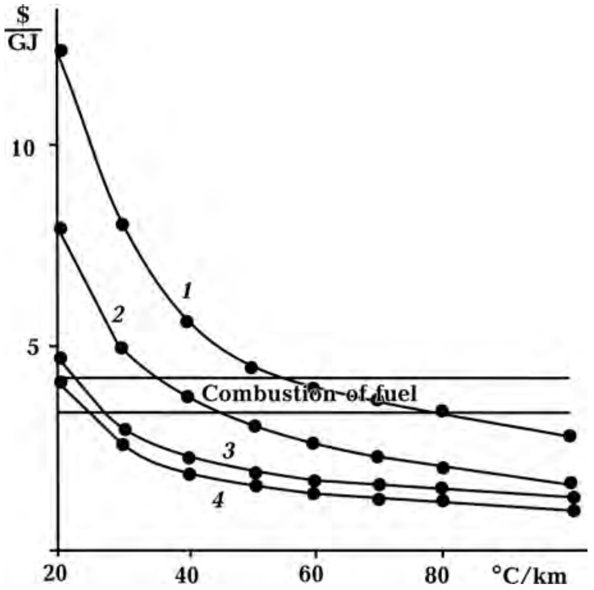


Fig. 1. Production costs of the heat extracted with the help of the geothermal circulation system (GCS) as a function of geothermal conditions and of the technological level. Economic model of the Massachusetts Technological University [Tester, Herzog, 1990]. The digits 1 to 4 designate versions of the GCS technology.

Actual sources of geothermal energy involve a feature that often tends to be misrepresented. We are talking about categorization of such sources as renewable. This is true, in principle: The heat extracted from the Earth's interior will, some day, be replenished with the heat coming from larger depths. However, in terms of the genuine thermal properties of the medium, the rate of such a renewal turns out to be incommensurably slower than what human history is aware of, i. e., it will eventually amount to zero.

We used in our analysis the data obtained for the territory of Ukraine due to two reasons: 1) the authors have contributed much to the detailed coverage of the territory in question; 2) we can show on this example the significance of geothermal energy for ordinary (not volcanic) region.

Calculation procedure. This is how the density of thermal resources is calculated [Dyadkin et al., 1991 and others]:

$$W = N \cdot K \cdot C_c \cdot \Delta T (H_{bd} - H_b),$$

where N is the fuel consumption norm per marketable heat. It equals $0.34 \cdot 10^{-10}$ tons of standard fuel divided by J (one ton of oil contains 1.47 tons of s.f.; one ton of coal — 0.9 tons of s.f.; (one ton of condensate — 1.54 tons of s.f.; 1,000 m^3 of gas — 1.25 tons of s.f.; and one ton of lignite — 0.49 tons of s.f.); K is the temperature extraction coefficient (adopted in the publication by [Dyadkin et al., 1991], as equaling 0.125); C_c — volumetric heat capacity of rocks. It is virtually invariable and amounts to $2.5 \cdot 10^6 \mathrm{J/(m^3 \cdot {}^\circ C)}$; ΔT — is the temperature differential (amounting to 40 °C) between the heat carrier and the water being discharged; H_{bd} — is the depth of the borehole at which the bottom T was measured; accordingly, $W = 0.000425 \times$ $\times (H_{bd} - H_b)$ in tons of s.f./m^2 (H in meters); H_b is the depth at which the average temperature in the $H_{bd} - H_b$ range amounts to 60 °C. It is determined from the formula $(T_{bd} - T_{tm})/0.5\gamma$, where T_{tm} stands for the temperature of the heat carrier, γ — is the average geothermal gradient within the depth interval.

If the temperature (T) at the lower point is high, the upper point turns out to occur above the surface. To prevent this situation from happening, we need to introduce a restriction for T: It has to be 10 °C higher than the temperature of the water to be dumped back, i. e., it must be 30 °C. In such a case, we need to take into account the difference between the average temperature of recoverable water and the standard temperature amounting to 60 °C. This produces an additional factor — $(T_{av} - 20)/40$ — in the W calculation formula.

Consequently, the task reduces to determining T for the given region (for the given distribution of thermal conductivity with depth) at dissimilar deep-seated heat flows (HF) characteristic of the region and to subsequent assessment of W for the drilling depth of 6,000 meters (evaluations were also performed for the depths of 4,500 and 3,000 meters). The use of the specific temperature at the surface on the site, where deep-seated temperatures were determined, produces variations in W values of up to ±4 % (for example, if 8 °C is replaced by 6 to 10 °C). Thus, it is possible, in principle, to adopt a single T_0 value in the determination of T in terms of the heat flow.

Clearly, the temperature extraction ratio is not a constant value. It has to be determined with a view to real conditions of the procedure.

The calculation shows that we do not need to take into account every single parameter of the process. To begin with, the temperature anomaly does not significantly exceed the limits of the fractured zone over the entire period of system operation. The time of the system existence may constitute a restriction. It is associated with silting of the fractured zone around the borehole. This prevents water being discharged from percolating back down in required amounts, so that more power is needed to operate injection pumps, and so on. Proceeding from available data, the geothermal circulation system may function for 25 years. If it operates for a shorter period of time, then the moment when the average temperature in the bed, from which water is extracted, reaches 60 °C, heat extraction must be halted.

Let us determine the system's operating time. According to [Tester, Herzog, 1990 and others], the layer in which fracturing occurs can reach 500 meters in thickness. We estimate the dimensions of the fractured area as 250 × 250 meters. The connected porosity accounts for about 0.1 of the rocks' volume. Its variation does not have any significant effect on the result: depending on porosity, the system will be filled through a single operation of the injection pump more frequently (with a lower single thermal effect) or more seldom (with a larger single thermal effect).

The amount of injected water, given affordable power consumption for injection operations, will amount to 1,000—7,000 m^3 a day. If we adopt a real value (to simplify the assessment) of 4,300 m^3 a day, it takes two years to fill up the porous system. The following formula describes temperature drop in the volume: $T_{a1} = 0.167\,dT$ (taking into account the ratio of volumetric heat capacities of water ($4.18 \cdot 10^6$ J/($m^3 \cdot$°C)) and of the rock). dT denotes temperature difference between the average T at the depth of 5,500—6,000 meters and 20 °C. The evaluation shows that the resulting anomaly remains intact in the body (not for just two years, but for the entire real period of observations). Therefore, T_{a2} equals $0.167\,(dT - T_{a1})$ and so on, until (dT — the sum of T_{a1}), etc. reaches 40 °C.

The estimated time for the drilling depth of 6 km at geothermal gradients amounting to 2—6 °C/100 meters ranges between 8 and 23 years; for 3 km, the estimated time will constitute 1.5 to 13 years. Therefore, the lifetime of the system is not exceeded and the coefficient K can be determined ($T_0 =$ = 10 °C) as $(5{,}750\gamma - 50)/(6{,}000 - 20/\gamma)\,6\gamma$, where γ is measured in °C/meter. At $\gamma =$ = 0.02, K amounts to 0.108, at 0.03 to 0.127, at 0.04 to 0.136, and at 0.05 to 0.141.

The calculations of abyssal temperatures in terms of deep (corrected) heat flow of the Earth (HF) values in the regions were conducted for a stationary distribution, and corrections were excluded from estimated temperatures. The point is that observed heat-flow values are not suitable for the task when we deal with large depths. In the Dnieper-Donets Basin (DDB), it was more suitable, instead of striking off the correction for hydrogeological conditions, to introduce somewhat elevated thermal conductivity in the upper portion of the profile.

The calculations used values of average effective thermal conductivities γ of rocks within the depth ranges of 0—1.5, 1.5—3, 3—4.5, and 4.5—6 km listed in Table 1 (in W/(m·°C)).

The suggested technique for estimating abyssal temperatures involves obvious sources of errors, primarily, the failure to account for real values of thermal conductivity at the evaluation point. To make up for this inconsistency, we conducted comparison between estimated and measured temperatures for all the regions in question at maximum depths of measurements. This did not include the Ukrainian Shield and its slopes, where virtually no deep boreholes are available (except for the boreholes in Krivoy Rog

Table 1. Thermal conductivities distribution versus depth in Ukrainian regions

ΔH, km	1	2	2-3	3	4	5 and 7	5, 7 slopes	6 pit walls	6	8	9	10
0—1.5	1.85	2.65	2.45	1.8	2.1	2.65	1.7	1.8	1.8	2	1.8	1.6
1.5—3	2.65	2.65	2.45	2.25	2.65	2.65	2.65	2.05	2.05	2.1	2.2	2.05
3—4.5	2.65	2.65	2.45	2.65	2.65	2.65	2.65	2.65	2.2	2.3	2.65	2.5
4.5—6	2.65	2.65	2.45	2.65	2.65	2.65	2.65	2.65	2.3	2.5	2.65	2.65
0—6	2.39	2.65	2.45	2.28	2.49	2.65	2.32	2.22	2.07	2.21	2.27	2.12

Numbering of regions: 1 — Transcarpathian, 2 — Carpathian, 3 — Ciscarpathian Trough, 4 — Volyno-Podolian plate, 5 — Ukrainian Shield and its slopes, 6 — Dnieper-Donets Basin, 7 — Voronezh Massif, 8 — Donbass, 9 — Southern Ukraine monocline, 10 — the Crimea.

and Kirovograd areas, 5 and 3 km, respectively). The resulting histograms display modal values of deviations in the Carpathian, Transcarpathian, and Donets Basin regions amounting to 1 °C. For the Dnieper-Donets Basin, the Crimea, the Volyn-Podolian Plate, and Southern Ukraine monocline, the deviations amount to 3—4 °C. The deviations increase sharply exclusively in areas with thick salt beds. They are, however, not suitable for the creation of geothermal circulation systems (GCS). Consequently, errors in temperature evaluations cannot have a significant effect on the determination of W. The predicted error of up to 10% does not exceed that in the measurements of the heat-flow.

Let us now determine the level of W, delineating areas with the territorial distribution of category C_3 resources. It amounts to 2.5 tons of standard fuel per square meter. Table 2 lists heat-flow values in various regions of Ukraine that are compatible with the aforementioned and other values of W. It is obvious that the relationship between the territorial distribution of geothermal sources and the value of the deep-seated heat flow (HF) is quite complicated, especially so at large values of W.

The estimates indicate that the density of resources falling into category C_3 are quite widespread.

Of certain interest is correlation between W values and the data on hydrocarbon deposits. Let us examine the territorial distribution of energy resources that can be extracted in the form of commercial heat from a large oil deposit in the Dnieper-Donets Basin (without taking into account the expenditure of energy on oil transportation and with the efficiency of its conversion into useful heat amounting to 0.8). If we adopt actual parameters of the deposit: thickness of the productive bed equaling 180 meters; porosity of the reservoir rocks — 0.15; the pore-filling coefficient — 0.75; the extraction coefficient — 0.37; and oil density — 0.8 t/m^3, we get 8.8 tons of standard fuel per m^2. In the case of minor deposits, which, in the conditions prevailing in Ukraine, are considered to be cost efficient for operation only provided that boreholes are already there, the reserves distribution density is smaller by an order of magnitude.

This suggests that, even in terms of concentration, geothermal energy in a number of areas is comparable with that comprised in traditionally mined hydrocarbon deposits. Territories where geothermal energy is available are much more sizable.

The above evaluation of K envisages "single-use" heat extraction technique. In this case, the value of $W(W_6)$ appears to be sharply lower. It is obvious that energy extraction can proceed further even after its source has been exhausted at the depth of 5.5—6.0 km (possibly, without the need of drilling additional boreholes). Energy is likely to be recovered from the depths of at least 2.5—3.0 km at the geothermal gradient of 20 °C/km. Relevant evaluations for other depths (H, in km) at the bottom of the interval being mined produce values of $W = (0.427H - 0.07)(\gamma - 2.7 + 0.3H)$. For example, given the heat flow of 45 mW/m^2 typical of the Dnieper-Donets Basin, the "full" value of W will be 4.5 time higher than W_6. It is noteworthy that by using the data for regions characterized by dissimilar values of W_6, we can readily obtain (for the range of $W_6 = 2.5 \div 10$), $W_3 = 0.53(W_6 - 1.5)$ and $W_{4,\,5} = 0.78(W_6 - 0.8)$.

Initial data. In our specific case, the evaluation of geothermal reserves distribution density was based on the available heat-flow values.

The authors have a lot of experience in the study of heat-flow. They took part in its research in the territories of Bulgaria, Poland, Moldova, Lithuania, Belarus, the European and Asian parts of Russia, Armenia, Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan [Gordienko, Tal-Viersky, 1990; Gordienko et al., 1992 and others]. They compiled TP maps of different scales of Ukraine, Europe, the European part of the USSR, the whole of the USSR [Buryanov et al., 1987; Gordienko et al., 1987, 1999, 2002a, b; Gordienko, Moiseenko, 1991; Gordienko, Zavgorodnyaya, 1993; and others].

The level of knowledge of Ukraine's territory in terms of heat-flow is unique [Kutas, Gordienko, 1971; Gordienko et al., 2002b, 2004; 2016 and others]. In the rest of Europe, about 4,000 HF values were determined in various boreholes, whereas in Ukraine (occupying just 6 % of the continent's area) the number of such determinations is 13,000. A comparable amount of HF is installed in the US, whose territory is more than 16 times. Thus, Ukraine is best suited for showing the potential possibilities of utilizing the Earth's heat in regions, the majority of which have not been known for a high-energy potential.

Table 2. Correlation between HF and W in different Ukrainian regions

W, tons of s.f. per m^2	HF, mW/m^2 in regions											
	1	2	2-3	3	4	5, 7	5, 7 slopes	6 pit wall	6	8	9	10
1	—	—	—	—	—	38	—	—	—	—	—	—
2	—	4	44	41	4	48	42	40	3	40	—	—
3	—	5	54	50	5	59	51	49	4	49	50	—
4	—	6	64	60	6	69	60	—	5	58	59	5
5	73	8	74	69	7	79	—	—	6	67	68	6
6	82	—	—	79	—	—	—	—	—	76	—	7
7	92	—	—	—	—	—	—	—	—	85	—	8
8	10	—	—	—	—	—	—	—	—	—	—	—
9	11	—	—	—	—	—	—	—	—	—	—	—
10	12	—	—	—	—	—	—	—	—	—	—	—
HF $C_{3\,\min}$	48	53	49	46	50	53	46	44	41	44	45	42

Evaluation of geothermal resources is not the sole purpose of heat-flow studies. The technique used for analyzing the heat-flow distribution in the territory of Ukraine is virtually unique. We apply patterns of deep-seated processes within the Earth's tectonosphere, based on the advection-polymorphism hypothesis [Gordienko, 2015, 2017 and others]. For the first time in the history of geological science, this hypothesis views the heat and mass transfer within the Earth as a source of energy and adheres to the energy conservation law. This approach makes it possible to explain, on a quantitative level, all known phenomena in geological history over 4.5 billion years on continents, in oceans, and transition zones without tailoring parameters. This enables us to explain anomalies of physical (primarily, thermal) fields by solving direct problems alone. Anomaly evaluation results agree with observed ones within margins of experimental and calculation errors.

In addition to a large body of information on the heat flow, Ukrainian explorers make use of values of the deep-seated heatflow. This implies introduction of allowances for the effect of near-surface distortions into observed values.

This primarily applies to the effect of the paleoclimate. Special studies have made it possible to select the length of the time sequence for paleotemperatures at the surface enabling us to adjust the values of T at various depths. The total length of the sequence amounted to 1.2 million years. Adjustments in shallow boreholes drilled through the shield sometimes account for one-third of the heat-flow value.

In many regions, the effect of groundwater cross-flows was significant. It is extremely diverse in form and intensity. In some cases, the geothermal gradient may decrease almost to zero. If the borehole pierces "underground rivers," there may also appear negative values of the geothermal gradient.

Less significant and less common in Ukraine are allowances for the structural effect, young thrusts, and sedimentation. Those features are large beneath the surface of the Black Sea floor, but no relevant data were used in the evaluation of W.

The HF values in adjacent (one minute of latitude and longitude apart) boreholes were averaged in line with the regional character of the study. As a result, the diagrams presented below cover 5,500 sites. The HF determination grid is very irregular. Clearly, the majority of values were obtained for petroliferous and coal-bearing areas, as well as fin local territories of ore fields. In other areas (primarily, in a larger part of the Ukrainian Shield and its slopes, at the Voronezh Massif slope, and partly, in Folded Carpathians), "blank spaces" prevail.

Fig. 2 shows the pattern of HF distribution. This version of the map is somewhat out of date [Rudenko, 2007], so that in the given case, it is simply a way to show a general picture of the parameter variations.

The difference between maximum HF values for the Transcarpathian Trough (120—130 mW/m^2) and minimum values for the Ukrainian Shield (30—35 mW/m^2) reaches a factor of 4, and the estimated values of W differ even more significantly (see below). Even before we proceed to estimating geothermal resources density, it can be surmised that they are mainly confined to three vast basins: western, southern, and eastern, divided by a territory at the center of Ukraine where the resources are scarce. The majority of the aforementioned basins cannot be shown in the maps presented below, yet it is precisely within those basins that the region's maximum geothermal energy is amassed (Fig. 3).

The lateral dimension of the anomalies amounts to a few kilometers, and the intensity of the disturbance (above the local background) is rather monotonous — about 20 mW/m^2, which corresponds to the W increase (see Table 2) by approximately 2 tons of s.f./m^2. Geological evidence and special evaluations indicate that the anomalies are confined to areas close to heated fluids whose source is located at a depth of 6—7 km in zones of recent activation [Aleksandrov et al., 1996; Gordienko et al., 2002b and others]. The width of the permeable zone through which the fluids percolate turns out to be small — at the level of a few hundred meters. A.E. Lukin built a similar model, not based on geothermal data, for a petroliferous structure in the Dnieper-Donets Basin [Lukin, 1997] (Fig. 4). It is noteworthy that in all cases the parameters of the circulation system are similar, despite the tectonic diversity of the regions in question.

Consequently, already at this stage of regional studies, one can talk about the discovery of individual geothermal energy resources that occur in virtually all regions of Ukraine, including the Ukrainian Shield, which is, in fact, not really promising for the mineral resource in question.

Geothermal resources in Ukraine's main region. Fig. 5 shows distribution of geothermal resources in the western region.

The W_6 level on the Volyn-Podolian plate conforms to the changeover from low values at the slope of the shield to elevated ones in the Carpathian geosyncline undergoing a stage of post-geosynclinal activation. In the north of the region, there lies a zone of extremely low W values (much lower than cost-efficient) confined to the site of the Volyn negative heat-flow anomaly. The average level of the geothermal energy concentration is quite low ranging from 1.5—2 to 2.5 tons of s.f./m^2. Elevated W_6 values are only observed within Yavoriv, Ternopil, and Chernivtsi heat-flow anomalies (up to 4—5 tons of s.f./m^2). The anomalies in question are confined to recent activation zones where other geological and geophysical indications of the process have also been registered.

A similar pattern has also been observed for the Ciscarpathian Trough (which, with the exception of its southwestern margin, overlies a Precambrian basement) where typical values of the heat flow are small and where larger heat-flow values have only been registered within western portions of the Yavoriv and Chernivtsi anomalies, as well as at the border with the Folded Carpathians.

The thermal field in the Folded Carpathians has largely been explored in the Skiby zone, which partly overlaps the foredeep. In the main part of the region, there are few boreholes covered by studies, so that we observe a large "blank space" there (see Fig. 5). The values of W_6 average 33.5 tons of s.f./ /m^2 despite the rather high HF. This is due to the considerable thermal conductivity of rocks reducing the geothermal gradient.

In the Transcarpathian Trough, the values of W_6 are the largest for the territory of Ukraine. In some areas, they come up to 10 tons of s.f./m^2. This region appears to be the most likely for making use of the Earth's heat. It is there that hot water is supplied to spa resorts and goes for heating purposes. There were plans to build a geothermal electric power plant there. Nowadays, however, the structure, designed for the plant, serves as a gas-storage facility for the transit gas pipeline.

Owing to the large territory the Volyn-Podolian plate occupies, the total amount of resources in the western basin makes it quite promising (despite the low W_6 values). Altogether, $0.25\cdot10^{12}$ tons of s.f. is accumulated in the basin (we are talking about the depth range of 5.5—6.0 km, and the resources can be considerably supplemented by those located at more shallow depths — see above).

In the southern basin (Fig. 6), at the transition from the Ukrainian Shield slope to the southern Ukrainian monocline, and then to the Scythian plate, the W_6 value gradually increases from north to south from 2.5 to 3.5—4.0 tons of s.f./m^2. A combination of geological and geophysical studies conducted in recent activation zones of the Crimea, northern Dobruja, and cis-Dobrujan Trough have identified anomalies of up to 7 tons of s.f./m^2. Some of them have been associated with the heating up of a stratum several kilometers in thickness by hot abyssal fluids [Gordienko et al., 2002b and others].

The total amount of geothermal resources in the basin is quite significant due to its vast territory: $0.3\cdot10^{12}$ tons of s.f.

The thermal field in areas of the eastern basin has been explored with dissimilar degrees of detail. In the Donets Basin, the coverage is the best (6,500 individual determinations of the heat-flow), whereas at the

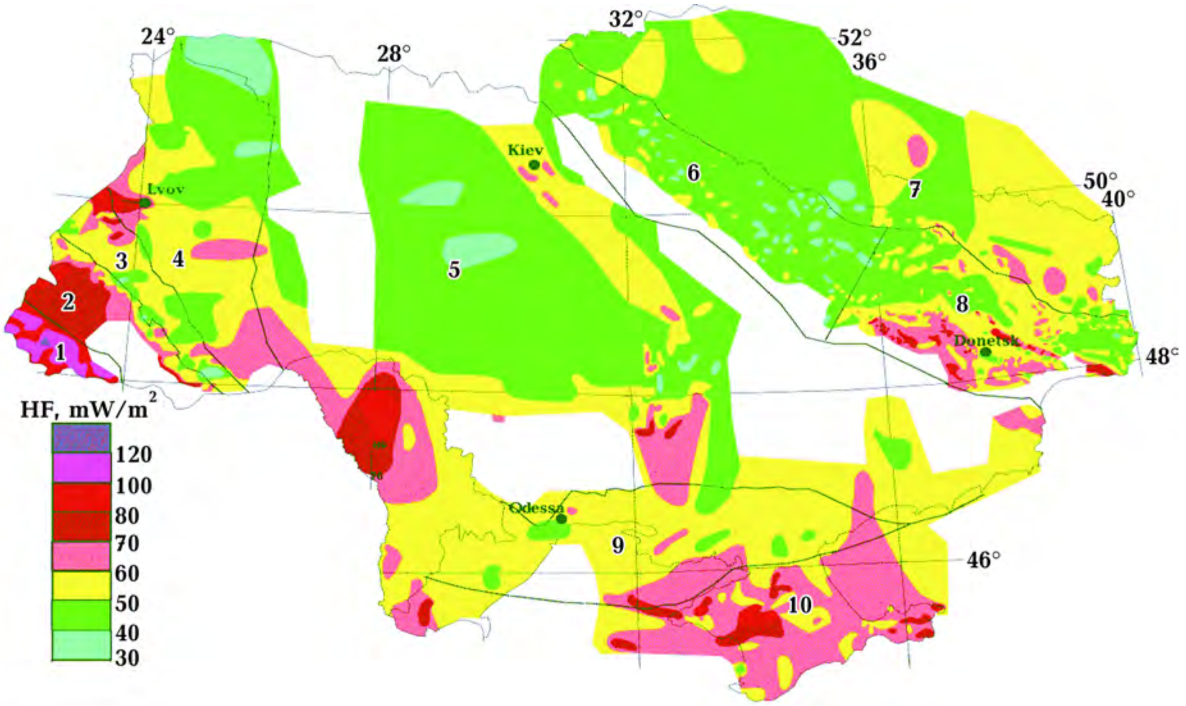


Fig. 2. Deep-seated heat flow on the territory of Ukraine and Moldova (numbers of regions see Table 1). The scale of the map varies from 1 : 200,000 to 1 : 2,000,000. Step isolines — two or three errors.

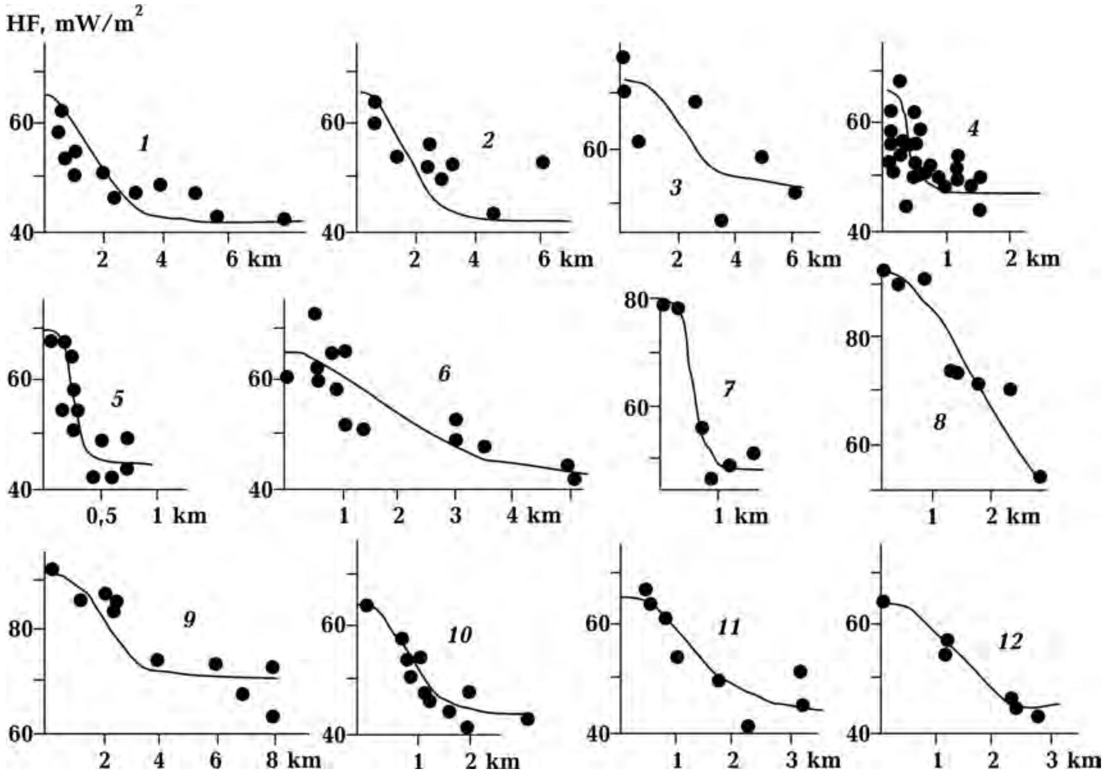
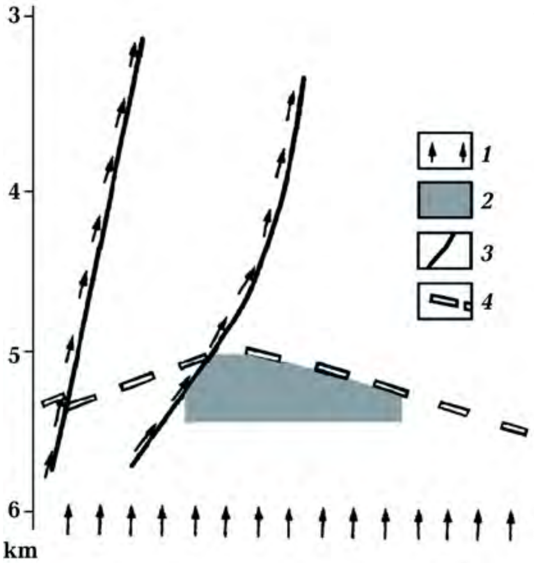


Fig. 3. Local anomalies of the deep-seated HF in various regions of Ukraine. The regions shown on the map: Volyn-Podolian Plate (*1*—*3*), CiscarpathianTrough (*4*), Ukrainian Shield (*5*, *6*), Donets Basin (*7*, *8*), Scythian Plate (*9*), and Dnieper-Donets Basin (*10*—*12*). The dots mark experimentally derived HF values and lines denote estimated values.



→ Fig. 4. Abyssal water injection through dislocations on the Machukha field [Lukin, 1997 adjusted for ease of reference]: *1* — direction of abyssal fluids movement under high-pressure, *2* — gas deposit, *3* — dislocations, *4* — unconformity surface (barrier?).

Fig. 5. Geothermal resources in the west of Ukraine: *1* — sites where the values of *W* were determined, *2* — boundaries of tectonic units. The periphery of the Pannonian Depression, the Transcarpathian Trough, the Folded Carpathians, the Ciscarpathian Trough, and the Volyn-Podolian plate extend from the southwest to northeast.

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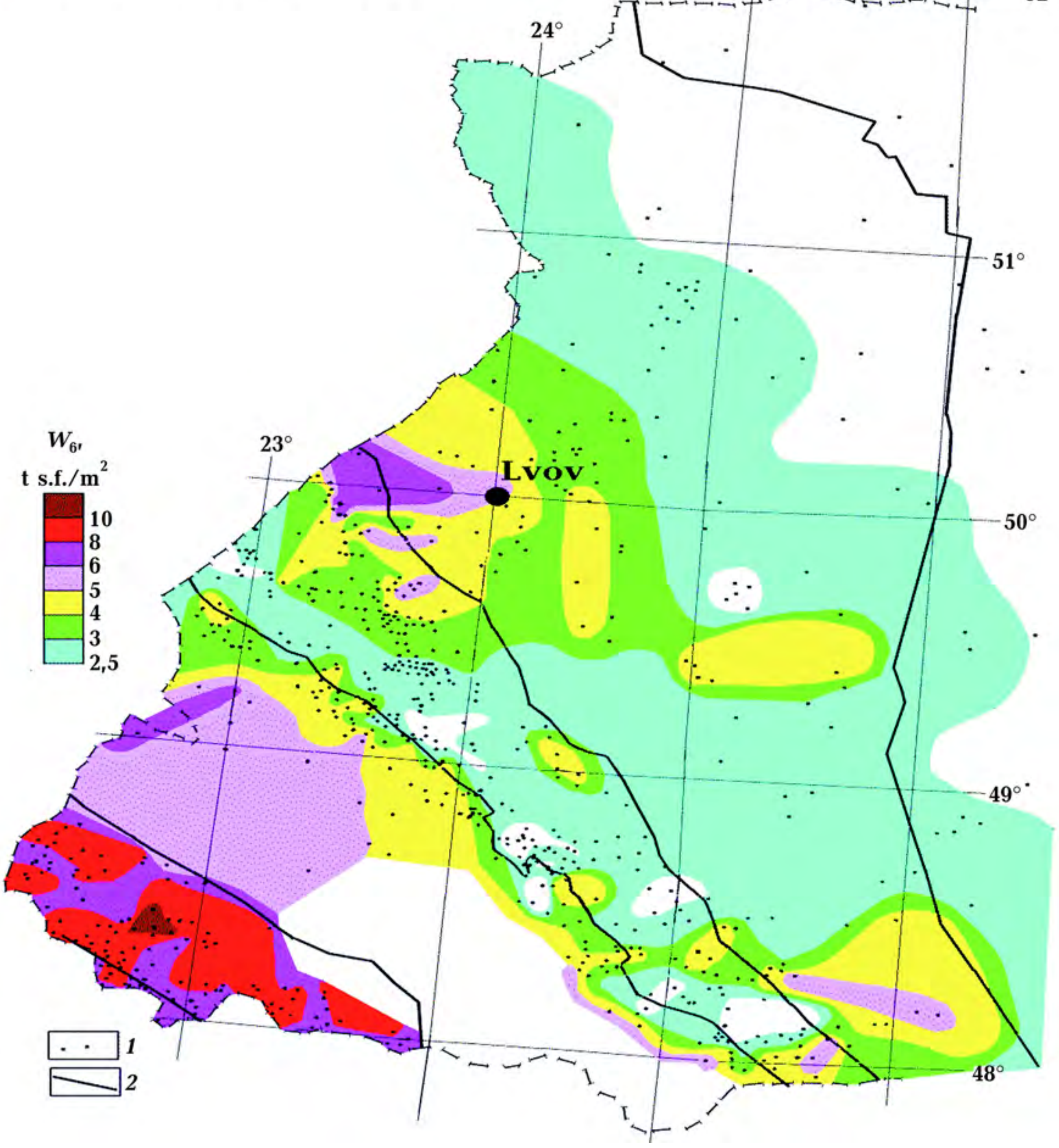


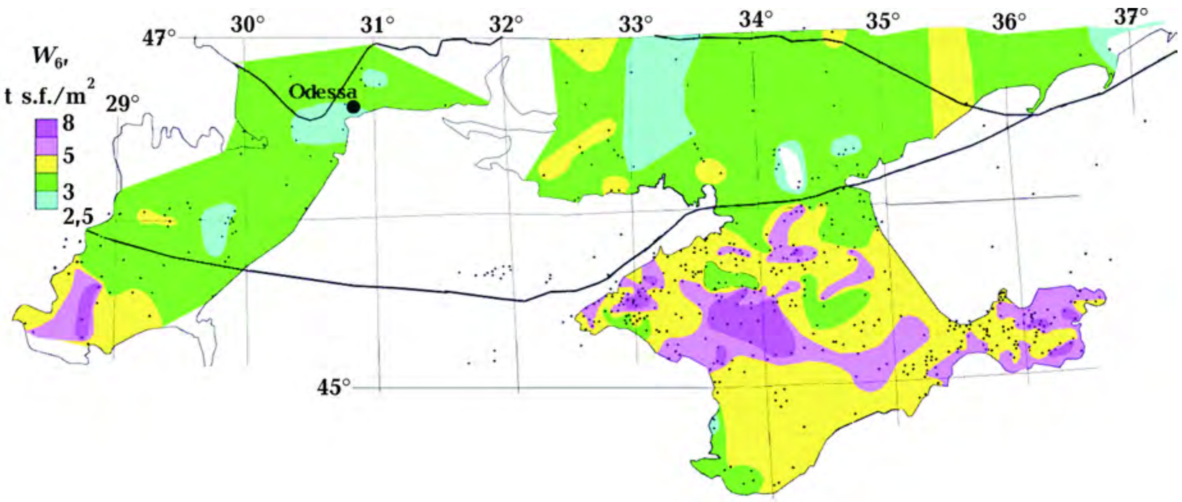


Fig. 6. Geothermal resources of the southern basin. See Fig. 5 for the legend.

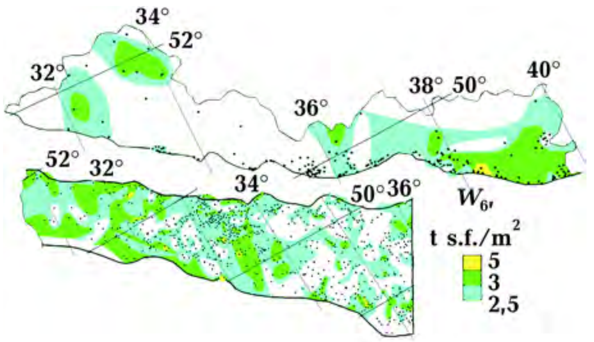
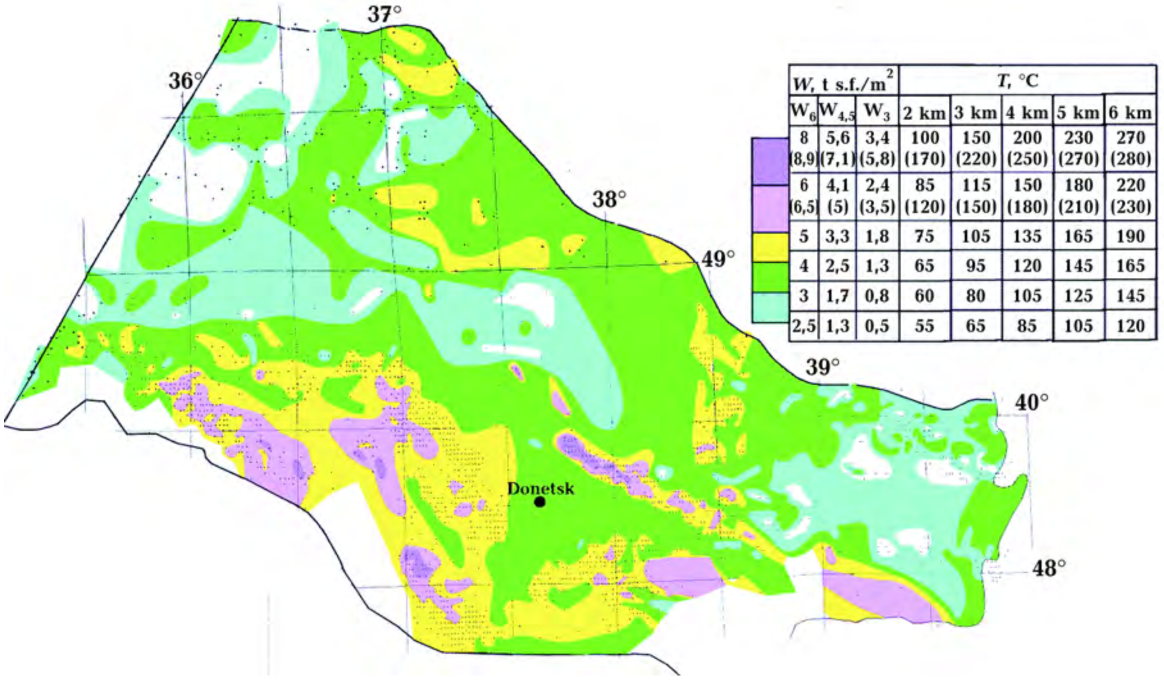


Fig. 7. Geothermal resources at the slope of the Voronezh Massif (the top diagram) and of the Dnieper-Donets Basin (the lower diagram). See Fig. 5 for the legend.



W, t s.f./m^2			*T*, °C				
W_6	$W_{4,5}$	W_3	2 km	3 km	4 km	5 km	6 km
8 (8,9)	5,6 (7,1)	3,4 (5,8)	100 (170)	150 (220)	200 (250)	230 (270)	270 (280)
6 (6,5)	4,1 (5)	2,4 (3,5)	85 (120)	115 (150)	150 (180)	180 (210)	220 (230)
5	3,3	1,8	75	105	135	165	190
4	2,5	1,3	65	95	120	145	165
3	1,7	0,8	60	80	105	125	145
2,5	1,3	0,5	55	65	85	105	120

Fig. 8. Geothermal resources of Donbass. See Fig. 5 for the legend.

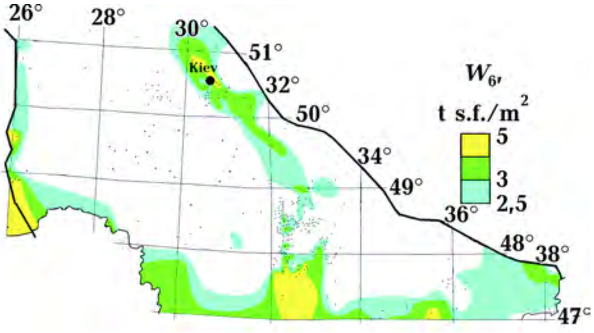


Fig. 9. Geothermal energy resources of the Ukrainian Shield and its slopes. See Fig. 5 for the legend.

Voronezh Massif slope it does not exceed the extent of coverage of the Ukrainian Shield. For that reason, parts of the basin are shown at different scales (Fig. 7, 8).

The data for the territory of Russia were also used for plotting the diagram of W_6 distribution at the Voronezh Massif slope. This only slightly affected the possibility of identifying areas with viable values of *W*, and "blank spots" there are common. It is only at the boundary with the Donets Basin that a small area was identified with the relevant parameter larger than 4 tons of s.f./m^2.

In the Dnieper-Donets Basin (DDB), territories promising for rich geothermal resources are widespread. Yet, usual concentrations of geothermal energy in the DDB are not high — about 2.5—3.0 tons of s.f./m^2. In rare cases only, can one encounter areas with *W* larger than 4 tons of s.f./m^2 (exceptions are mentioned earlier in the paper). The boundary between the DDB and Donbass proper is in the given case drawn quite arbitrarily: a straight line replaces the vast transition area. It roughly separates the territory with a dense survey grid at the Donbass mining fields from the territory with a sparse survey grid — at hydrocarbon deposits in the Dnieper-Donets Basin (see Fig. 7).

The concentration of geothermal energy in Donbass is much higher than in the Dni-

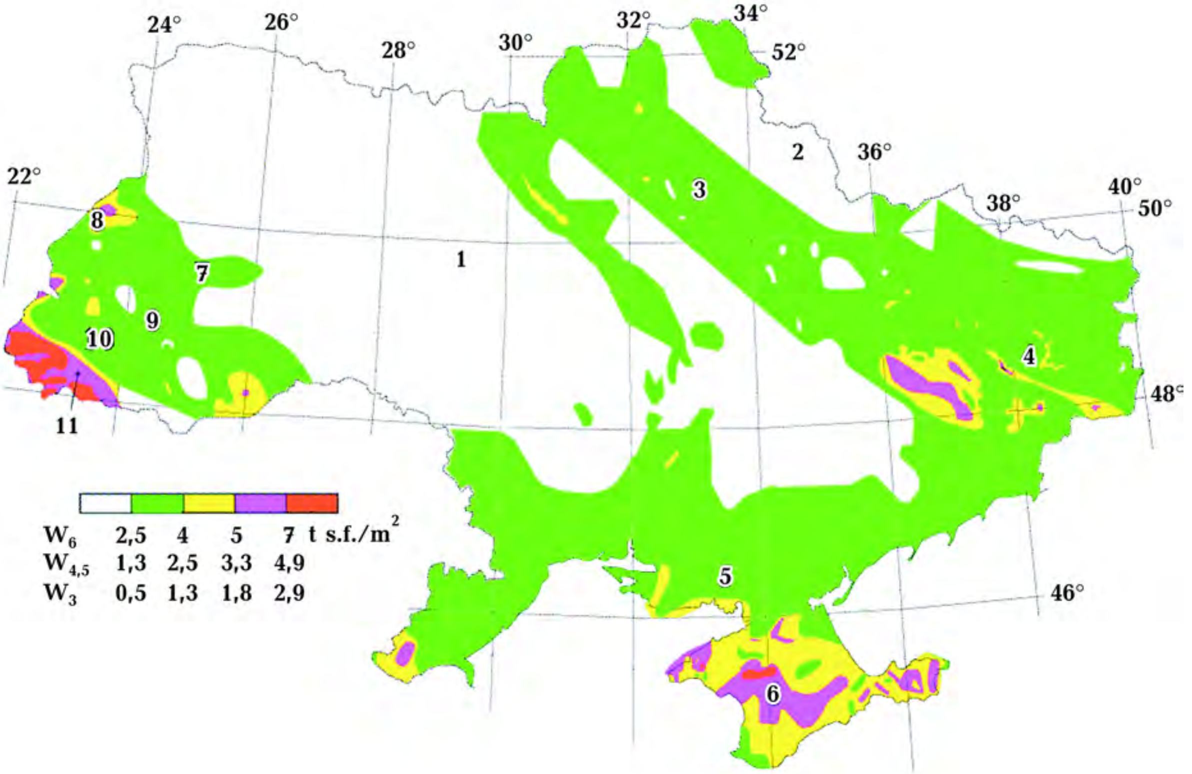


Fig. 10. Regional distribution of *W* values on the territory covered by studies. The digits mark tectonic regions (see Table 1).

eper-Donets Basin (see Fig. 8). However, in Donbass, elevated values of estimated W_6 are largely associated with water percolation through permeable fault zones. The temperature distribution with depth (down to 6 km) in them is virtually invariable, even though it should have differed from that derived according to the formula. It might be easy to amend the values, but such procedure would only make sense in the case of more detailed studies (the available estimates are provided in parentheses in the table attached to Fig. 8). It is unlikely that detailed studies would radically alter the W_6 values. The subparallel strike of the faults near the axes of the Main and the Druzhkovka-Konstantinovka anticlines is probably responsible for a significant expansion of the thermal anomalies. That is why one can observe them on the map.

The average concentration of geothermal energy in Donbass amounts to about 4.0—4.5 tons of s.f./m^2, increasing to 6.0—7.0 tons of s.f./m^2 in the northwestern part of the Main anticline and in southwestern Donbass. W_6 anomalies are quite common in the region. It only remains to point out that values of the estimated parameter in southwestern Donbass with a thin sedimentary veneer are somewhat overestimated. The determinations there used the same value of γ as for other areas of the region. Actually, however, a considerable depth range there is composed of crystalline rocks of the basement with an average thermal conductivity higher by 15—20 percent. A comparison between observed and estimated temperatures does not detect the error since the depths of the boreholes, in which temperatures were measured, are not sufficiently large (about 1 km).

As pointed out earlier in the paper, the insufficiently detailed coverage of much of the Ukrainian Shield makes it impossible to describe the thermal field on its large territories. This also naturally applies to the distribution of *W* values. The data presented in Fig. 9 testify to the fact that areas promising for category C_3 resources may be available on the Ukrainian Shield and its slopes, but their identification and exploration have yet to be carried out. If we apply the concept of a low heat flow to the entire shield outside the Kirovograd anomaly (and to a few other spatially small HF disturbances), the W_6 value there may be estimated at 1.8 tons of s.f./m^2.

Northeast of the shield (already in Belarus), there appears a zone of relatively high W_6 values in the Pripyat Trough. In reality, however, the entire Belarusian Massif and the Pripyat Swell are characterized as zones of abnormally low HF and, accordingly, low *W* values.

The poor exploration maturity of the Ukrainian Shield territory and the detection of quite intensive heat-flow anomalies in its best-explored parts show that, at least in individual zones, commercial reserves of geothermal energy may be discovered in the future. Their detection is likely within the still not fully explored Dnieper anomaly at the northeastern part of the Ukrainian Shield. The northwestern part of the Ukrainian Shield and the adjoining territory of the Volyn-Podolian plate, as well as some territories in the northern part of the shield are the only areas that have no prospect of containing geothermal resources. It is unlikely to expect there heat-flow values (even close to average for the region) at which the level of promising resources can be achieved. This is due to the high thermal conductivity of crystalline rocks.

Conclusions. Fig. 10 shows a joint map of geothermal energy resources. It is poor in detail but illustrates possibilities for consecutive utilization of the Earth's heat from various depth intervals.

In three basins and in the central part of Ukraine, known for the low thermal potential, the total amount of thermal resources amounts to about 10^{12} tons of standard fuel. Let us compare the resulting data with information on Ukraine's of fossil fuel reserves shown in Table 3 [The National ..., 1999].

The total value of W_6 exceeds reserves of fossil fuel (mainly, hard coal) by a factor of 25. In view of the fact that geothermal energy is more advantageous ecologically,

Table 3. Energy reserves in Ukraine's fossil fuel deposits

Fuel type	Reserves	Reserves in tons of s.f.
Hard coal	$4.31141 \cdot 10^{10}$ tons	$3.880 \cdot 10^{10}$
Lignite	$0.25848 \cdot 10^{10}$ tons	$0.127 \cdot 10^{10}$
Peat	$0.0659379 \cdot 10^{10}$ tons	$0.025 \cdot 10^{10}$
Oil	$0.01467 \cdot 10^{10}$ tons	$0.022 \cdot 10^{10}$
Gas	$129 \cdot 10^{10}$ m^3	$0.161 \cdot 10^{10}$
Condensates	$0.00807 \cdot 10^{10}$ tons	$0.012 \cdot 10^{10}$
Total	—	**$0.04 \cdot 10^{12}$ tons of s.f.**

we can appraise the utilization of the Earth's heat in Ukraine as a very promising trend.

Evaluation of geothermal resources that can be used without additional heating, so that we obtain steam suitable for producing electricity, has shown that, at the drilling depth of 4.5 km, minimal resources emerge in the zone of maximum heat-flow values in the Transcarpathian Trough (>120 mW/m^2). The temperature of the fluid is 210 °C and that of the water being discharged 70 °C, i. e. the fluid being discharged may be used for heat supply. With the drilling depth of 6 km, we obtain values matching those of W_6 for the version discussed above (T of the heat conductor is 60 °C and of the discharge 20 °C): 6 — 0; 7 — 2.5; 8 — 3.8; 9 — 5; 10 — 8 tons of s.f./m^2. In other words, conditions suitable for the extraction of steam are present solely in the Transcarpathian Trough and in a rather limited number of areas in the Crimea and Donbass.

There exist quite promising projects for the utilization of hot water (provided that exploration boreholes are already available) that can produce steam by way of additional heating with the help of burning associated gas from line wells in the Dnieper-Donets Basin fields, methane from abandoned coal mines of Donbass, shale gas, etc.

The assumption, voiced at the beginning of the paper regarding high advantages offered by the use of thermal energy, has been validated by relevant studies. This traditional alternative source could be quite timely for Ukraine.

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Geotermal resources of Ukraine

I. V. Gordienko, V. V. Gordienko, O. V. Zavgorodnyaya, 2018

Geothermal resources (*W*) are quite a novel type of extractable resources. Their consumption, however, is among the world's fastest growing power industries. Our evaluations of *W* were largely focused on 1) resources that can be used for heat supply, 2) on the extraction, with the help of a geo-circulation system (GCS), of water at a temperature (*T*) of at least 60 °C, and 3) on its (water) release back into the Earth at $T = 20$ °C. Economic appraisals point to a plausible achievement of commercial viability (provided that the most efficient technologies are employed) starting from the geothermal gradient equaling 0.02—0.025 °C/m ($W = 2.5$ tons of standard fuel per m^2 (t s.f./m^2) with the drilling to a depth of 6 km). Calculations were performed not just for the depth of 6 km, but also for the drilling depths of 3 and 4.5 km. It has to be mentioned that the estimated *W* magnitude is not exhaustive as regards heat reserves within the Earth. After the energy has been extracted from the depths of 5.5 to 6 km, it can be further recovered from shallower depths. In the Dnieper-Donets basin (DDB), for example, heat reserves estimated with the help of the formula for 6 km can be increased by a factor of 4.5 if other depth intervals are also exploited. To calculate *W* the mean rock thermal conductivity values (1.7—2.65 W/m · °C) were used. *W* was calculated for all the 5,500 sites with known values of deep-seated heat flow. The contour interval was approximately matched with the double error in the *W* determination. The maps show that cost-effective fossil fuel energy resources abound in three large basins: western, eastern, and southern. In central Ukraine, they only occur within small areas. Yet, the said territory, largely the Ukrainian Shield and its flanks, is least covered by studies in terms of the deep-seated heat flow. Marketable resources have been found within the only well-explored portion of the area (at the center of the shield and its northeastern margin). The richest *W* resources amounting to 10 t s.f./m^2 have been located in Transcarpathia's (TC) western basin. This estimate exceeds reserves of major deposits of oil or gas. But the average *W* (hereinafter referring to the drilling depth of 6 km) is about 3.5—4 t s.f./m^2. The total amount of energy in the basin is about 0.2 trillion t s.f./m^2. High *W* in the eastern basin has only been recorded in isolated areas of the Donbas (5—7 t s.f./m^2). In the main part of the DDB, *W* equals about 3 t s.f./m^2. Therefore, the average *W* value for the basin is 3—3.5 t s.f./m^2. The total estimated resources come up to about 0.3 trillion tons of standard fuel. In the southern basin of the central Crimea *W* reaches 7—8 trillion tons of standard fuel per m^2, but on the considerable part of the territory *W* is about 3—4 t s.f./m^2. The composite amount of energy in the basin is about 0.3 trillion tons of standard fuel. Ukraine's total fossil fuel resources (as discovered to date) within the depth range of 5.5—6 km are 20 times higher than all fossil fuel reserves on its territory. Minimal amounts of fossil fuel resources suitable for the production of steam electricity without additional heating can be found with the drilling depth of 4.5 km only in some parts of TC. With the drilling depth of 6 km, the resources might reach commercial level in TC and in isolated areas of the Crimea and the Donbas.

Key words: Earth's deep-seated heat flow, geothermal energy, assessment of geothermal resources.

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