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Geology

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ГЕОТЕРМИЧЕСКОЕ ПОЛЕ ГРОДНЕНСКОГО РЕГИОНА РЕСПУБЛИКИ БЕЛАРУСЬ

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Рассмотрено геотермическое поле платформенного чехла в пределах Гродненской области и прилегающих к ней районов Беларуси. Платформенный чехол залегает на кристаллическом фундаменте докембрийских пород. Карты распределения температуры для глубин 100; 200 и 300 м ниже земной поверхности были составлены на основе термограмм, зарегистрированных в скважинах, и дополнены картой теплового потока. Они выявляют геотермические аномалии распределения как температуры, так и плотности теплового потока в пределах региона. Температура в области монотонно возрастает с глубиной при сохранении общих особенностей теплового поля. Выявленные на 100-метровой карте аномалии сохраняются на глубинах 200 и 300 м. Основную роль в формировании температурных аномалий играют приповерхностные факторы, такие как циркуляция подземных вод и влияние палеоклиматических изменений на поверхности Земли в прошлом. Низкий тепловой поток (<30 мВт/м^2), отмеченный в восточной части карты, постепенно увеличивается до 50 мВт/м^2 в районе Гродно. Его площадная изменчивость связана с распространением гранитоидных и бластомилонитовых пород в кристаллическом фундаменте. Повышенный тепловой поток характерен для массивов кислых пород с повышенным содержанием долгоживущих радиоактивных изотопов урана, тория и калия. Их распад создает дополнительную радиогенную составляющую теплового потока.

Ключевые слова: геотермические аномалии; распределение температуры; тепловой поток; Гродненский регион; Беларусь.

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GEOTHERMAL FIELD OF THE GRODNO REGION OF THE REPUBLIC OF BELARUS

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The geothermal field of the platform cover within the Grodno region is considered. The cover rests on a crystalline basement of Precambrian rocks. Temperature distribution maps for depths of 100; 200 and 300 m below ground level were compiled based on thermograms recorded in boreholes and were supplemented by the heat flow map. These reveal geothermal anomalies both of temperature and heat flow density distribution within the region. The temperature in the region monotonously increases with depth, while preserving the general features of the thermal field. The anomalies identified on the 100 m map persist for depths of 200 and 300 m. The main role in the formation of temperature anomalies is played by near-surface factors, such as groundwater circulation, and the influence of paleoclimatic changes on the Earth's surface in the past. A low heat flow (<30 mW/m^2) in the eastern part of the region gradually increases up to 50 mW/m^2 in the vicinity of Grodno. Its areal variation relates to the distribution of granitoid and blastomylonite rocks in the crystalline basement. Increased heat flow is typical of silicic rock massifs with elevated concentrations of long-living radioactive isotopes of uranium, thorium and potassium. Their decay creates an additional radiogenic component of heat flow.

Keywords: geothermal anomalies; temperature distribution; heat flow; Grodno region; Belarus.

Introduction

Belarus lies in the geographical center of Europe (fig. 1), geologically belonging to the vast Precambrian East European Platform. The crystalline basement of whole country, including the Grodno region, is hidden under a platform cover of variable thickness. The Belarusian Anteclise is the main positive structure within the region, it occupies the central and western parts of the country and extends into eastern Poland.

Fig. 1. The studied region:
GR – Grodno region;
KE – Kaliningrad enclave, Russia

The East European Platform is colder than the young platforms of central and western Europe [1; 2]. Geothermal research within Belarus began in the Pripyat Trough (outside the studied region), a deep sedimentary basin in the southeastern part of the country [3]. Such research has been carried out regularly since the 1960s across the Belarusian Anteclise [4; 5]. Before the late 1970s, the number of thermal logs within the anteclise did not exceed 10. During subsequent years the number of thermograms gradually increased [6]. Based on these geothermal measurements, rare for that time, the first estimates of temperature values on the surface of the crystalline basement were made by L. A. Tsybulya [7; 8] by extrapolating thermograms of relatively shallow boreholes down to the basement top to compile the first schematic map of isotherms at the surface at the crystalline basement. At that time with such a sparse network of studied boreholes, it was not possible to identify the main geothermal anomalies within the Belarusian Anteclise.

Dozens of thermal logs were obtained following regular geothermal research in the 1980–90s as a result of field-works carried out by researchers of the geothermal laboratory of the Institute of Geochemistry and Geophysics, the National Academy of Sciences of Belarus.

However, within the entire country geothermal field parameters are still poorly studied. During the last 30 years new geothermal measurements have been carried out within the Belarusian Anteclise including of the Grodno region.

Geological settings

The territory of the Grodno region is located in the western part of the East European Platform. The Precambrian strata are overlain by deposits of varying thickness up to 500 m, throughout the region. This shrinks within the Bobovnya Buried Inlier, where the thickness decreases to 80–100 m. The central part of the region is occupied by the Belarusian Anteclise with its Central Belarusian Massif and Bobovnya Buried Inlier (fig. 2). To the south are the Podlasie – Brest Depression, Polesian Saddle and Ivatsevichi Buried Inlier. The Baltic Syneclise adjoins the Belarusian Anteclise to the north outside the border of Belarus. The Pripyat Trough is a deep sedimentary basin located in the southwestern part outside the region studied. The Belarusian Anteclise extends in northeastern Poland towards the edge of the platform.

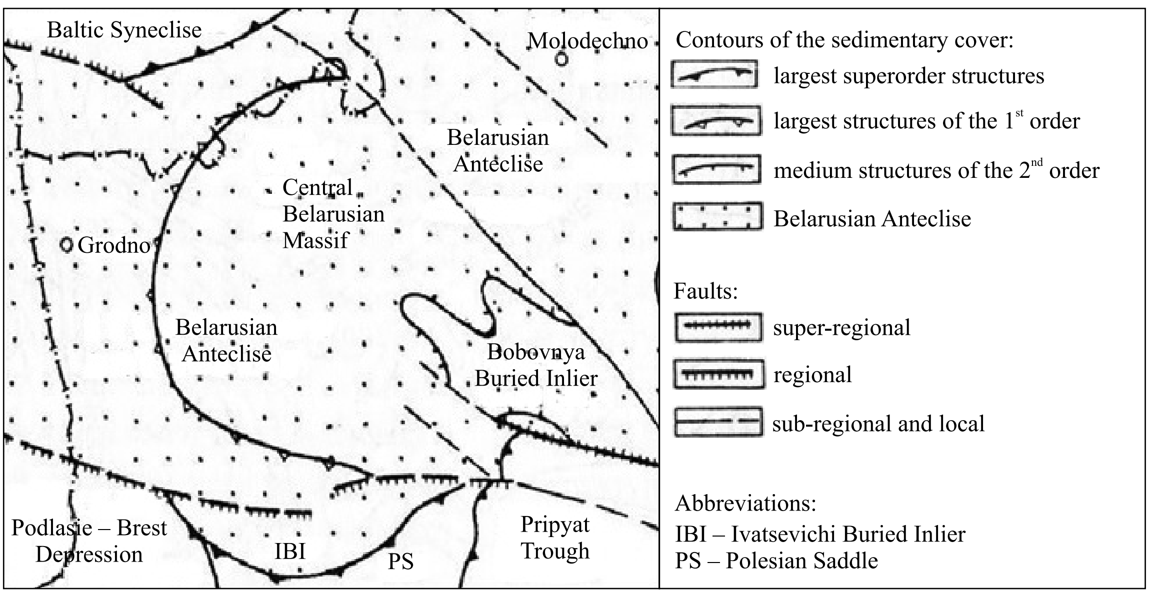

Fig. 2. Geologic settings of the studied region (after [9], modified)

Geologically the studied area belongs to the Belarusian Anteclise. Boreholes available for recording thermograms, as a rule, were drilled to a depth of a few hundred meters. Many of them were used for water supply. The thickness of the platform cover increases towards the Podlasie – Brest Depression and outside the region studied towards the Baltic Syneclise, where several boreholes have been drilled to a depth over 1 km. Locations of the studied boreholes, and depths reached by thermometers in the Grodno region are shown in fig. 3.

Locations of the studied boreholes and the depths reached by the borehole thermometer are shown in the form of coloured circles. The depths reached by the thermometer, in most cases, correspond to the zone of fresh-water (active water exchange zone). Only in some of boreholes drilled for mineral waters (sanatoria at Porechye, Radon, etc.) they go slightly beyond the base of the fresh water.

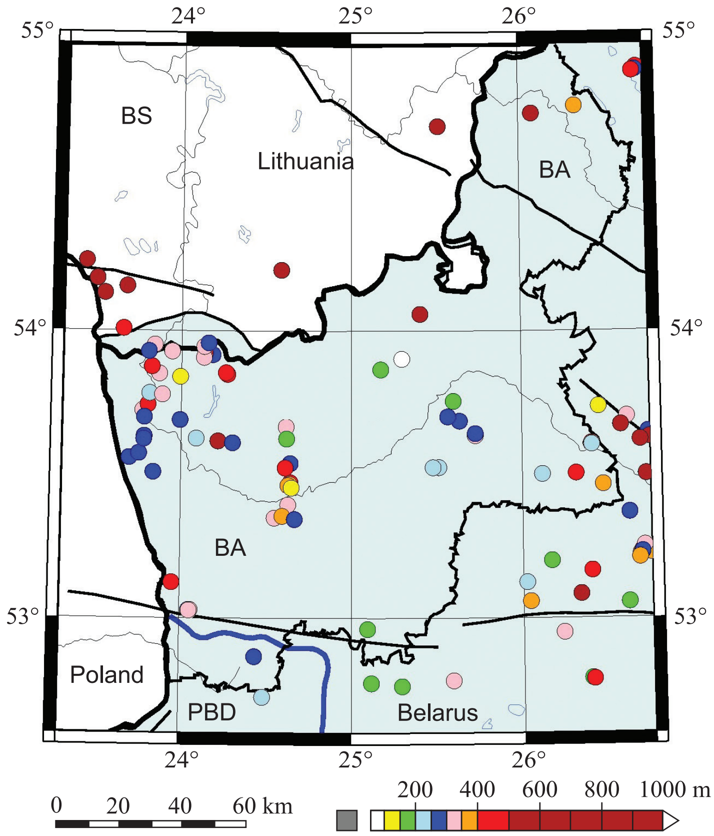

Fig. 3. Locations and depths of boreholes in the Grodno region with recorded thermograms. Here and in fig. 7–12 are given the following notations: BA – Belarusian Anteclise; BS – Baltic Syneclise; PBD – Podlasie – Brest Depression; PS – Polesian Saddle. The blue line shows the boundary of the Belarusian Anteclise and the eastern part of the Podlasie – Brest Depression within Belarus. Black lines are the main faults

Geothermal exploration within the region

Most of the thermal logs in the vicinity of Grodno were recorded with a borehole thermistor thermometer during field-works in 1989–1991 by V. I. Zui, A. A. Voytik and D. P. Prishchep. The registration of them with a similar thermometer of lightweight design using a twisted single-core seismic wires was repeated in some of the boreholes 2 years later by V. I. Zui and V. G. Levashkevich. The slight difference in the thermal logs obtained by the two types of thermistor thermometers, caused mainly by their instrumental errors, is not analysed here.

To the north of Grodno, near the Belarus – Lithuania border, a number of exploratory boreholes were drilled in the Privalka – Porechye area in the early 1990s for mineral waters of the type used in the Druskininkai sanatorium, Lithuania. The temperature logs in them were recorded mainly one or two months after drilling completion.

To draw reliable temperature maps near the junction of Belarus, Poland and Lithuania, it would be necessary to have temperature logs recorded in boreholes of the adjacent countries. Several such logs, available for analysis, were recorded prior to 1991 in the Lazdijai and Varena areas of Lithuania.

We had no such logs in the Polish area within the immediate vicinity of Belarus (personal communication of Bruszewska and Szewczyk, 2007). The closest boreholes studied here are Krasnopol-IG-5 with a non-stationary thermogram, Grajewo-1TU, and two boreholes Krzemianka-IGH-1 and Udryń-PIG-1, drilled into the Suwałki Massif, where temperature logs indicated temperature inversion within the depth interval of 350–450 m [10] with a deep position of up to 500 m of the «neutral layer».

A number of boreholes for fresh and mineral waters were drilled in the northern part of the Grodno region. Temperature logs were recorded in many of them with a borehole thermistor thermometer, calibrated against mercury-in-glass thermometers with a precision value of 0.01 °C in laboratory conditions. The instrumental error of the used thermometers is estimated at ±0.05 °C.

Selected thermal logs from the Grodno region and the adjacent territory, recorded during field works in 1989–1991, are shown in fig. 4. Most of these show a restored thermal regime disturbed by drilling.

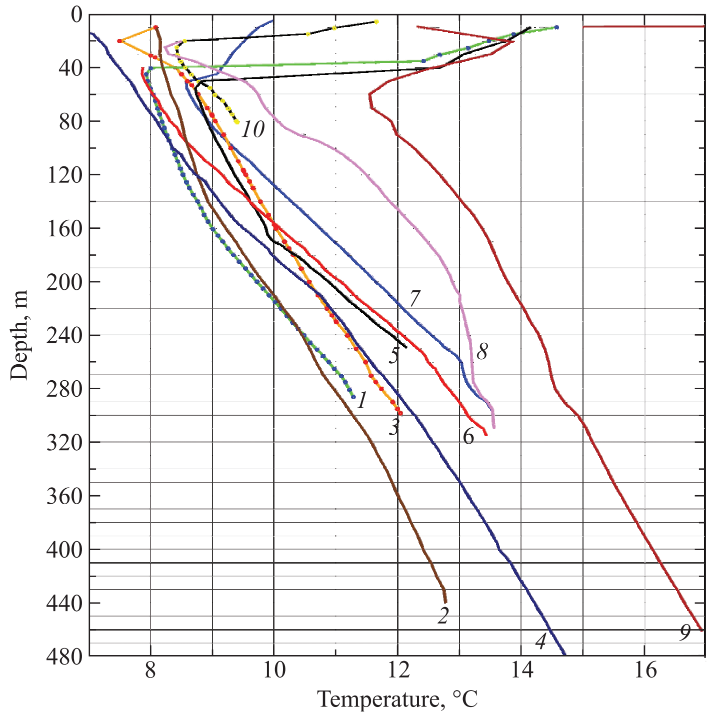

Fig. 4. Selected temperature logs of boreholes
in the vicinity of Grodno:
1 – Grodno-10; *2* – Vorony-1; *3* – Grodno-8;
4 – Bershty-6; *5* – Grandichi-16; *6* – Tsydovichi-6; *7* – Grodno-1;
8 – Balesolnoye; *9* – Grandichi-15; *10* – Grodno-2a

Only, a few logs were acquired in the non-stationary thermal regime. One example is the water supply well Balesolnoye located on the western bank of the Neman River near Grodno in the area of a garden partnership. This has been in operation for a number of years and was stopped due to a failure of the pump. About two weeks after its removal, the temperature log recording was made. Another example is the Grandichi-15 temperature log, which reflects a typically disturbed regime due to the short time elapsed since drilling completion.

Temperature logs of selected individual boreholes recorded within the Privalka and Porechye areas near the Belarus – Lithuania border are shown in fig. 5. Similar logs with a disturbed thermal regime were observed for two boreholes, Privalka-4a and Privalka-4b, located ~30 m from each other. The borehole Privalka-4b yields permanent surface flow of fresh water with a flow rate of ~4.5 dm^3/min. This distorts the upper part of the temperature log to a depth of 200 m in the adjacent borehole Privalka-4a that lacks such surface flow. Below this depth the thermogram is essentially undisturbed.

Most of the temperature logs were recorded in the boreholes a few months after their drilling completion, when thermal conditions in the boreholes, disturbed by the circulation of drilling fluids, had been restored to an equilibrium state.

Only a few boreholes deeper than 500 m were available in the area of investigation to record thermal logs. In most cases they were acquired at depths not exceeding a few hundred meters, usually from 100 to 300 m (fig. 6).

Most temperature records acquired in the studied region were recorded in boreholes 100–300 m deep. Some logs were extrapolated to deeper horizons. Calculation of temperature values below the bottoms of the boreholes requires knowledge of the heat flow and thermal conductivity of the underlying rocks. In most cases the latter is a priori unknown. Therefore, it has been decided, as in the Geothermal Atlas of Europe [11], that the downward extrapolation should not exceed 50 % of the actual borehole depth using geothermal gradients recorded near the bottom-hole intervals.

As a result, the available data restrict the temperature maps within the region to a depth of only ~300 m. A few deep boreholes (400–1000 m) in the region do not allow the construction of conditioned temperature distribution maps for deeper levels.

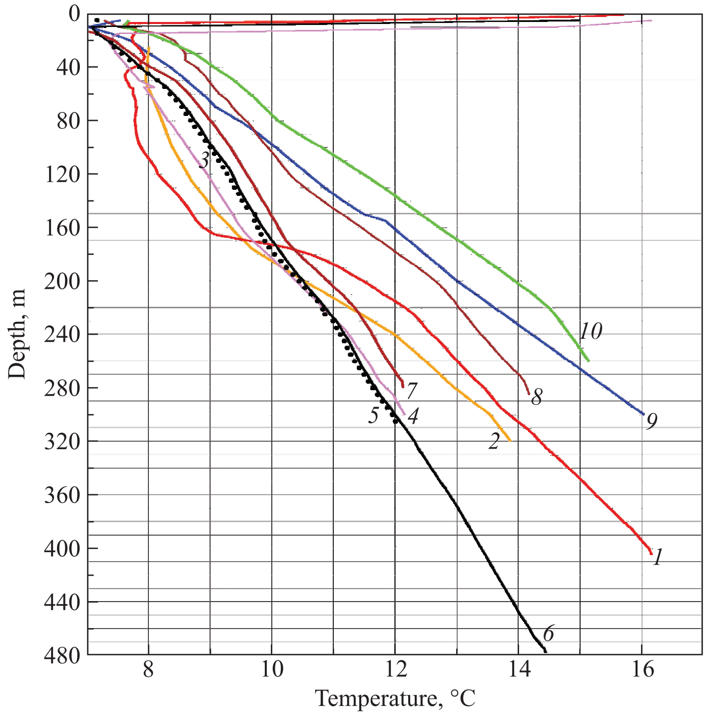

Fig. 5. Selected temperature logs of boreholes
in the Privalka and Porechye areas:
1 – Privalka-4; *2* – Privalka-3; *3* – Privalka-11;
4 – Porechye-14; *5* – Porechye-17; *6* – Porechye-12; *7* – Porechye-18;
8 – Privalka-5a; *9* – Privalka-1; *10* – Privalka-9

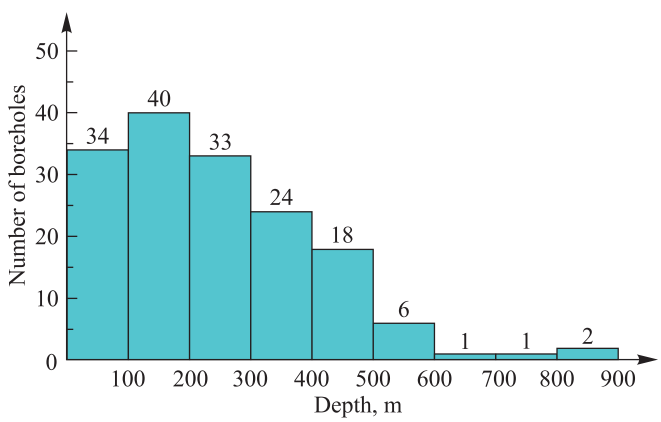

Fig. 6. Depths reached by thermometers in studied boreholes of the region

Temperature distribution at 100 m depth

Based on the temperature logs recorded in the boreholes of the Grodno region (see fig. 3) temperature distribution maps were compiled, which made it possible to identify the relationship between parameters of the geothermal field and the geological features of the region.

The temperature map at 100 m depth within the Grodno region is shown in fig. 7. Temperature ranges within it from 7 to 9.5 °C. An anomaly of low values of 7–7.5 °C is highlighted in the northeastern part of the area, and this continues into the northern part of the Minsk region outside the eastern frame of the map. The 8 °C isotherm can be taken as the boundary between this anomaly and an area with elevated temperature. The distance between isotherms is 0.5 °C, which as acceptable, keeping in mind that the instrumental error of the used borehole thermometer was ±0.05 °C.

Three local anomalies of temperatures above 9 °C were identified for the depth of 100 m. These are North-Grodno, South-Grodno (Skidel – Mosty) and Novogrudok (see fig. 7). The first two are separated by a comparatively narrow strip of ~8.5 °C, apparently caused by some cooling of the strata by downflow water from surface precipitation.

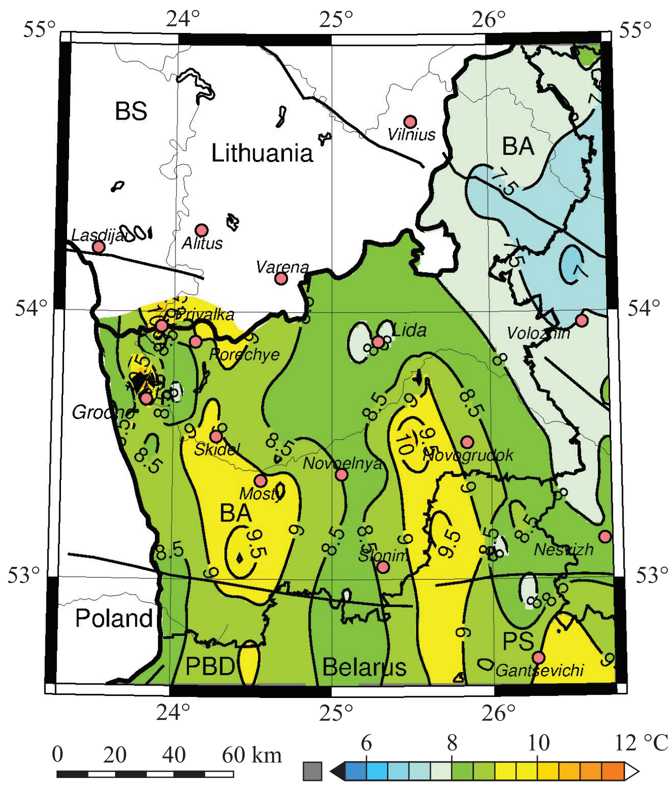

Fig. 7. Temperature distribution at 100 m depth within Grodno region

A dense network of boreholes is located within the vicinity of Grodno and in the Privalka and Porechye areas. Isotherms near and beyond the borders of Belarus with Lithuania and Poland are shown in outline only presumably due to a lack of data.

Temperature distribution at 200 m depth

The temperature distribution at 200 m depth contrasts compared with that at 100 m (fig. 8).

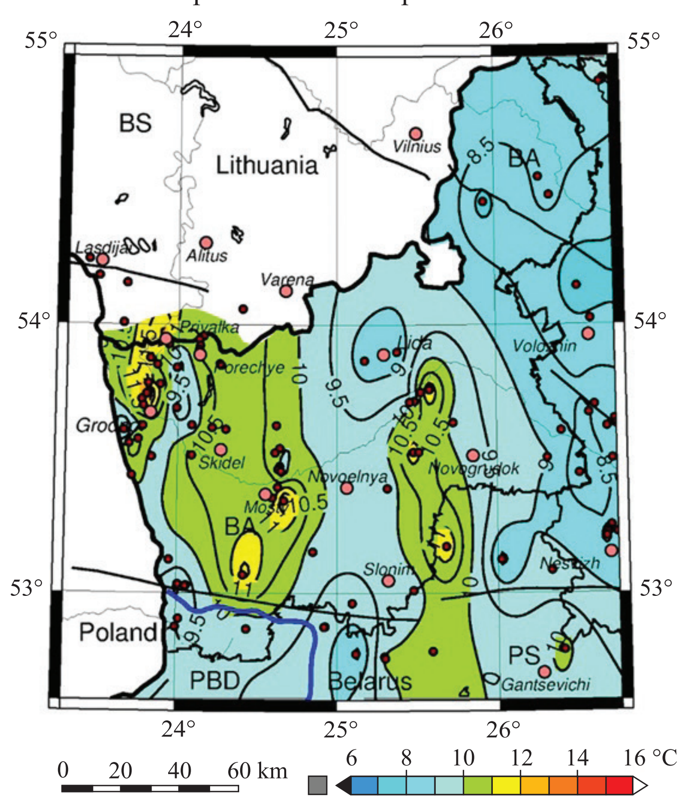

Fig. 8. Temperature distribution at 200 m depth within the Grodno region.
Location of used temperature logs are shown by small circles

As in the previous case, there is a low temperature anomaly (<8 °C) along the eastern boundary of the Grodno region. This continues beyond its boundary eastwards to the neighbouring Minsk region. A lack of data from southwestern Lithuania makes it impossible to show the isotherms to the north.

The temperature increases, reaching 11 °C, in the central and western parts of the region. The maximum values (>12 °C) are observed to the north of Grodno. This anomaly stretches along the Neman valley towards the north. Apparently, it continues into the territory of Lithuania in the direction of a positive anomaly of temperature and heat flow, previously identified in western Lithuania and in the Kaliningrad enclave of Russia [12–14]. The small number of thermograms available from southwestern Lithuania does not allow correct estimation of the shape and boundaries of this anomaly.

Temperature distribution at the depth of 300 m

The geothermal field at 300 m depth is shown in fig. 9. The number of temperature logs decreases with the depth, but positive and negative anomalies are more clearly distinguished. The temperature ranges from 9 °C in the east to ~15 °C in the west, while on the map for a depth of 100 m it averages ~8 °C. The positive anomaly in the area of the Grodno also expands to the north and to the east.

A low-temperature anomaly of ~9 °C is still observed in the eastern part of the region. It gradually increases in northwest ward direction up to values of 14 °C within the area of Grodno. Several local small thermal anomalies are revealed, the temperature of which exceeds 12 °C.

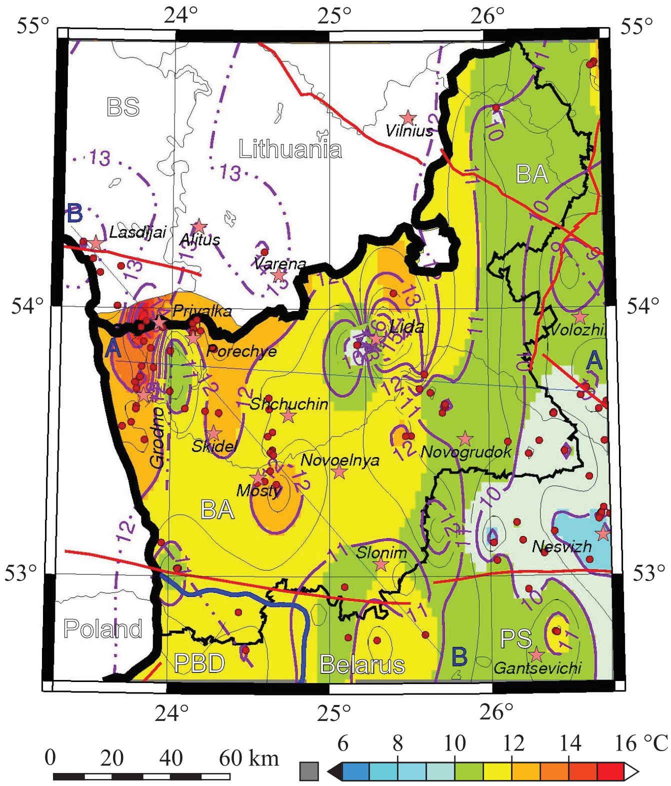

Fig. 9. Temperature distribution at 300 m depth within the Grodno region.
A – A and B – B are geothermal profiles

There is a gradual temperature increase in the direction of the Paleozoic Podlasie – Brest Depression in the southern part of the mapped region.

The southern boundary between Grodno and Brest regions crosses a vast forest area, the Belovezhskaya Pushcha, where deep drilling was not carried out. Geothermal measurements were completed here only in three shallow boreholes, which do not allow characterisation of the geothermal field of this territory in detail. Therefore, isotherms in these parts of the maps have a smooth pattern.

Geothermal profiles

The position of two profiles A – A and B – B are shown at the temperature distribution map for the depth of 300 m. Temperature isolines are plotted along them in order to identify whether there is a sufficient influence of near-the-surface factors on the formation of temperature anomalies and to show the general tendency for the geothermal field to change in these two directions.

A generally monotonic increase in temperature was noted for these three considered depths from the east to the west of the region in the latitudinal profile A – A. Several local peaks of low and high temperatures are shown on them changing quite synchronously. Their centers are slightly shifted with increasing the depth, which is apparently caused by the vertical circulation of groundwater, as there is a decrease in the downward filtration rate of meteoric waters between aquifers as the depth increases. On the whole, for entire profiles, a monotonic increase in temperature with depth is observed (fig. 10).

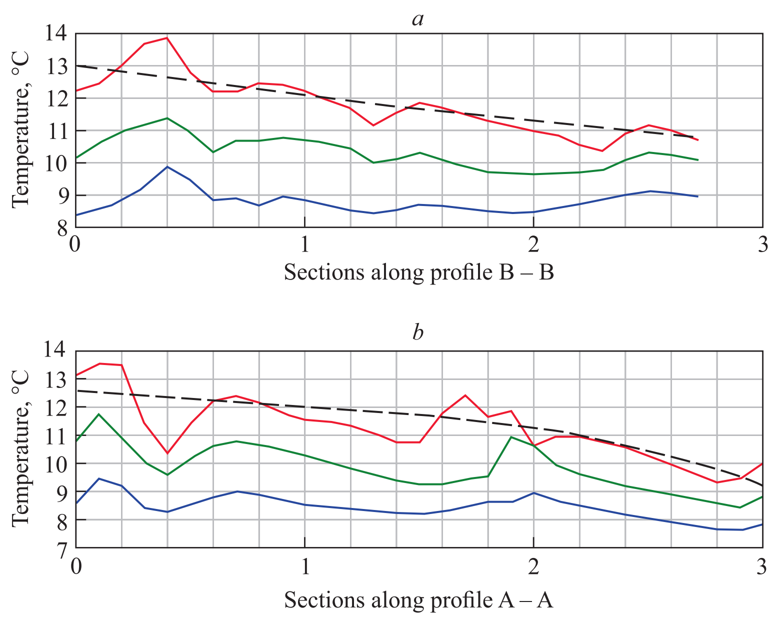

Fig. 10. Temperature distribution along B – B (*a*) and A – A (*b*) profiles of the Grodno region at depths of 100 m (blue line), 200 m (green line), and 300 m (red line)

The profile B – B reflects, on the whole, a monotonic increase in temperature at the three considered depths from the southeastern to northwestern parts of the region. They also show several local peaks of low and high temperatures changing rather synchronously. On the whole, along the entire profile, a synchronous course of isotherms is observed against the general background of an increase in temperature with depth.

The dashed lines, shown on each of the profiles, characterise the general trend of temperature increase as we approach the Grodno geothermal anomaly. Temperature distribution profiles and trend profiles were built using the grdtrend and grdtrack modules of the *Generic Mapping Tools* software package [15; 16].

Heat flow density distribution

The map of heat flow density distribution within the area of investigation was compiled on the basis of the heat flow catalogue for the entire territory of Belarus [17] in the format described in [18]. No paleoclimatic and other corrections were applied to the catalogue data. Figure 11 represents the observed heat flow distribution within the region without corrections.

In general, the heat flow density pattern correlates well with the temperature distributions at the depths of 100; 200 and 300 m discussed above. A low heat flow anomaly with values of 25–30 mW/m^2 is distinguished in the eastern part of the map, stretching along the eastern border of the Grodno region and extending eastwards. The heat flow gradually increases from 35 to 45 mW/m^2 in the central and western parts of the Grodno region. Local anomalies with the heat flow exceeding 45 mW/m^2 were identified and with values of >50 mW/m^2 at the junction of borders between Belarus, Lithuania and Poland. A single value of 52 mW/m^2 was observed in its central part [19]. This anomaly apparently continues into Lithuania and, possibly, it reaches a high heat flow anomaly within western Lithuania and the Kaliningrad enclave [12; 14].

To show a possible origin of the positive heat flow anomalies, a map of the distribution of granitoid and bastomylonite massifs composed of rocks such as granites, gneisses, crystalline shists (fig. 12) reflecting plastic deformation at the surface of the crystalline basement [20] was combined with contours of observed heat flow.

Boreholes, in which the heat flow density was determined and indicated heat flow anomalies in central and western parts of the region, are commonly within or in a close proximity to the granitoid bodies.

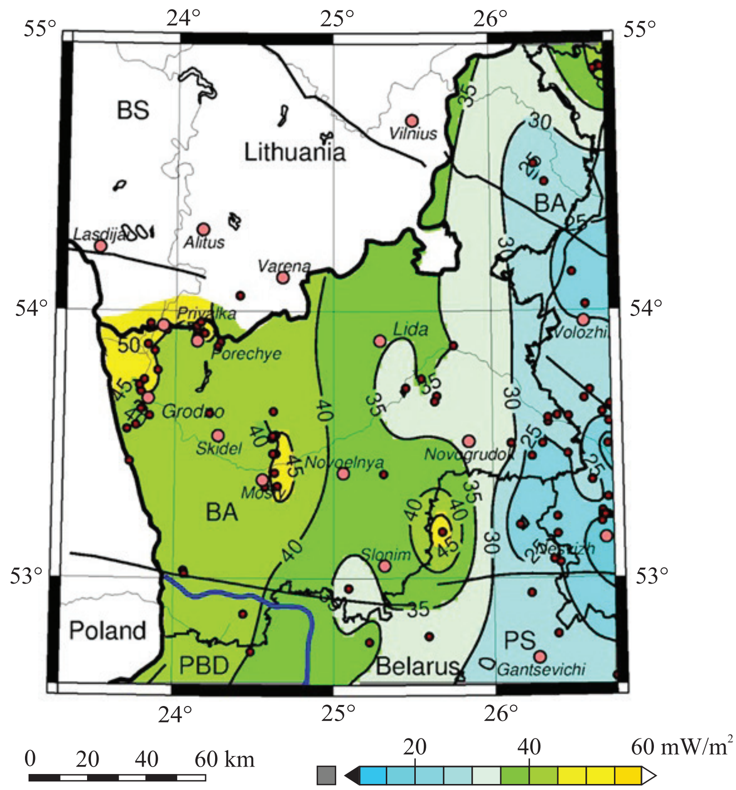

Fig. 11. Heat flow density map

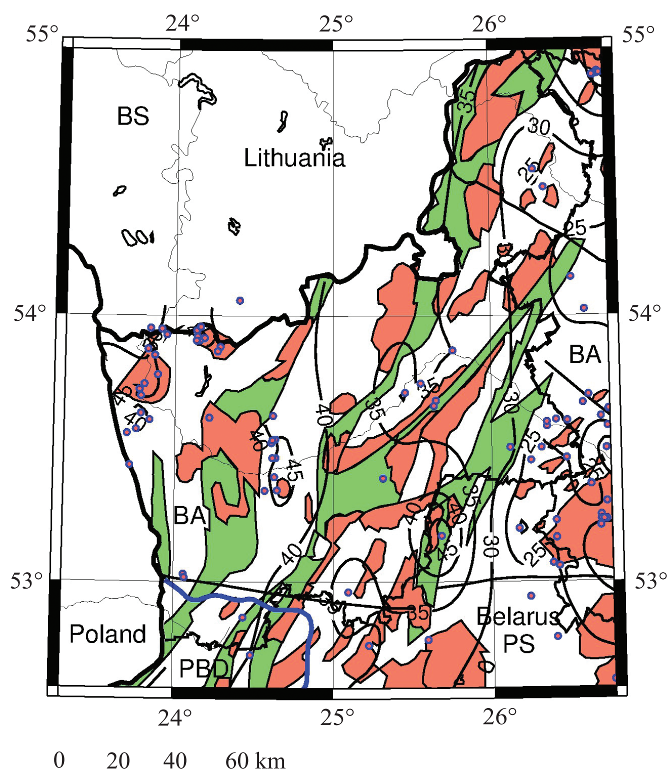

Fig. 12. Locations of the studied boreholes (small circles) and heat flow contours on a map of granitoids (red) and blastomylonites (green) in the crystalline basement of the Grodno region (after [20], simplified)

Felsic rocks (e. g. granitoids), compared with basic rocks, contain an increased concentration of long-lived radioactive isotopes of uranium, thorium and potassium [21]. An increase of the heat flow density in these areas might be explained by radiogenic heat production, creating local positive thermal anomalies. We measured the concentration of ^{235}U, ^{238}U, ^{232}Th and ^{40}K in the laboratory for a few tens of rock samples from the crystalline basement of the Grodno region which showed a similar correlation [22; 23]. However, we had no samples for analyses from the crystalline basement for boreholes where the heat flow was determined.

Discussion and conclusions

When constructing temperature distribution maps, some temperature logs for shallow boreholes were extrapolated to deeper horizons. The calculation of temperature values below bottoms of boreholes requires knowledge of the heat flow and thermal conductivity of the underlying rocks. The latter is a priori unknown. Therefore, it was decided, as with the Geothermal Atlas of Europe [11], that downward extrapolation, based on the geothermal gradient actually reached by the thermometer in its lowest intervals, should not exceed 50 % of the borehole depth. If this condition was not observed, the temperature logs were rejected. Also, thermograms of boreholes with disturbed thermal conditions were not used. Locations of boreholes with thermograms for preparation of temperature distribution maps for horizons of 100; 200 and 300 m depth are shown by circles in these maps.

The temperature in the region monotonously increases with depth, while preserving the general features of the thermal field. The anomalies identified in the 100 m map persist for depths of 200 and 300 m. Some changes in the configuration of isotherms with depth are observed. They result, firstly, from a decrease in the number of thermograms used with increasing depth and, secondly, by reduction with depth in infiltration rates of meteoric waters. The extensive low temperature anomaly in the eastern part of the region and the Grodno positive thermal anomaly persists in all three maps. A pattern of the heat flow density distribution corresponds to them. The highest heat flow up to 50 mW/m^2 was observed in the northern part of the Grodno anomaly. Contrary, an extensive low anomaly of 30–35 mW/m^2 is present in the eastern part of the region. The heat flow data based on borehole temperature logs closely along the Poland – Grodno region border are not known, a similar situation exists in the southern border area of Lithuania. This does not allow tracing reliably isotherms and heat flow contours beyond borders of Belarus.

The spatial variability in heat flow was compared with the development of granitoid and blastomylonite massifs in the crystalline basement of northwestern Belarus. A satisfactory correlation exists between positive thermal anomalies and the location of granitoids containing higher concentration of long-lived radioactive isotopes, for example, within the granitoid massif of Mosty. The decay of radioactive elements produces thermal energy and leads to an increase in the observed heat flow [24; 25]. Determinations of radiogenic heat production in the western part of the Grodno region (ranging from 0.2 to ~2.0 μWm^3) were performed earlier on a small number of samples from the crystalline basement [22; 23]. However, neither samples nor gamma ray logs were available from studied boreholes drilled within the Grodno geothermal anomaly, nor from other granitoid massifs of the region. This does not allow more detailed analysis of the contribution of radiogenic heat production to the total heat flow within this area.

The temperature maps for mentioned depths and heat flow density, considered above, were constructed using the *Generic Mapping Tools* software package [15; 16]. This study has shown the heterogeneity of the thermal field of the Grodno region, the crystalline basement of which is represented by Precambrian rocks. The main role in the formation of anomalies at shallow levels is played by near-surface factors, such as the circulation of ground and meteoric waters and, probably, the influence of paleoclimatic factors related to the Weichselian glaciation [10; 26]. The role of the latter factor has been studied in Poland in the boreholes Krzemianka-IGH-1, Udryń-PIG-1 and others drilled within the Suwałki Massif (Suwałki County, Podlaskie Voivodeship) in the northeastern part of the country near the junction of the borders of Poland, Lithuania and the Kaliningrad enclave [10; 27]. For this region, it was shown that during the last glaciation, the temperature of the Earth's surface dropped to around –10 °C and there developed a zone of permafrost. The temperature logs indicated temperature inversion within a depth interval of 350–450 m [10].

The paleoclimatic correction was fulfilled by for all of Europe [26]. It was shown that for this entire region an average correction is quite sufficient (uncorrected heat flow: 56.0 mW/m^2, SD 20.3 mW/m^2; corrected heat flow: 63.2 mW/m^2, SD 19.6 m/Wm^2). From small-scale maps of corrected heat flow, it is possible to estimate that within northwestern Belarus the corrected heat flow values could be around 10 mW/m^2 higher than uncorrected ones. A more detailed map of the paleoclimatically corrected heat flow for the Polish area was published by J. Szewczyk and D. Gientka [28]. There is no detailed data on the Polish side near the Grodno region. These values, according to the interpolation used in this map, are around 10–15 mW/m^2 higher than uncorrected ones.

Heat flow values obtained from shallow boreholes of the Grodno region (mostly <300 m deep) are underestimated and require corrections. There are no wells deeper than 1000 m within this region. The maps (see fig. 11 and 12) were compiled using the observed heat flow data not subjected to corrections for paleoclimate, ground water circulation, etc. It is planned to correct such estimates and present them in a separate paper for the whole territory of Belarus. The paleoclimatic correction for the Grodno region, which covers ~12 % of the country, may not be representative.

Библиографические ссылки

1. Lyubimova EA, Karus EV, Firsov FV, Starikova GN, Vlasov VK, Lyusova LN, et al. Terrestrial heat flow on Pre-Cambrian shields in the USSR. *Geothermics*. 1972;1(2):81–89. DOI: 10.1016/0375-6505(72)90017-X.
2. Kutas RI, Zui VI. Geothermal regime along the northern part of the Eurobridge. In: Wiszniewska J, Wybraniec S, Petecki Z, Bogdanova S, Niemczynow-Burchart G, editors. *Between Eurobridge and TESZ. 7th Eurobridge Workshop; 1999 May 26–30; Szelment near Suwałki, Poland*. Warszawa: Polish Geological Institute; 1999. p. 64–65.
3. Беляков МФ. Геотермические измерения в Белоруссии. *Нефтяное хозяйство.* 1954;11:50–51.
4. Богомолов ГВ, Протасеня ДГ. Белорусская ССР. В: Макаренко ФА, редактор. *Термальные воды СССР и вопросы их теплоэнергетического использования*. Москва: Издательство Академии наук СССР; 1963. с. 27–33.
5. Богомолов ГВ. Изучение геологических структур методами геотермии. *Доклады Академии наук БССР*. 1968;12(2): 145–147.
6. Жук МС. Изучение теплового потока в пределах Белорусской антеклизы и его связь с теплогенерацией и геофизическими характеристиками в земной коре. В: Гарецкий РГ, редактор. *Сейсмологические и геотермические исследования на западе СССР.* Минск: Академия наук Беларуси; 1993. с. 188–195.
7. Богомолов ГВ, Цыбуля ЛА. Температурные условия поверхности кристаллического фундамента на территории Белоруссии. *Доклады Академии наук БССР.* 1967;11(1):41–44.
8. Богомолов ГВ, Цыбуля ЛА, Атрощенко ПП. Тепловое поле западной части Восточно-Европейской платформы. В: Субботин СИ, редактор. *Глубинный тепловой поток европейской части СССР*. Киев: Наукова думка; 1974. с. 65–78.
9. Махнач АС, Гарецкий РГ, Матвеев АВ, редакторы. *Геология Беларуси.* Минск: Институт геологических наук НАН Беларуси; 2001. 815 с.
10. Szewczyk J. The deep-seated lowland relict permafrost from the Suwałki region (NE Poland) – analysis of conditions of its development and preservation. *Geological Quarterly*. 2017;61(4):845–858. DOI: 10.7306/gq.1378.
11. Hurtig E, Haenel R, Čermak V, Zui VI, editors. *Geothermal Atlas of Europe*. Gotha: Geographisch-Kartographische Anstalt; 1991. Explanatory Note 156 p., 36 maps.
12. Зуй ВИ, Урбан ГИ, Веселко АВ, Жук МС. Геотермические исследования в скважинах Калининградской области и Литовской ССР. В: Гарецкий РГ, редактор. *Сейсмологические и геотермические исследования в Белоруссии.* Минск: Наука и техника; 1985. с. 88–94.
13. Цыбуля ЛА, Урбан ГИ. Тепловое поле Балтийской синеклизы и некоторые аспекты его связи с глубинной структурой земной коры. В: Гарецкий РГ, Хотько ЖП, редакторы. *Комплексные исследования глубинного строения территории Белоруссии и смежных областей*. Минск: Наука и техника; 1988. с. 28–34.
14. Урбан ГИ, Цыбуля ЛА. *Тепловой поток Балтийской синеклизы.* Москва: Институт физики Земли имени О. Ю. Шмидта РАН; 2004. 157 с.
15. Smith WHF, Wessel P. Gridding with continuous curvature splines in tension. *Geophysics*. 1990;55(3):293–305. DOI: 10.1190/1.1442837.
16. Wessel P, Smith WHF. Free software helps map and display data. *EOS, Transactions, American Geophysical Union*. 1991; 72(41):441–446. DOI: 10.1029/90EO00319.
17. Зуй ВИ, редактор. *Геотермический атлас Беларуси*. Минск: Национальная библиотека Беларуси; 2018. 89 с.
18. Jessop AM, Hobart MA, Sclater JG. *The World heat flow data collection – 1975*. Ottawa: Earth Physics Branch; 1976. 125 p. (Geothermal series; issue 5).
19. Жук МС, Зуй ВИ, Козел ВП. Тепловой поток Подлясско-Брестской впадины и сопредельных структур. *Доклады Академии наук БССР.* 1989;33(3):257–260.
20. Гарэцкі РГ, картограф. Карта крышталічнага фундамента, 1 : 1 200 000 [карта]. В: Мясніковіч МУ, ПіроЖнік II, Цэйрэфман КА, Явід ПП, Шымаў УМ, Пашкевіч МФ, рэдактары. *Нацыянальны атлас Беларусі.* Мінск: Белкартаграфія; 2002. с. 41.
21. Haenel R, Stegena L, Rybach L, editors. *Handbook of terrestrial heat-flow density determination*. Dordrecht: Springer; 1988. 486 p. (Solid Earth Sciences Library; volume 4). DOI: 10.1007/978-94-009-2847-3.
22. Лосева ЕИ, Зуй ВИ, Аксаментова НВ. Радиогенная теплогенерация горных пород главных структурных зон и интрузивных массивов кристаллического фундамента Беларуси. В: Аношко ЯИ, Богомолов ЮГ, Зуй ВИ, Кудельский АВ, Махнач АА, редакторы. *Проблемы водных ресурсов, геотермии и геоэкологии. Материалы Международной научной конференции, посвященной 100-летию со дня рождения академика Г. В. Богомолова; 1–3 июня 2005 г.; Минск, Беларусь*. Минск: Институт геохимии и геофизики НАН Беларуси; 2005. с. 270–272.
23. Зуй ВИ, Аксаментова НВ, Лосева ЕИ. U, Th, K и радиогенная теплогенерация в породах кристаллического фундамента Беларуси. В: Лукашёв ОВ, редактор. *Современные проблемы геохимии, геологии и поисков месторождений полезных ископаемых. Материалы Международной научной конференции, посвященной 100-летию со дня рождения академика Константина Игнатьевича Лукашёва (1907–1987); 14–16 марта 2007 г.; Минск, Беларусь*. Минск: Издательский центр БГУ; 2007. с. 20–23.
24. Rybach L. Radioactive heat production in rocks and its relation to other petrophysical parameters. *Pure and Applied Geophysics*. 1976;114:309–318. DOI: 10.1007/BF00878955.
25. Rybach L. Radioactive heat production: a physical property determined by the chemistry of rocks. In: Strens RGJ, editor. *The physics and chemistry of minerals and rocks*. London: Willey & Sons; 1976. p. 309–318.

26. Majorowicz J, Wybraniec S. New terrestrial heat flow map of Europe after regional paleoclimatic correction application. *International Journal of Earth Sciences*. 2010;100(4):881–887. DOI: 10.1007/s00531-010-0526-1.

27. Šafanda J, Szewczyk J, Majorowicz J. Geothermal evidence of very low glacial temperatures on a rim of the Fennoscandian ice sheet. *Geophysical Research Letters*. 2004;31:L07211. DOI: 10.1029/2004GL019547.

28. Szewczyk J, Gientka D. Terrestrial heat flow density in Poland — a new approach. *Geological Quarterly*. 2009;53(1):125–140.

References

1. Lyubimova EA, Karus EV, Firsov FV, Starikova GN, Vlasov VK, Lyusova LN, et al. Terrestrial heat flow on Pre-Cambrian shields in the USSR. *Geothermics*. 1972;1(2):81–89. DOI: 10.1016/0375-6505(72)90017-X.

2. Kutas RI, Zui VI. Geothermal regime along the northern part of the Eurobridge. In: Wiszniewska J, Wybraniec S, Petecki Z, Bogdanova S, Niemczynow-Burchart G, editors. *Between Eurobridge and TESZ. 7th Eurobridge Workshop; 1999 May 26–30; Szelment near Suwałki, Poland*. Warszawa: Polish Geological Institute; 1999. p. 64–65.

3. Belyakov MF. [Geothermal measurements in Belarus]. *Neftyanoe khozyaistvo*. 1954;(11):50–51. Russian.

4. Bogomolov GV, Protasenya DG. Belorusskaya SSR. In: Makarenko FA, editor. *Termal'nye vody SSSR i voprosy ikh teploenergeticheskogo ispol'zovaniya* [Thermal waters of the USSR and problems of their heat and power use]. Moscow: Izdatel'stvo Akademii nauk SSSR; 1963. p. 27–33. Russian.

5. Bogomolov GV. [The study of geological structures by geothermal methods]. *Doklady Academii nauk BSSR*. 1968;12(2): 145–147. Russian.

6. Zhuk MS. [Study of the heat flow within the Belarusian Anteclise and its relationship with heat generation and geophysical characteristics in the earth's crust]. In: Garetskii RG, editor. *Seismologicheskie i geotermicheskie issledovaniya na zapade SSSR* [Seismological and geothermal research in the west of the USSR]. Minsk: Academy of Sciences of Belarus; 1993. p. 188–195. Russian.

7. Bogomolov GV, Tsybulya LA. [Temperature conditions of the surface of the crystalline basement in the territory of Belarus]. *Doklady Akademii nauk BSSR*. 1967;11(1):41–44. Russian.

8. Bogomolov GV, Tsybulya LA, Atroshchenko PP. [Thermal field of the western part of the East European platform]. In: Subbotin SI, editor. *Glubinnyi teplovoi potok evropeiskoi chasti SSSR* [Deep heat flow of the European part of the USSR]. Kyiv: Naukova dumka; 1974. p. 65–78. Russian.

9. Makhnach AS, Garetskii RG, Matveev AV, editors. *Geologiya Belarusi* [Geology of Belarus]. Minsk: Institute of Geological Sciences of National Academy of Sciences of Belarus; 2001. 815 p. Russian.

10. Szewczyk J. The deep-seated lowland relict permafrost from the Suwałki region (NE Poland) – analysis of conditions of its development and preservation. *Geological Quarterly*. 2017;61(4):845–858. DOI: 10.7306/gq.1378.

11. Hurtig E, Haenel R, Čermak V, Zui VI, editors. *Geothermal Atlas of Europe*. Gotha: Geographisch-Kartographische Anstalt; 1991. Explanatory Note 156 p., 36 maps.

12. Zui VI, Urban GI, Veselko AV, Zhuk MS. [Geothermal research in boreholes of the Kaliningrad Region and the Lithuanian SSR]. In: Garetskii RG, editor. *Seismologicheskie i geotermicheskie issledovaniya v Belorussii* [Seismological and geothermal research in Belarus]. Minsk: Nauka i tekhnika; 1985. p. 88–94. Russian.

13. Tsybulya LA, Urban GI. Thermal field of the Baltic Syneclise and some aspects of its relationship with the deep structure of the Earth's crust. In: Garetskii RG, Khot'ko ZhP, editors. *Kompleksnye issledovaniya glubinnogo stroeniya territorii Belorussii i smezhnykh oblastei* [Comprehensive studies of the deep structure of the territory of Belarus and adjacent regions]. Minsk: Nauka i tekhnika; 1988. p. 28–34. Russian.

14. Urban GI, Tsybulya LA. *Teplovoi potok Baltiiskoi sineklizy* [Heat flow of the Baltic Syneclise]. Moscow: Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences; 2004. 157 p. Russian.

15. Smith WHF, Wessel P. Gridding with continuous curvature splines in tension. *Geophysics*. 1990;55(3):293–305. DOI: 10.1190/1.1442837.

16. Wessel P, Smith WHF. Free software helps map and display data. *EOS, Transactions, American Geophysical Union*. 1991; 72(41):441–446. DOI: 10.1029/90EO00319.

17. Zui VI, editor. Geotermicheskii atlas Belarusi [Geothermal Atlas of Belarus]. Minsk: National Library of Belarus; 2018. 91 p. Russian.

18. Jessop AM, Hobart MA, Sclater JG. *The World heat flow data collection – 1975*. Ottawa: Earth Physics Branch; 1976. 125 p. (Geothermal series; issue 5).

19. Zhuk MS, Zui VI, Kozel VP. Heat flow of the Podlyasie – Brest Depression and adjacent structures. *Doklady Akademii nauk BSSR*. 1989;33(3):257–260. Russian.

20. Garetskii RG, cartographer. Crystalline basement map of the Republic of Belarus, 1 : 1 200 000 [map]. In: Mjasnikovich MU, Pirozhnik II, Cjejrjefman KA, Javid PP, Shymaw UM, Pashkevich MF, editors. *Nacyjanal'ny atlas Belarusi* [National atlas of Belarus]. Minsk: Belkartagrafija; 2002. p. 41. Belarusian.

21. Haenel R, Stegena L, Rybach L, editors. *Handbook of terrestrial heat-flow density determination*. Dordrecht: Springer; 1988. 486 p. (Solid Earth Sciences Library; volume 4). DOI: 10.1007/978-94-009-2847-3.

22. Loseva YeI, Zui VI, Aksamentova NV. Radiogenic heat generation by rocks of the main structural zones and intrusion massifs of the crystalline basement of Belarus. In: Anoshko YaI, Bogomolov YuG, Zui VI, Kudel'skii AV, Makhnach AA, editors. *Problemy vodnykh resursov, geotermii i geoekologii. Materialy Mezhdunarodnoi nauchnoi konferentsii, posvyashchennoi 100-letiyu so dnya rozhdeniya akademika G. V. Bogomolova; 1–3 iyunya 2005 g.; Minsk, Belarus'* [Problems of water resources, geothermy and geoecology. Proceedings of the International Scientific Conference dedicated to the 100th anniversary of academician G. V. Bogomolov; 2005 June 1–3; Minsk, Belarus]. Minsk: Institute of Geochemistry and Geophysics of the National Academy of Sciences of Belarus; 2005. p. 270–272. Russian.

23. Zui VI, Aksamentova NV, Loseva YeI. [U, Th, K and radiogenic heat generation in the rocks of the crystalline basement of Belarus]. In: Lukashev OV, editor. *Sovremennye problemy geokhimii, geologii i poiskov mestorozhdenii poleznykh iskopaemykh. Materialy Mezhdunarodnoi nauchnoi konferentsii, posvyashchennoi 100-letiyu so dnya rozhdeniya akademika Konstantina Ignat'evicha Lukasheva (1907–1987); 14–16 marta 2007 g.; Minsk, Belarus'* [Modern problems of geochemistry, geology and prospecting for mineral deposits. Proceedings of the International Scientific Conference dedicated to the 100th anniversary of the birth of academician

Konstantin Ignatievich Lukashev (1907–1987); 2007 March 14–16; Minsk, Belarus]. Minsk: Publishing Center of the Belarusian State University; 2007. p. 20–23. Russian.

24. Rybach L. Radioactive heat production in rocks and its relation to other petrophysical parameters. *Pure and Applied Geophysics*. 1976;114:309–318. DOI: 10.1007/BF00878955.

25. Rybach L. Radioactive heat production: a physical property determined by the chemistry of rocks. In: Strens RGJ, editor. *The physics and chemistry of minerals and rocks*. London: Willey & Sons; 1976. p. 309–318.

26. Majorowicz J, Wybraniec S. New terrestrial heat flow map of Europe after regional paleoclimatic correction application. *International Journal of Earth Sciences*. 2010;100(4):881–887. DOI: 10.1007/s00531-010-0526-1.

27. Šafanda J, Szewczyk J, Majorowicz J. Geothermal evidence of very low glacial temperatures on a rim of the Fennoscandian ice sheet. *Geophysical Research Letters*. 2004;31:L07211. DOI: 10.1029/2004GL019547.

28. Szewczyk J, Gientka D. Terrestrial heat flow density in Poland – a new approach. *Geological Quarterly*. 2009;53(1):125–140.

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