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Low Heat Flow in the Orsha Depression, Belarus

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ABSTRACT

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 Anteclise, Orsha Depression, western slope of the Voronezh Anteclise their bottom holes are within the zone of active water exchange, where the groundwater circulation sufficiently influences on recorded thermograms. The geothermal field has considerable differentiation both in temperature and heat flow within studied depths. General features of geothermal field are considered on an example of the Precambrian Orsha Depression situated within the northeastern part of Belarus. Observed heat flow density for studied boreholes is low and ranges on average from 15–20 until 35–40 mW/m^2. At this background, within 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 fresh water intervals. Their base is spread here up to depths of 200–250 m. The most of heat flow observations within these parts of the Orsha Depression were studied in boreholes which depths is only 200–300 m, or sometimes less, as deeper wells are seldom within this geologic structure. Groundwater circulation within loose sediments cools their, 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 fresh water zone, relatively to the heat flow observed within deep horizons of the platform cover. In some of studied boreholes, the observed heat flow is as low as 5–15 mW/m^2. In most cases, the observed heat flow has a tendency to stabilise only at intervals deeper than 600–800 m. It requires the detailed analysis when compiling heat flow maps.

1. INTRODUCTION

The territory of Belarus lies within the western part of the East European Platform of the Precambrian age. A thin platform cover of up to 500 m covers the basement of the adjoining Belarusian Anteclise, which occupies a central place in the geological structure of the region; its capacity is reduced to 80–100 m within the Central Belarusian Massif. For comparison, in the most lowered blocks of the Pripyat Trough, its thickness increases to 5–6 km. The vast majority of geothermally studied boreholes in the country and the studied region 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. It is well known that Precambrian platforms are generally “colder” compared to younger blocks of the earth's crust and characterized by a relatively uniform thermal field in terms of temperature distribution at comparable depths as well as their heat flux density.

2. GEOTHERMAL KNOWLEDGE OF THE REGION

The registration of thermograms of wells were undertaken during a number of years, and the determination of the heat flow density in the studied depth intervals, carried out since the early 70s. They led to the conclusion of sufficient variability in temperature distribution, interval geothermal gradient values and calculated values of heat flow density not only throughout the country, but also within individual geological structures – the Belarusian Anteclise 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 adjacent Pripyat Trough as early as in 60s, Protasenya (1962a, 1962b). At those time, it was believed that geothermal regime in this part of the country was rather uniform. Later, as field works were carried out and thermograms of boreholes were accumulated, allowed to fulfil 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 were compiled. A number of geothermal anomalies were outlined within territories of the region, Zui (2013); Geothermal... (2018).

Available at present geothermal exploration of Belarus is 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, usually completed by drilling in the zone of active water exchange (in the zone of fresh water), 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 more precisely characterized for depths of the first hundreds of meters. According to the available knowledge at present, a series of geothermal maps was included in the Geothermal Atlas of Belarus, which was compiled recently, Geothermal... (2018).

Nevertheless, regular geothermal studies in the republic 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 Anteclise and Orsha Depression including territories along the borders with Lithuania, Latvia, and Russia have been poorly studied.

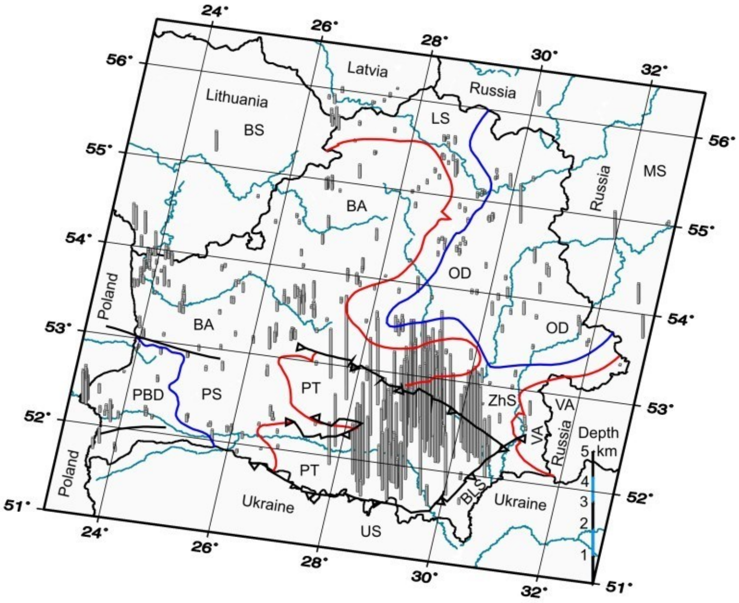

Figure 1: - Geothermal exploration of the territory of Belarus, Zui (2017).

Legend: 1 – red lines indicate the boundaries of the Belarusian and Voronezh anteclises; 2 – blue lines show borders of the Orsha and Podlaska-Brest depressions; 3 – main faults; abbreviations: BA – Belarusian Anteclise, BLS – Bragin–Loyev Saddle, BS – Baltic Syneclise, VA – Voronezh Anteclise, ZhS – Zhlobin Saddle, LS – Latvian Saddle, MS – Moscow Syneclise, 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 OF THE REGION

The largest number of wells studied is available for depths of 100–200 meters. For instance, to compile a temperature distribution map at a depth of 100 m, we used all accessible results of 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, of 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 influence of groundwater filtration is reflected in the shape of thermograms. The total depth of studied boreholes often does not exceed 150–250 m. Here, the effect of the convective component of heat transfer takes place within the whole wellbore intervals. Let us show this by the example of thermograms of individual wells of the north-eastern Belarus, figure 2.

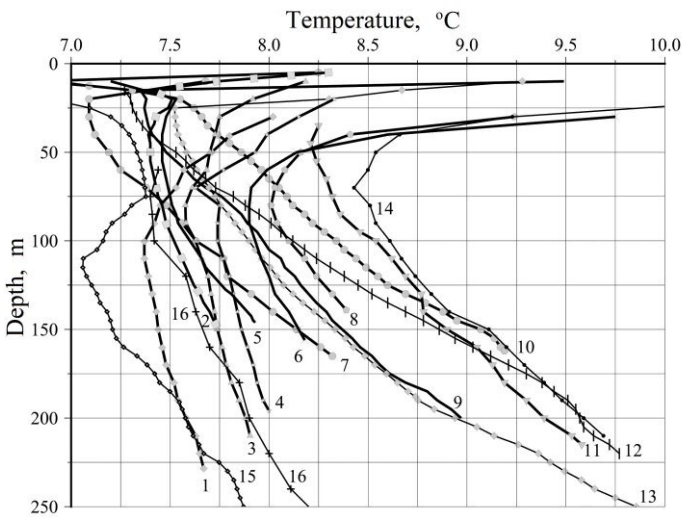

Figure 2: Thermograms recorded in wells of the Orsha Depression in the north-eastern part of Belarus.

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-9lpl; 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 a concave shape, 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 the whole sedimentary cover into the crystalline basement and is 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.

The opposite situation of the groundwater circulation is its upward movement, which leads to the "heating up" of thermograms in the zone of active water exchange. It is caused by the discharge of groundwater into valleys of rivers, lakes, or along faults that penetrate into the platform cover. We do not consider here the influence of salt swells and domes, which are encountered within sedimentary cover beneath the earth's surface. An example of such groundwater influence on shapes of thermograms can be clearly visible in boreholes Livye 82 and 107, figure 3.

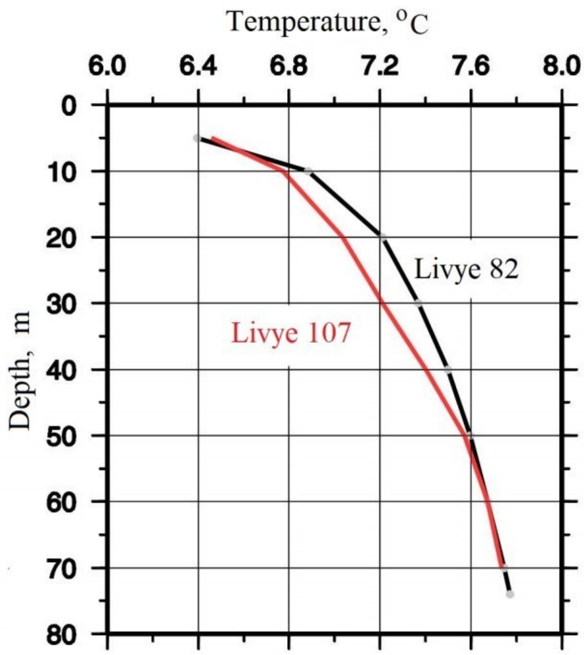

Figure 3: Example of thermograms of wells Livye-82 and Livye-107 (Belarusian Anteclise)

These thermograms illustrate the effect of upward filtration of groundwater in the zone of its discharge, they both have a convex shape to the depth axis. Most often, this form of thermograms are in the valleys of rivers, lakes, canals, etc. Obviously, such thermograms are unsuitable for calculating the heat flow and constructing of geothermal maps being subjected to distortion by nearsurface 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 map, "anomalies" arise that do not have an unequivocal geological explanation.

When drawing isotherms, the interval of 0.5 °C was used, it can be considered as justified one bearing in mind that the absolute error of the downhole electric thermometers was no more than ± 0.03–0.05 °C, and the wells themselves had a long time elapsed before recording thermograms. The position of the studied wells is shown on the map, figure 4 by circles. 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 syneclises, as well as the Latvian Saddle, the Ukrainian Shield, the western slope of the Voronezh anteclise remain poorly studied.

The temperature at a depth of 100 m varies in the region from 7 to 11.5 °C, the difference between the 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 there are 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 Anteclise.

The temperature field at a depth of 100 m has a contrasting appearance. Regional and local anomalies are clearly visible. Let us briefly discuss the most extensive low temperature anomaly. In the eastern part of the Orsha Depression in the triangle between the towns Orsha – Smolensk – Cherikov exists the extensive East-Orsha anomaly of low temperatures of 6.5–7.5 °C, Zui (2013). This anomaly is continued into Russian territory. However, reliable geothermal observations in boreholes are very seldom within the adjacent to the Belarusian border parts of Orsha Depression within Russian territory. Only a few thermograms were recorded there under conditions when the thermal equilibrium was not reached after completion of their drilling. Hence, it does not allow tracing eastwards the continuation of this anomaly beyond the Belarus – Russia state border.

The low temperature anomaly includes almost the entire Mogilev Syncline of the Orsha Depression. It also highlights the strip of elevated temperatures of the submeridional direction. It can be traced in the western part of the Orsha Depression and the eastern slope of the Belarusian Anteclise along the towns Rechitsa – Svetlogorsk – Klichev – Belynichi – Berezino – Borisov – Lepel – Chashniki – Ezerische and continues to Russia. It is called as the West Orsha anomaly of elevated values of temperature. In its northern part, this anomaly splits in the eastern direction from the city of Ezerishche through Vitebsk and reaches the latitude of Orsha. Outlined geothermal anomalies are shown in the figure 4 for the depth of 100 meters.

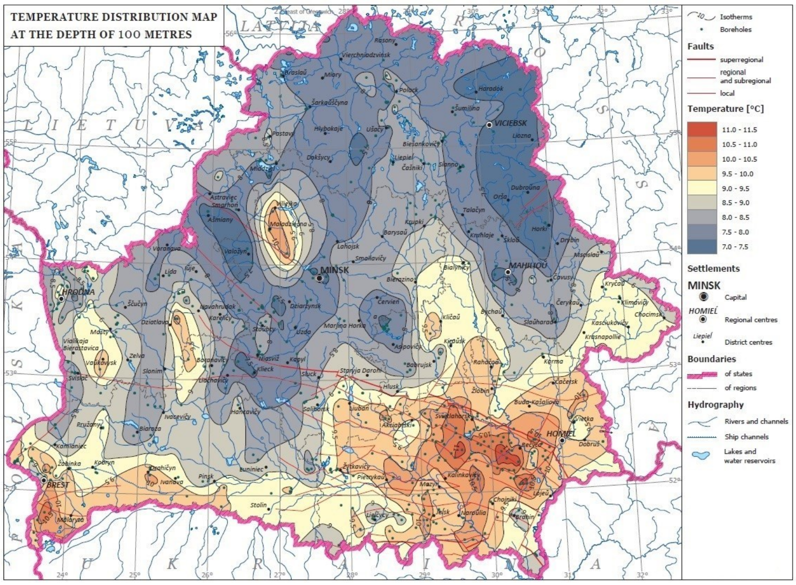

Figure 4: Temperature distribution in Belarus at the depth of 100 m with the vast low temperatures in its north-eastern part within the Orsha Depression [Geothermal ..., 2018].

The northern end of the low temperature anomaly in the region is uncertain due to lack of data in the near-border area. On the Belarusian side north of Vitebsk, only two wells were studied here (Ruba and Surazhskaya-1s2). The temperature values within the West Orsha anomaly vary from 8 °C in its central part to 10.0–11.5 °C in the northern zone of the Pripyat Trough. All these anomalies were observed in similar maps for depth of 200–500 m, but the area occupied by these anomalies is reduced.

4. INTERVAL VALUES OF HEAT FLOW DENSITY

As an example, we will show heat flow values, which can be obtained using thermograms of wells from the zone of active water exchange within the considered region of the Orsha Depression and eastern slope of the Belarusian Anteclise. Quaternary loose rocks (sand, sandy loam, thin loam interlayers, etc.) with an abundance of hydrogeological windows lie in the substrate of Devonian sediments, they are as a rule cavernous dolomites. Descending groundwater caused by prolonged autumn rains and thawing of snow in spring, cools the upper part of the section and leads to a deeper occurrence of the “neutral layer”, low values of the geothermal gradient and consequently low heat flow density, figure 5, Zui (2018).

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
Sudilovichi 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: The dependence of the density of heat flow in the zone of active water exchange from the depth of the “neutral layer”.

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 shape. Let us pay the attention to the extensive low-temperature anomaly within the Orsha Depression, which is highlighted mainly based on the results of temperature recording in shallow wells. Their careful analysis is required before use them to determine the heat flow.

The surface distribution of the 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 №№ 1 4, 5–7 (see. fig. 2). However, their interval values in the zone of active water exchange remain low (less than 20 mW/m^2) and for deeper intervals in wells, such as Smolensk-1, Orsha-2op, Surazhskaya-1s2, the heat flow is higher.

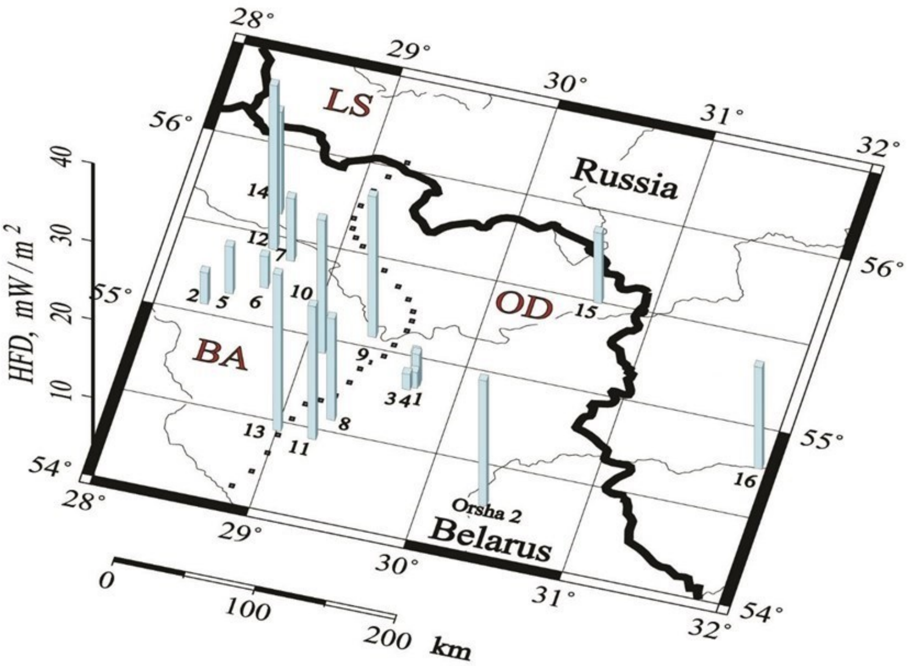

Figure 6: Distribution of the wells studied in the heat flow in the region

Legend: BA – Belarusian Anteclise; LS – Latvian Saddle; OD – Orsha Depression. Numbers at vertical bars correspond to numbers of boreholes, given in the figure 2. Small squares show the border between the Belarusian Anteclise and the Orsha Depression.

The depth pattern of the fresh groundwater base in the considered region varies approximately from 150 till 300 m, the lowest values were found in the northern, eastern and southern parts of the map, figure 7. Only in the western part of Belarus, outside frames of this map it exceeds 400 m. The solid isohypses on the diagram indicate the zones of confident observations, and the dashed lines indicate the estimated depth of its occurrence.

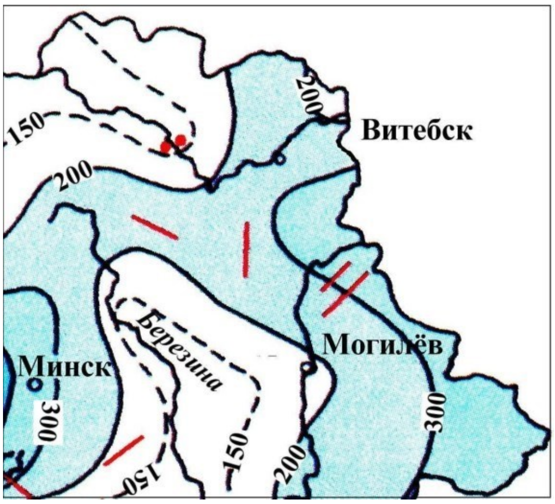

Figure 7: Fragment of the depth map of the freshwater base (m) in the north-eastern part of Belarus, Kudelsky et al. (2000). Legend: The main rivers are Zapadnaya Dvina, Berezina and Dnieper and main towns are: Minsk, Mogilev and Vitebsk. Red dots show water springs with mineralization slightly above 1 g/dm^3 within the Zapadnaya Dvina valley; red lines represent known faults penetrating into the platform cover.

At shallow depths of the considered region, the sedimentary cover includes a number of aquifers; schematically it is shown in figure 8, separated by low-permeable sediments with numerous hydrogeological windows. From this point of view, in the first approximation, the depth interval of 100–200 m can be considered as a single groundwater and geothermal horizon.

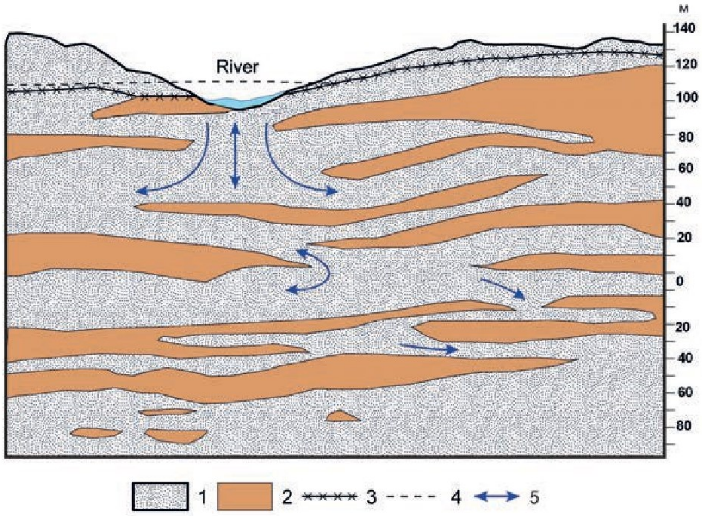

Figure 8: Structure of the upper part of the geological section in the zone of fresh water distribution with hydrogeological windows.

Legend: 1 – aquiferous sediments, 2 – relative aquitards, 3 – position of the groundwater table, 4 – position of the groundwater table during periods of high water. 5 – directions of groundwater circulation.

At many thermograms of the Orsha Depression cooled sediments are observed due to infiltrating waters within the upper part of the sedimentary cover. The concave shapes of thermograms indicate the downward water filtration (see figure 2) up to the depth of 500 – 600 m. Similar situation takes place concerning interval values of heat flow, which is clearly observed for the deep borehole Smolensk-1, figure 9. Obviously, this leads to a decrease in the geothermal gradient in the upper part of the platform cover and in a number of considered shallow wells to its very low values (3–5 mK/m).

5. DISCUSSION

Let us consider in more details the thermogram of the Smolensk-1 deep borehole, Orsha Depression, Russia, which was mentioned in figure 5. It 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.

Figure 9 shows both the stationary well thermogram and the results of calculating the heat flow density (mW/m^2) for eight depth intervals (from 100 to 900 m), where core samples were available and the heat conductivity of rocks was measured. Vertical variability of interval values of heat flow density here can be traced down to the depth of about 800 m. Vertical lines in the diagram indicate the depth intervals studied, the numbers near them denote interval heat flow density values (mW/m^2) for each of the studied intervals.

In the upper part of the section to the depth of about 400 m, there is a low heat flow of 10–14–15 mW/m^2, which practically corresponds to its observed values in the shallow wells of the Belarusian part of the Orsha Depression, discussed above (see figures 5 and 6). It is clearly follows from the figure 9, that the vertical variability of the interval values of the heat flow as a whole is observed up to a depth of about 800 m. Only starting from a depth of more than 600 m the interval values start stabilizing (30, 32 and 33 mW/m^2). The last of them is included into the heat flow catalogues as the value of heat flow for the borehole Smolensk-1, undisturbed by surface factors. The HFD – depth curve at the figure 9 shows monotonic increase of heat flow with the depth. Now suppose, we have only shallow part of the thermogram for the Smolensk-1 borehole, for example 200 – 250 m, at which interval heat flow of 14–15 mW/m^2 only, then it becomes comparable with those for other shallow wells, shown in figure 6.

The interval values of the heat flow density vary from 10 mW/m^2 in the upper part of the geologic section to 33 mW/m^2 at the 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. The 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 shallow boreholes within this area, for instance those shown in figures 5 and 6. These data require further investigations for applying corrections for ground water circulation within the zone of active water exchange.

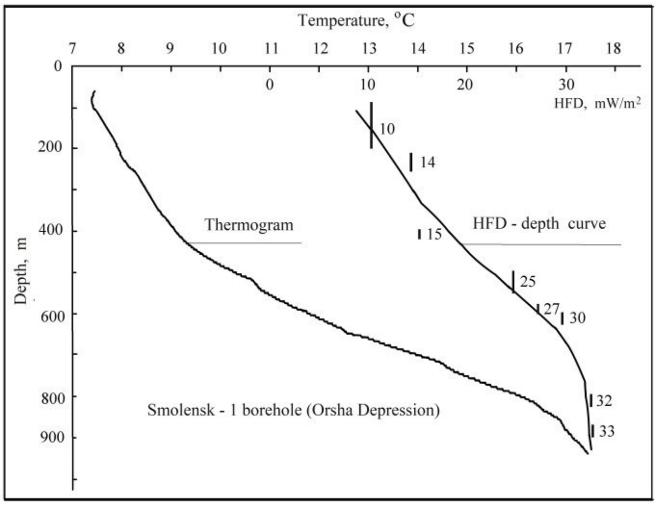

Figure 9: Thermogram of the Smolensk-1 well and the change in the interval values of the heat flux density (mW/m^2) over the depth of the well.

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 are typically low values of both temperature and interval values of heat flow density (4–20 mW/m^2) and only occasionally 25–30 mW/m^2. In this case, a number of geothermal anomalies are distinguished, which are not caused by the deep structure of the platform cover and the crystalline basement, but by the circulation of groundwater. The latter circumstance requires careful selection of the obtained data when they are used on the heat flow map.

An ability of hydrogeological windows within upper part of the platform cover within the considered region with thin aquitards or their absence in a number of local zones results in groundwater penetration from the surface into relatively deep horizons, which in turn cools the upper part of sediments. Hence, low heat flow values are observed there until the depth of several hundred meters.

The groundwater circulation has the greatest influence in the zone of active water exchange (fresh water layers). Here, predominantly loose sediments, composing the upper part of the platform cover, are good washed with meteoric waters. To account for the convective component of heat transfer, it is necessary to know the filtration rate in each particular depth interval. However, such data in the studied region were absent, and this component was not quantified. These very low HFD values require further investigations for applying corrections for ground water circulation within the zone of active water exchange in the considered region.

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