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Low Heat Flow at Shallow Depth Intervals: Case Studies from Belarus

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Abstract

The territory of Belarus belongs to the western part of the Precambrian East European Platform. Its heat flow pattern is representing by alternating low and high heat flow anomalies. An overwhelming majority of heat flow determinations and in general of geothermal observations in Belarus were fulfilled in boreholes finished in the platform cover. Within the Belarusian Antecline, Orsha Depression, western slope of the Voronezh Antecline their bottom holes are typically within the zone of active water exchange, where the groundwater circulation sufficiently influences on recorded thermograms. For instance, observed heat flow density for a number of studied boreholes is low and ranges on average from 15–20 until 35–40 mW/m² within the Orsha Depression. In a number of studied holes in the northern part of the structure, its values are surprisingly low. They are observed within upper horizons of the zone of active water exchange with pronounced groundwater circulation. Permeable rocks within the geologic section comprise the platform cover with a number of freshwater intervals. Their base is spread here up to depths of 150–250 m. The most of heat flow observations within this area were studied in boreholes which depths is only 200–300 m, sometimes less, as deeper wells are seldom within this geologic structure. Groundwater circulation within loose sediments cools them, most of thermograms here have a concaved shape to the depth axis. As a rule, heat flow values are sufficiently lower in a number of intervals in boreholes finished in the freshwater zone, relatively to the heat flow observed within deeper horizons of the platform cover. In some of studied boreholes, the observed heat flow is as low as 5–15 mW/m². In most cases it has a tendency to stabilise only at intervals deeper than 600–800 m. It is the main reason for observed low heat flow zones.

1. Introduction

The territory of Belarus lies in the center of Europe within the western part of the Precambrian East European Platform. A thin platform cover of up to 500–600 m overlaps the basement within the adjoining Belarusian Antecline, which occupies a central place in the geological structure of the region; its thickness is reduced to 80–100 m within the Central Belarusian Massif. It reaches 1.5–1.7 km in the adjacent Orsha and Brest depressions and up to 5–6 km in the most lowered blocks of the Paleozoic Pripyat Trough. The majority of geothermally studied boreholes in the country were completed in a platform cover. Only in some of them, geothermal measurements were made in the uppermost intervals of the crystalline basement. Geothermal investigations in the region were started back in the mid-60s – 70s of the last century

2. Methodology

It is well known that Precambrian platforms are generally “colder” compared to younger blocks of the earth's crust.

Hundreds of thermograms were recorded in wells of Belarus during a number of years, and the heat flow density determination in the studied depth intervals were carried out since the early 70s. They led to the conclusion of sufficient variability in temperature distribution, interval geothermal gradients, and calculated values of heat flow density not only throughout the country, but also within individual geological structures: the Belarusian Antecline with its saddles, the Orsha and Podlyaska-Brest depressions.

A significant contrast in the temperature distribution and the estimated heat flow density (using published data on heat conductivity) was noted in the country as early as in 60s, Protaseny (1962a, 1962b) in the adjacent Pripyat Trough of Paleozoic age. At those time, it was believed that geothermal regime in the rest part of the country was rather uniform. Later, as field works were carried out and thermograms of boreholes were accumulated, allowed to fulfill a determination of heat flow density, a number of geothermal maps of temperature distribution, geothermal gradient and heat flow density, as well as the density of recoverable geothermal resources compiled showed rather contrast pattern of the geothermal

field. A number of geothermal anomalies were outlined within territories of the region, as reported by Zui (2013) and also in Zui (2017).

Positions of boreholes with geothermal measurements accumulated during decades in Belarus are shown in Figure 1. The lengths of the vertical bars in this figure show at the scale, given in the lower right corner of the map, the depth reached by borehole thermometers in each of the studied wells. Within the country, the deepest studied wells are located in the Pripyat Trough. Relatively shallow wells, frequently completed by drilling in the zone of active water exchange (in the zone of freshwater), as a rule, predominate in the rest of the territory beyond the trough. In this regard, the geothermal field of the platform cover throughout the country is characterized for depths of the first hundreds of meters. Based on these measurements, a series of geothermal maps was included in the Geothermal Atlas of Belarus (Zui, 2018a).

The main tectonic units of the region are the Belarusian, and Voronezh anticlises, the Baltic Syncline, the Orsha and Podlaska-Brest depressions, Bragin–Loyev and Polesian saddles, Bobruysk Inlier, Zhlobin and Latvian saddles, Moscow Syncline, the Pripyat Trough and the Ukrainian Shield.

Nevertheless, regular geothermal studies in the country have been conducted since the late 60s – early 70s of the previous century; but up to date the deep horizons of the Belarusian part of the Belarusian Antecline and Orsha Depression including a strip along the borders with Lithuania, Latvia, and Russia have been poorly studied.

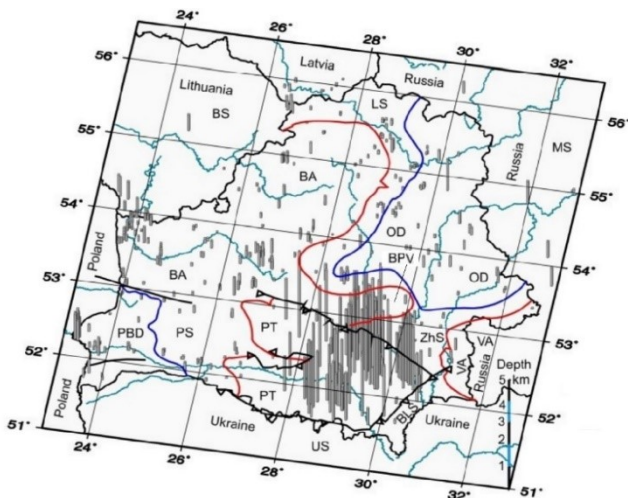


Figure 1 - Positions of geothermally studied boreholes within the territory of Belarus, Zui (2017).

Legend: 1 – red lines indicate the boundaries of the Belarusian (in the center) and Voronezh (in the east) anticlises; 2 – blue lines show borders of the Orsha and Podlaska-Brest depressions; 3 – black lines show main faults; abbreviations: BA – Belarusian Antecline, BLS – Bragin–Loyev Saddle, BPV – Bobruysk Buried Inlier, BS – Baltic Syncline, VA – Voronezh Antecline, ZhS – Zhlobin Saddle, LS – Latvian Saddle, MS – Moscow Syncline, OD – Orsha Depression, PBD – Podlaska-Brest Depression, PT – Pripyat Trough, PS – Polesian Saddle, US – Ukrainian Shield.

3. Geothermal measurements in the zone of active water exchange in the platform cover

The largest number of wells studied is available for depths of 100–200 meters. For instance, to compile a temperature

distribution map at the depth of 100 m, we used all accessible results approaching up to 1000 thermograms with reliable temperature measurements in wells that knowingly reached their thermal equilibrium after drilling was completed. Of the available production thermograms, drilled with exploration or oil prospecting purposes, only a few more reliable data were used and only for wells drilled in areas where no other measurements were available. The depth of 100 meters belongs entirely to the freshwater zone (active water exchange zone), where the groundwater filtration influences shapes of thermograms. The depth of studied boreholes often does not exceed 150–250 m. The convective component of heat transfer takes place here and influences the whole wellbore intervals. It is evident from the example of thermograms recorded in individual wells drilled in the northeastern Belarus, Figure 2.

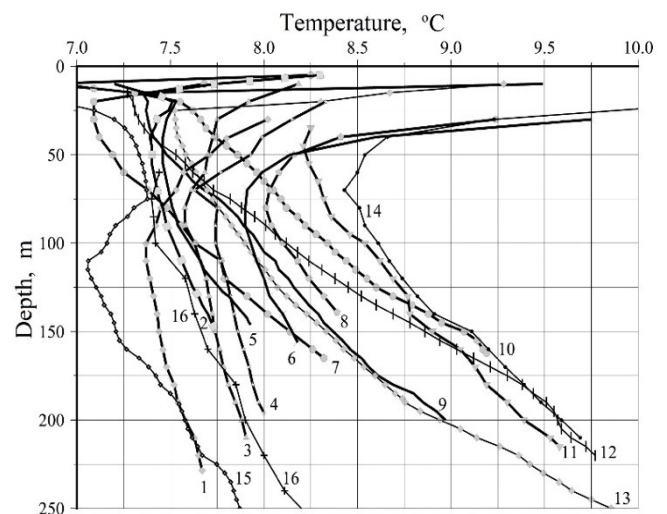


Figure 2 - Thermograms recorded in wells of the Orsha Depression in the north-eastern part of Belarus.

Legend: Numbers in the figure are thermograms of studied boreholes: 1 – Kozlovka-37csh; 2 – Kosari-25lp; 3 – Senno-36csh; 4 – Kozlovka-34csh; 5 – Sudilovichi-20lp; 6 – Ushachi-9lp; 7 – Ksty-5pl; 8 – Zaborye-22tl; 9 – Komoski-25csh; 10 – Brazdetskaya Sloboda-51csh; 11 – Sinichenka-37tl; 12 – Zaskorki-2pl; 13 – Samosedovka-36tl; 14 – Polotsk-49pl; 15 – Surazhskaya-1s2; 16 – Smolensk-1

Most thermograms are characterized by concave shapes, typical for conditions of the downward movement (infiltration) of atmospheric water into permeable deposits that cools the upper part of the platform cover. The Smolensk-1 deep well, which was drilled through a whole sequence of sediments into the crystalline basement and located in the Russian part of the Orsha Depression, have the same shape of thermograms in its upper part. In its form, it resembles thermograms of shallow wells in the Belarusian part of this depression, shown in the Figure 2.

These thermograms illustrate the effect of downward filtration of groundwater in the zone of its recharge. They typically have a convex shape to the depth axis within zones of groundwater discharge into river valleys. Hence, an upward water movement leads to the “heating up” of thermograms in the zone of active water exchange. It is caused also by the discharge of groundwater into valleys of rivers, lakes, or along faults that penetrate into the platform cover. These

thermograms are acceptable to create temperature distribution maps, but most often, they must be discarded as unsuitable ones for calculating and constructing heat flow maps as subjected to distortion by near-surface factors.

In most cases, such thermograms, recorded in the zone of active water exchange at a mapped depth of 100–200 m, reflect the influence of convection, which causes their concave or convex shapes. At the same time, when they are put on the heat flow map, “anomalies” arise that do not have an unequivocal geological explanation.

When drawing isotherms, the temperature interval of 0.5 °C was used, it can be considered as justified bearing in mind that the absolute error of the downhole electric thermometers was no more than $\pm 0.03\text{--}0.05$ °C, and the wells themselves had a long time elapsed before geothermal recording. The position of studied wells is shown on the map, Figure 3 by black dots. In some cases, when they are located close to each other, they were merged into one point at a selected map scale. The distribution of boreholes studied in the region is uneven. Within the framework of the map, areas adjacent to the Baltic and Moscow Syncline, as well as the Latvian Saddle, the Ukrainian Shield, the western slope of the Voronezh Antecline remain poorly studied.

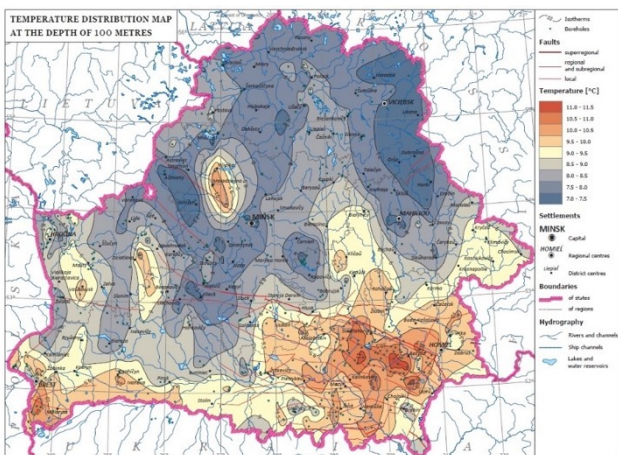


Figure 3 - Temperature distribution in Belarus at the depth of 100 m with the vast low temperature zones in its central and north-eastern parts (Zui, 2018a).

The temperature at the depth of 100 m varies in the region from 7 to 11.5 °C, the difference between its extreme values reaches 4.5 °C. Temperatures above 8 °C are characteristic of the northern zone of the Pripyat Trough and the Podlaska-Brest Depression, where exist positive geothermal anomalies. The 9 °C isotherm extends beyond the North-Pripyat limiting fault and can be traced within the North-Pripyat Shoulder, the Zhlobin Saddle and the western slope of the Voronezh Antecline. It subdivides the low temperature anomaly in eastern and western parts.

The temperature field at depth of 100 m has a contrasting appearance. Regional and local anomalies are clearly visible. There are several extensive low temperature anomalies. In the eastern part of the Orsha Depression: in the triangle between towns Orsha – Smolensk – Cherikov an extensive anomaly with temperatures of 6.5–7.5 °C is present East-of Orsha (Zui, 2013). This anomaly continues onto Russian territory. However, reliable geothermal observations in boreholes are very seldom within areas adjacent to the Belarusian border

zone of the Russian territory. Only a few thermograms were recorded there under conditions in which thermal equilibrium in rocks has not been reached after completion of drilling. Hence, it is difficult to trace reliably the eastward extension of this anomaly beyond the Belarus – Russia state border.

In the eastern parts, the low temperature anomaly includes almost the entire Mogilev Syncline of the Orsha Depression, that is limited by the strip of elevated temperatures in the sub meridional direction. It can be traced in the western part of the Orsha Depression and the eastern slope of the Belarusian Antecline along the string of towns of Rechitsa, Svetlogorsk, Klichev, Belynichi, Berezino, Borisov, Lepel, Chashniki and Ezerische and continues onto Russia. It is called as the West Orsha anomaly of elevated temperatures. In its northern part, this anomaly splits in the eastern direction from the city of Ezerishche through Vitebsk and reaches the latitude of Orsha.

The northern end of the low temperature anomaly in the region is uncertain due to lack of data in the area beyond the state border. Only two wells were studied here (Ruba and Surazhskaya 1s2) in the Belarusian side north of Vitebsk. The temperature values within the West Orsha anomaly vary from 8 °C in its central parts to 10.0–11.5 °C in the northern zone of the Pripyat Trough.

All these anomalies were observed also in maps for depths of 200–500 m, but the area occupied by these is relatively smaller. An example of the temperature map for a depth of 200 m is shown in Figure 4. All geothermal anomalies of high and low temperature values are preserved, already outlined in the map for a depth of 100 m. Here both the West Orsha anomaly of increased temperature values and zones of low temperature are reflected more clearly. Temperature values within its limits vary from 9 °C in the central part of the Orsha Depression to 14.0–14.5 °C in the northern zone of the Pripyat Trough. Low temperature anomalies break down here into a series of smaller zones.

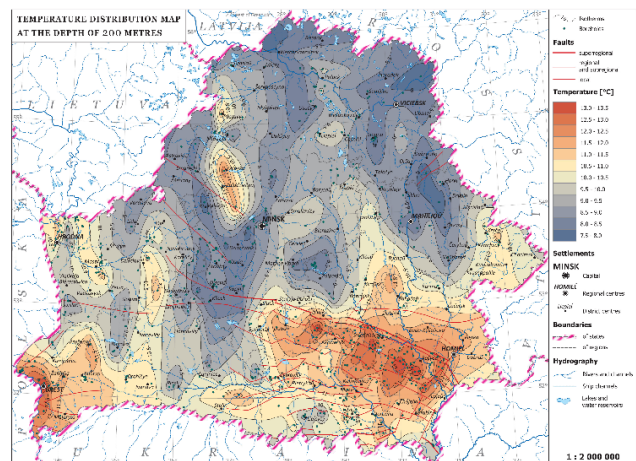


Figure 4 - Temperature distribution in Belarus at the depth of 200 m with the vast low temperature zones in its central and north-eastern parts (Zui, 2018a).

It is possible to conclude that the groundwater circulation reaches depths of 200 m within many areas of the country and is responsible for the formation of vast zones of cooled rocks. The depth of 200–250 m represents the base of freshwater zone in the north-eastern part of the country. In other words, the cooling effect of an infiltration is dominant within the whole zone of active water exchange in the region.

4. Interval values of heat flow density within Orsha Depression

As an example, we consider heat flow values that can be obtained using thermograms of wells in the zone of active water exchange within the Orsha Depression and in eastern slope of the Belarusian Antecline. Under compacted Quaternary rocks (such as sand, sandy loam and thin loam interlayers) with an abundance of hydrogeological features that allow down flow of ground water overlies Devonian sediments, which are in general cavernous dolomites. Downflow of groundwater arising from prolonged autumn rains and thawing of snow in spring, cools the upper section and leads to a deep occurrence of a “neutral layer” with low values of the geothermal gradient and consequently low heat flow density (see Figure 5).

Well and its Number	Neutral Layer Depth, m	Heat Flow, mW/m ²
Brazdetskaya Sloboda 51csh	10	23
Zaskorki 2pl	15	30
Komoski 25csh	15	19
Ksty 5pl	25	18
Samosedovka 36tl	25	31
Smolensk 1 (upper part)	35	14
Kosari 25lp	40	6
Sinichenka 37tl	45	22
Sudilovich 20lp	50	10
Orsha 2op (upper part)	50	17
Polotsk 49pl	70	22
Kozlovka 34csh	70	6
Kozlovka 42csh	70	6
Zaborye 22tl	80	14
Ushachi 9lp	85	5
Kozlovka 37csh	105	3
Senno 36csh	120	4

Figure 5 - Density of heat flow variation in the zone of active water exchange below the depth of the “neutral layer”, Zui (2018b).

In most cases, such thermograms recorded in the zone of active water exchange, at depths of 100–200 m, reflects the influence of convection, which causes their concave, or sometimes a convex shape. Consider now the extensive low-temperature anomaly within the Orsha Depression, which is highlighted mainly based on the results of temperature recording in shallow wells. Careful analysis is required before using these to determine heat flow.

The surface distribution of wells under consideration is shown in Figure 6. The heat flow density (HFD) scale is shown in the lower left corner of the map. Unrealistically low heat flow values refer to shallow wells Nos. 1, 4, 5–7 (see. Figure 2). However, their interval values in the zone of active water exchange remain low (less than 20 mW/m²) and for deeper intervals in wells, such as Smolensk-1, Orsha-2op, Surazhskaya-1s2, the heat flow is higher.

A number of wells with unrealistic low heat flow were not included in the heat flow catalogue of the country. Individual heat flow values are based on recorded thermograms and thermal conductivities of rock samples measured in laboratory conditions.

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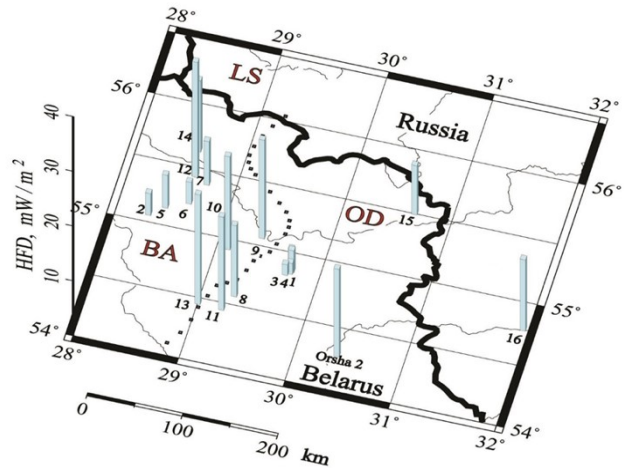


Figure 6 - Distribution of wells employed in study of the heat flow in the north-eastern region.

Legend: BA - Belarusian Antecline; LS - Latvian Saddle; OD - Orsha Depression. Numbers adjacent to vertical bars refer to the numbers of boreholes, illustrated in figure 2. Small squares indicate the border between the Belarusian Antecline and the Orsha Depression.

The depth pattern of the fresh groundwater base in this region varies approximately between 150 and 250–300 m. The lowest values occur in the northern, eastern and southern parts, as illustrated in Figure 7. Only in the western part of Belarus, outside frames of this map, it exceeds 400 m. The solid lines of isohypses in the diagram indicate zones of reliable observations, and the dashed lines indicate the estimated depth of their occurrence.



Figure 7 - Part of the depth map of the freshwater base in the north-eastern part of Belarus, Kudelsky et al. (2000). The red lines indicate local faults. Curves of isolines show the limits of groundwater occurrence within the region.

At shallow depths the sedimentary cover includes a number of aquifers, the depth distributions of which are illustrated schematically in Figure 8. These are separated by low-permeability sediments with numerous hydrogeological windows.

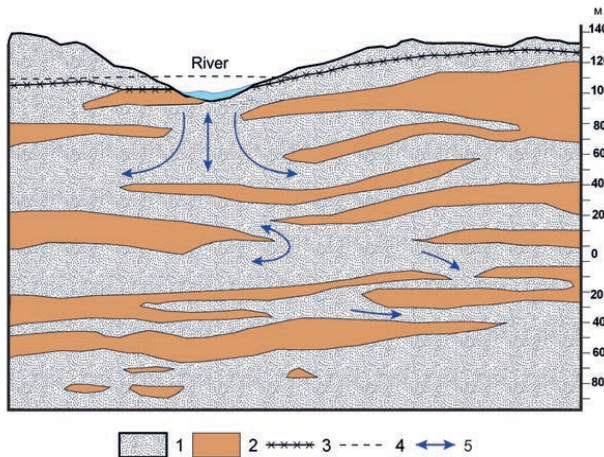


Figure 8 - Schematic illustration of freshwater flow system in the upper part of the zone with hydrogeological windows. Legend: 1 – aquifers, 2 – aquitards, 3 – position of groundwater table, 4 – position of the groundwater table during periods of high water, 5 – directions of groundwater movements.

In many thermograms of the Orsha Depression low-temperature sediments are observed, due to infiltration of near-surface waters within the upper part of the sedimentary cover. The concave shapes of thermograms indicate down flow (see Figure 2) which affect temperatures up to depths of 500 – 600 m. Similar situation occurs for interval values of heat flow, which are clearly observed for the deep borehole Smolensk-1, Figure 9. Obviously, this leads to decrease in geothermal gradient in the upper part of the platform cover. In a number of shallow wells gradient values drop down to 3–5 mK/m.

5. DISCUSSION

We consider in more details the thermogram of the Smolensk-1 deep borehole drilled a few meters into the crystalline basement, Orsha Depression, Russia, which was mentioned above (see Figure 5), only for shallow intervals. This thermogram was registered by a thermistor electric thermometer after a long (about 14 years) well stay at rest. The samples of a drill core were collected, and we studied their thermal properties in the laboratory of Geothermics of the Institute of Geochemistry and Geophysics of the National Academy of Sciences of Belarus.

In the upper part of the section to a depth of about 400 m, heat flow values are in the range of 10 to 15 mW/m², which practically corresponds to their observed values in shallow wells of the Belarusian part of the Orsha Depression, discussed above (see Figures 5 and 6). It is clear from the Figure 9, that the vertical variability of the interval values of the heat flow is significant up to depths of about 800 m. For depths greater than 600 m the interval values fall in the interval of 30 to 33 mW/m². The high value is included in the heat flow catalogue as the representative one for the borehole Smolensk–1, undisturbed by surface factors. The HFD – depth curve in Figure 9 shows monotonic increase of heat flow with the depth. Considering only the shallow part of the thermogram for the Smolensk-1 borehole, for example up to 200 – 250 m, heat flow is lower (14–15 mW/m²), comparable with results of other shallow wells, shown in Figure 6.

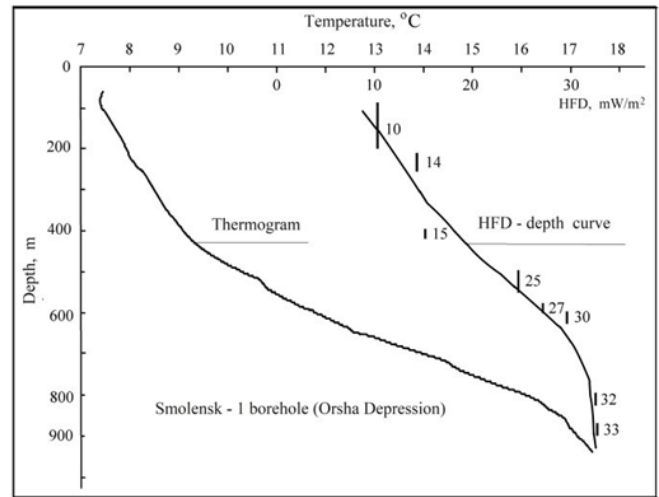


Figure 9 - Thermogram of the deep Smolensk-1 well and change in its interval values of the heat flow density (in units of mW/m²) along the depth of the well.

The interval values of the heat flow density vary from 10 mW/m² in the upper part of the geologic section of the Smolensk-1 well to 33 mW/m² near the surface of the crystalline basement at a depth of about 900 m. At the same time, the heat flow in the Smolensk–1 borehole increases almost threefold with depth. It shows a considerable influence of near-surface factors at the geothermal gradient, as well as on observed heat flow density until the depth at least of 600 – 800 m. Ability of hydrogeological windows within upper part of the platform cover promotes the water penetration from the surface into relatively deep horizons, which in turn cools the upper part of sediments. This phenomenon explains unrealistic low observed heat flow for other considered shallow boreholes within this area, for instance those shown in Figures 5 and 6. The rate of vertical overflow of groundwater was not estimated; therefore, no corrections for the influence of groundwater circulation were applied. These data require further investigations for applying such corrections first of all for ground water circulation within the zone of active water exchange.

6. CONCLUSIONS

The paper discusses features of studying the distribution of temperature and heat flow for wells completed by drilling in the zone of freshwater distribution. Almost all of them, with the exception of the Smolensk-1, Surazhskaya-1s2 and Orsha-2op wells, were completed by drilling in the zone of freshwater distribution. In this zone typically low values of both temperature and low interval values of heat flow density (4–20 mW/m²) were observed, and only occasionally it reaches 25–30 mW/m². In this case, a number of geothermal anomalies are distinguished in geothermal maps, which are not result of the geologic structure of the platform cover and features of the crystalline basement but caused by the groundwater circulation. The latter circumstance requires careful selection of the available data when they are used to create the heat flow map.

It is clear that hydrogeological windows within upper parts of the platform cover with thin aquitards result in groundwater penetration from the surface into relatively deep strata, which in turn cools the upper part of sediments. Consequently, low

heat flow values occur until the depth of several hundred meters.

These low values correlate with the depth of so called “neutral layer” (the depth to which annual temperature variations at the ground surface penetrate), which can reach 120 m for the Senno–36csh well. It follows from the Figure 5 that for high position of this layer (for instance wells Brazdetskaya Sloboda-51csh and Zaskorki-2pl with rather high position of 10–15 m of this layer, heat flow increases to 23–30 mW/m². An opposite situation exists when observed heat flow drops to unrealistic 3–4 mW/m². It concerns wells Kozlowka–37csh and Senno–36csh, where depths of the “neutral layer” are 105 and 120 m, respectively. It is possible to conclude that the deeper this layer, the lower the interval heat flow values.

Groundwater circulation has the greatest influence on temperatures in the zone of active exchange. Here, meteoric waters penetrate predominantly loose sediments in the upper part of the platform cover. To account for the convective component of heat transfer associated with this downflow it is necessary to understand the filtration rate in each particular depth interval.

These very low HFD values require further investigations for applying corrections for ground water circulation within the zone of active water exchange in the region of the present work.

7. Acknowledgments

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References

- Kudelsky, A.V., Pashkevich, V.I., Karabanov, A.K., Pavlovskaya, I.E., Korin V.D. 2000 Hydrosphere of Belarus at the newest tectonic stage. Reports of the National Academy of Sciences of Belarus (In Russian), 44(6), 79–83.
- Protaseny, D.G. 1962a On Some Issues of Hydro and Thermodynamics of the Pripyat Graben, Proceedings of the conference of young scientists of the Academy of Sciences of the BSSR, AN BSSR. Minsk (In Russian) P. 193–199.
- Protaseny, D.G. 1962b Some regularities of Geothermics of deep parts of the Pripyat Trough, Doklady AN BSSR (In Russian), 6(1), 49–52.
- Zui, V.I. 2013 Thermal field of the platform cover of Belarus. Econopress, Minsk (In Russian). 256 p.
- Zui, V.I. 2017 Fundamentals of Geothermics. BSU, Minsk (In Russian). 287 p.
- Zui, V. I. 2018a Geothermal Atlas of Belarus. National Library of Belarus, Minsk (Edited by V.I. Zui). 91 p. (In Russian and English).
- Zui, V.I. 2018b Heat flow in the zone of active water exchange in the north-east of Belarus, Problems of the geology of Belarus and adjacent territories. Proceedings of the

International scientific conference dedicated to the 100th anniversary of the birth of Academician of the National Academy of Sciences of Belarus Alexander Semyonovich Makhnach, Minsk, November 21–22 (In Russian). p. 49–53.