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Underground temperature background of Saksagan iron-ore region in Kryvyi Rih basin

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Для аналізу та розрахунків параметрів температурного фону використано банк даних, що охоплював дані 46 глибоких, детально відібраних розвідувальних свердловин, пробурених уздовж Саксаганської залізорудної смуги Кривбасу, а також дані щодо її поперечного розрізу, зокрема Криворізької надглибокої свердловини НГ-8. Наведено методичні прийоми осереднення рядових спостережень для визначення узагальнених значень температури та інших параметрів температурного фону. Показано розподіл температури вздовж простягання згаданої смуги з південного заходу на північний схід в інтервалі глибин 0—2000 м. Територію поширення Саксаганської залізорудної смуги від широти шахти "Родіна" на півдні, було розбито на 7 ділянок, приблизно однакових за площею, в кожній з яких пробурено не менше 4 свердловин. Дані щодо кожної з ділянок усереднено за площею і глибиною. Глибинний інтервал осереднення — 500 м. Аномальне поле смуги описано як чергування негативних і позитивних теплових полів, що ускладнені у північному напрямку локальними аномаліями. Схарактеризовано геотермальний градієнт за осередненими даними 46 глибоких свердловин. Зроблено висновок щодо високої варіативності його значень. Отримані результати важливі для визначення особливостей загальної структури Кривбасу, особливо його західного борту й тектоніки центральної частини, а також для гідрогеологічної та гірничої служб стосовно подальшого заглиблення шахт. Температурні дані потрібно використовувати для виявлення ділянок і зон неотектонічної та сейсмічної активізації.

Ключеві слова: підземний температурний фон, геотермальний градієнт, Саксаганська залізорудна смуга.

Kryvyi Rih iron-ore basin is located within the Ukrainian Shield (US). Thermal background investigations of the US were carried out in sufficient details by many researchers [Kutas, Gordienko, 1971; Gordienko, 2000, 2005; Gordienko et al., 2002]. It was discovered that the Precambrian US has a basically low thermal background compared to its geologically younger framing. This is fully consistent with the studies conducted in other similar regions [Mechnikov, Volkov, 2018]. At the same time, areas with intense and diverse thermal anomalies were noticed in the background of common stable low values in some areas, especially in those adjacent to the big deep faults and the edges of the shield [Gordienko, 2000, 2005]. In terms of this fact, Kryvyi Rih-Kremenchuk deep fault, in the zone of which Kryvyi Rih iron-ore deposit is located (Kryvyi Rig iron-ore basin), is of particular interest.

Temperature studies in Kryvyi Rih basin, which conducted together with the extraction of iron-ores, began in the late 40's of the twentieth century. By the time of the final analysis of thermometric data in 1985—1990, almost all area covered by detailed geological surveys was also studied in terms of the subsoil temperature observations. The analysis of the temperature background of the deep layers of Kryvyi Rih iron-ore deposit was carried out by the South-Ukrainian expedition of the super-deep drilling when correlating super-deep drilling data to the results of studies of the Kryvbas framework [Sheremet, 2011; Mechnikov, Volkov, 2013].

Subsequently, the data were analyzed by the authors in order to determine the correct averaged values of the underground thermal field, which would characterize the most distinctive features. To solve this task, 46 deep boreholes, located along the strike of the Saksagan iron-ore strip, were selected. They characterize the behavior of the temperature background along the strip. In addition, the temperature background was analyzed across the strike of the Kryvyi Rih structure in the northern part, on the traverse of the super-deep borehole SD-8 and complementary boreholes.

The data of 46 deep boreholes were combined and averaged within individual sections to determine the most likely temperature indexes (Fig. 1). The averaging procedure included determining the arithmetic mean value for all boreholes located within the site at identical abyssal elevations. 7 sites were identified. They are evenly located from the latitude of the "Rodina" Mine in the south, to the latitude of the Mine named after V.I. Lenin in the north. Each site has a different number of boreholes. This is due to the fact that complex logging, which included thermal observations, was carried out to solve specific geological tasks being different for each site. Four deep boreholes were the smallest amount of those on a site. In other areas, the number of boreholes varied from 5 till 10.

The need to determine the most likely averaged values of temperature measurements is due to several reasons. The first one is that recommended or calculated terms of boreholes calm standing have not always been respected during the industrial cycle of exploration, as well as in terms of the technical capabilities for saving the stability of the boreholes walls, from the moment of active drilling and run time to the moment of temperature measuring. It means that timescales of these terms were not always similar. The terms of calm standing of a borehole al-

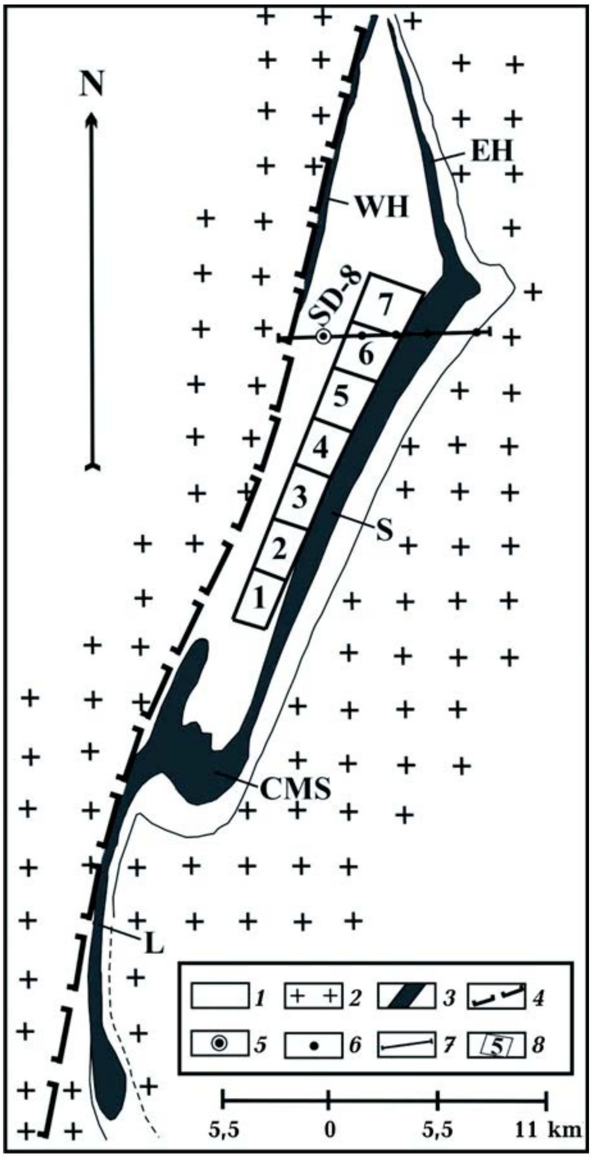

Fig. 1. Diagram of investigated areas within the Kryvyi Rih basin: *1* — rocks forming the Kryvyi Rih metamorphic series of the Paleoproterosoic; *2* — granitoid complexes of the Archaean; *3* — iron-ore strips within the Kryvyi Rih basin (L — Likhmanivka, CMS — closure of the main synclinal, S — Saksagan, EH — East-Hannivka, WH — West-Hannivka); *4* — the zone of the Western fault, which limits the Kryvyi Rih structure from the west; *5* — Kryvyi Rih super-deep borehole SD-8; *6* — deep boreholes; *7* — latitudinal (cross-sectional to the Kryvyi Rih structure) geological profile; *8* — location of the studied areas within the Saksagan strip.

so changed depending on the drilling depths achieved, diameter and depth of the casing. The second important reason for the discrepancy of indexes in closely located boreholes at the same depths is the instability of the hydrogeological regime. On the one hand, this is due to the existence of large fault tectonic zones, some of which represent the ways of transporting fluids of different temperatures. On the other hand, it is due to the existence of a large network of water pumping from existing mines and open-pits. These factors led to the excluding of a large number of boreholes located within the limits of depressive hydrogeological reservoirs or close to them from the analysis.

A rather significant factor that causes instability of the temperature at similar depths and which is impossible to be neutralized is the high variability of thermal properties of the rocks of the Kryvyi Rih series. Under the conditions of the steep dip of the metamorphogenic volcanic-sedimentary strata of diverse composition, the probability of occurring of different thermal parameters rocks at the same depth is very probable.

Averaging of specific data for certain depths was also carried out. This also had to be done due to the high variation of temperature parameters with the depth. Their growth is different in individual boreholes with the increase of depth. The data, that were averaged over several boreholes in each cell, were also averaged within 500 m intervals to reduce the influence of local factors.

The temperature distribution along the strike of the Saksagan iron ore strip. The presented data were calculated after average data from several boreholes, as well as average data within 500-meter intervals to the depth of 2000 m. The analysis shows the temperature to increase gradually with depth, but in a different way, in each of the studied areas the parameter pattern changes individually.

In the Fig. 2 schematic longitudinal projection of the temperature background distribution is shown from the south-east to the north-west along the Saksagan iron-ore strip (depth interval 0—2000 m). The isotherms of the averaged temperature indexes are shown as well.

The behavior of isotherms clearly shows an uneven growth of the thermal field to the depth of 2000 m. This process is manifested the most clearly in the upper horizons (interval 0—1000 m). The isotherms have a wavelike shape with well-defined ups and downs. Also, the isotherm +30 °C has a fluctuating shape, which characterizes significant temperature changes in the deepest range of 1500—2000 m.

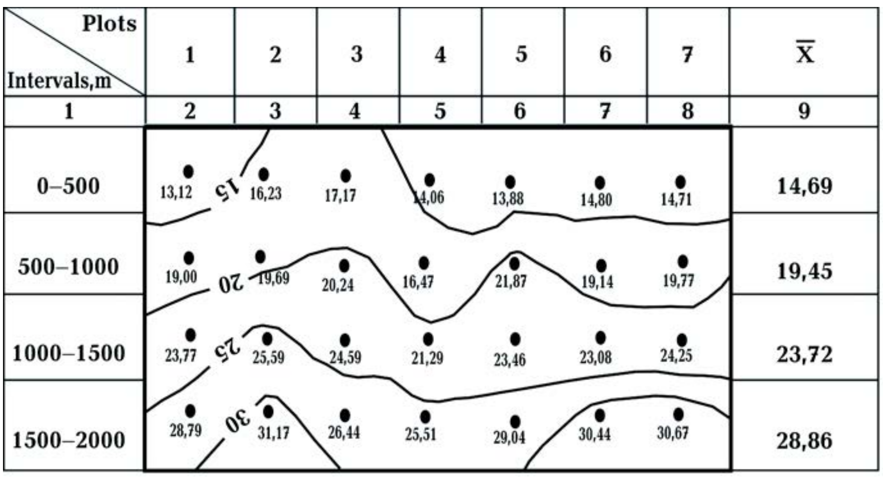

Fig. 2. Schematic vertical projection of the temperature background (°C) (stretching from south-west to north-east) along the Saksagan iron-ore strip (the range of depths 0—2000 m).

Such configuration of the temperature field is typical to the depth of 1000 m (in the south) and up to 1500 m in the north. At lower depths, the local maxima slightly displace: from the first (southern) site, they migrate to the south, from the seventh (northern) site they migrate in the northern direction. This behavior of the temperature field can indicate the possible presence of two outflows of thermal energy sources from the subsoil that are located at some depth to the south of the first site and to the north of the seventh (northern) site.

To determine the most complete characterization of the local thermal field anomalies influence on the general nature of its regional growth, the calculation of average values of temperatures for each 500-meter interval was conducted with the subsequent estimation of the difference between the calculated mean of the parameter in the depth intervals and the preliminary calculated values of the parameter in each cell. The results of the calculations are shown in the Fig. 3. A schematic longitudinal vertical projection of anomalous temperature values along the Saksagan iron-ore strip in the depth range 0—2000 m is shown there.

The figure is presented in the form of anomalous isotherms that have positive and negative values as the deviation of the temperature from the average values to the higher (+) or lower (–) side. The term "anomalous" is used here for temperature values that are different from the average interval temperature value calculated for each 500-meter horizontal interval in all seven sites.

The general layout of distribution of anomalous temperature values shows its heterogenity. Both the regional changes along the strike of the Saksagan strip and the peculiar local features are observed here.

Regional features of the distribution of anomalous temperature values include the interchange of negative vertical accumulations by positive ones along the Saksagan strip. Both negative and positive anomalies occupy the entire depth of research from 0 to 2000 m. The most clearly the mentioned fact is observed in the southern and central parts of the described area.

Local anomalies are located within the boundaries of the regional fields and have the same sign. Within the first site in the extreme southern negative anomaly, there is an anomalous minimum of the field (–1.57 °C) within the range of depths 0—500 m. In the next positive anomalous field, which replaces the previous one in the north direction, there are two local anomalies. One of them, the upper anomaly, is also located in the third site within the range of 0—500 m. Its inten-

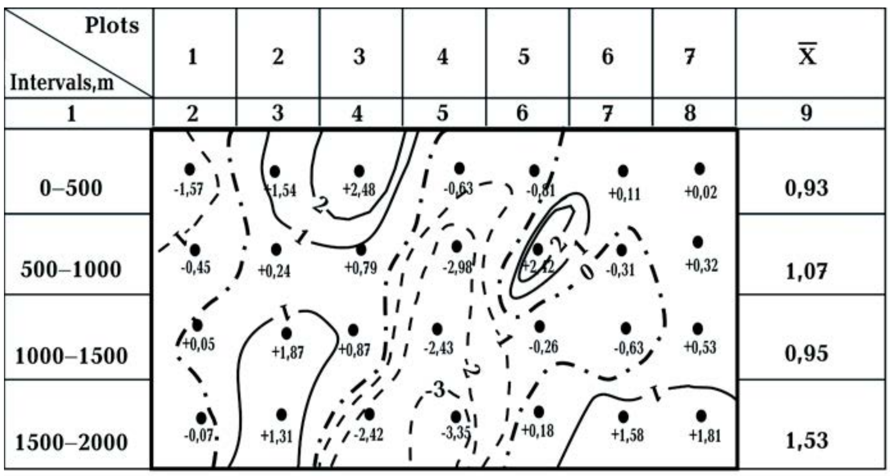

Fig. 3. Schematic longitudinal vertical projection of averaged anomalies of the temperature background (°C) (south-west—north-east) along the Saksagan iron-ore strip (the range of depths 0—2000 m).

sity reaches the value of +2.48 °C. The second one is located within the second site and covers intervals from 1000 m to 2000 m. Its maximum value is +1.87 °C.

A clearly outlined field of negative anomalous values occupies the central part. On the surface it occupies the sites 4 and 5. Getting down to the bottom it covers the sites 3 and 4 (it tends to incline toward the south). One clearly outlined and rather intense anomaly is noticed here, it's the central part is located within the site 4. Its intensity is –3.35 °C.

A positive field of anomalous values is located in the northern part of the area; it includes two local positive anomalies. One of them, having the intensity of +2.42 °C, is located within site 5 and within the range of depths 500—1000 m, the second one, the intensity of which varies from +1.58 °C to +1.81 °C, is recorded within the range of depths of 1500—2000 m.

The spatial location of anomalous thermal field within the Saksagan iron-ore strip shows that there are some reasons for its changes in the regional plan, which lead to the general wave-like nature, where negative values occurred along the strip are replaced by positive ones, which, in turn, change to negative values.

Local thermal anomalies occur within similar regional fields. Centers of local anomalies are noticed both in the upper intervals, within 0—1000 m, and in the lower intervals of 1000—2000 m.

The field of anomalous negative values in the central part of the Saksagan strip (section 3—5) is seen the most clearly, it tends to increase the intensity of negative values from –0.63 °C within the range of 0—500 m to –3.35 °C within the range of 1500—2000 m. This field also tends to have a steep southern inclination.

Distribution of temperature in transverse section of the Saksagan iron-ore strip. It is possible to estimate the temperature distribution in the transverse latitudinal section of the Kryvyi Rih structure within the latitudinal depth section going through the Kryvyi Rih super-deep borehole SD-8. Unfortunately, the temperature background analysis can only be done within this profile after individual boreholes data, and not after those of a group of boreholes, as it was fulfilled for the estimation along the iron-ore strip. The section includes the following boreholes from west to east: the super-deep SD-8 and the complementary deep borehole-2 (borehole 22 350) to the super-deep SD-8, and two other deep boreholes (boreholes 19 929 and 17 752).

The average temperature is calculated as the average value of temperature within the range of 500 m. The resulting value is considered to be the middle of the interval. According to these data, a section was compiled in isotherms (Fig. 4), as well as a section of anomalous temperature values calculated according to the previous procedure (Fig. 5). The figures give a general idea of the distribution of actual temperature and additional anomalous heat sources in the transverse section of Kryvyi Rih structure.

The first of them (see Fig. 4) clearly shows a decrease in the temperature in the middle of the section (borehole 19 929). It is the borehole 19 929 that is located within the Hdantsivka suite, in the area close to the contact with the Saksagan iron-ore suite in the Saksagan thrust zone, which is one of the series of tectonic fault layers. It turned up that boreholes SD-8 and 22 350 in their upper parts, namely to a depth of 1000 m, also encounter the rocks of the Gleyuvatka and the Hdantsevka suites. It means that thermal properties of crystalline rocks have a very small influence on the nature of temperature changes.

The structural position, the location closer to the central part of the syncline and the fault zone, outlined by the negative anomalous field, obviously reveals the greatest influence.

Fig. 5 shows more precisely the distribution of positive and negative additions to regional temperature changes.

It should be noted again that the configuration and the intensity of the thermal anomalies presented in the schematic figures make it possible to estimate only the general features of the thermal field. For further definition and rectification, thermal studies

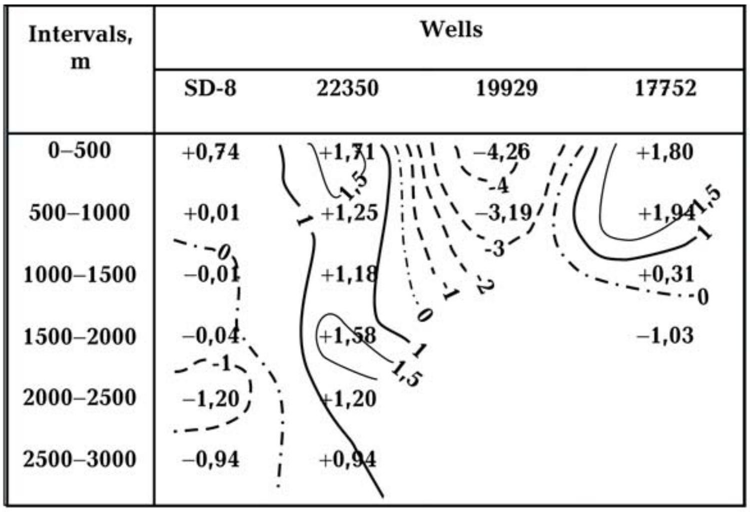

Fig. 4. Schematic section across the strike of the Kryvyi Rih structure in isotherms.

should be continued, they will provide new geophysical information on underground conditions, which makes the biggest interest for many scientific researchers and for mining operations.

Geothermal gradient. In order to determine the geothermal gradient (GTG), we analyzed temperature change data with increase in depth for all 46 boreholes studied. As was noted above, the data of the initial me-

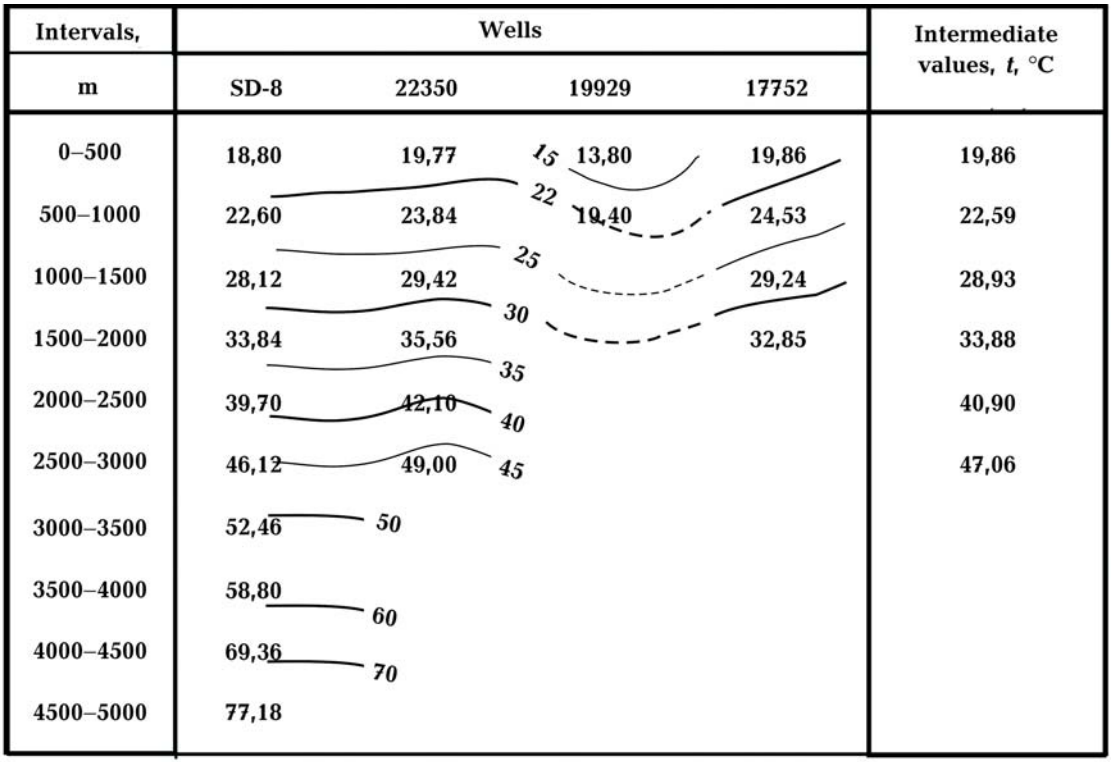

Fig. 5. Schematic section across the strike of the Kryvyi Rih structure in isotherms of anomalous thermal field.

asurements of temperatures vary considerably at similar depths [Mechnikov, 2016]. In order to determine a constant for the region, the method of averaged data within horizontal intervals was used. 100 m was considered to be the main interval; it was averaged over depth intervals of 500 m. Determining local geothermal gradients in dependence on the geological structure will be considered to be the purpose of further research.

The behavior of the averaged geothermal gradient, determined along the Saksagan iron-ore strip, is shown in Fig. 6.

The curve of geothermal gradient °C/100 m, shown in Fig. 6 can be divided into two identical parts.

The first, the upper part, which is located within the range of 0—1000 m, has a relatively small deviation from the average value of the GTG, determined for the full range of depths 0—2000 m (its value is 1.056 °C/100 m). The values of the GTG here are from 0.79 to 1.15 °C/100 m, the deviation from the above mentioned average does not exceed –0.27 and +0.09 °C/100 m. The upper part of the curve, in turn, can also be divided into two parts — the first one, from 0 m to the depths of 500 m, is fluctuating, where the major deviations of the values of the GTG are seen, and the second one, within the range of depths 500—1000 m, where the gradient values are very close to each other (0.85—1.01 °C/100 m).

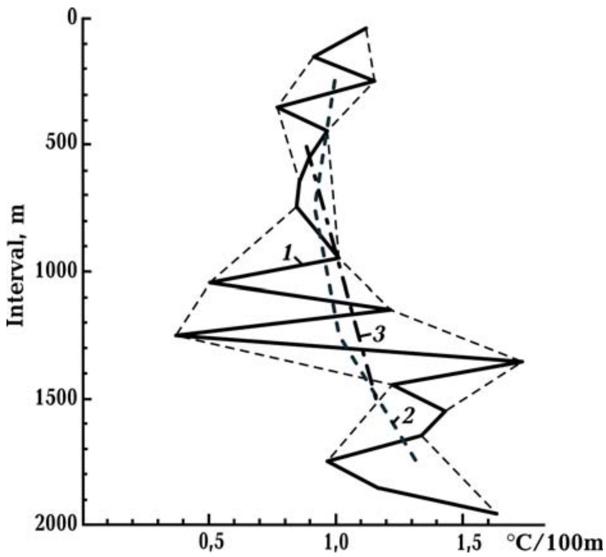

Fig. 6. Geothermal gradient of 46 deep exploratory boreholes drilled along the Saksagan iron-ore strip in the depth range 0—2000 m: *1* — line of geotermal gradient °C/100 m; *2* — line of geotermal gradient °C/100 m, averaged over an interval 500 m; *3* — line of geotermal gradient °C/100 m, averaged over an interval 1000 m.

The second lower part of the GTG curve (depth intervals of 1000—2000 m), is characterized by a large scatter of the GTG values. The biggest differences are noted within the interval 1200—1400 m. The values of the GTG here vary from 0.38 to 1.72 °C/100 m, the deviation from the average value (1.056 °C/100 m) is –0.68 and +0.62 °C/100 m. Lower, starting at a depth of 1400 m, we see the values of GTG to exceed the indicated average value for the interval of 200 m, except of one of them, which is equal 0.96 °C/100 m within the range of depths 1700—1800 m.

The averaged data of 500 and 1000 m intervals shows the main tendencies of the GTG behavior, which is about 1 °C/100 m in the upper part, and in the lower one it gradually increases up to 1.31 °C/100 m.

The highly variable nature of the GTG values are indicative of quite active geological processes, especially in the lower part of the studied depth interval.

Discution and conclusion. The results of thermal background studies within the Kryvyi Rih iron-ore basin both along the Saksagan iron-ore strip, which is the richest in ore deposits, and on a transverse profile, which included the Kryvyi Rih super-deep borehole (SD-8), have first shown the underground thermal field within the basin to be rather deformed. Within the range of depths 0—2000 m, both regional changes along the Saksagan iron-ore strip and a number of local anomalous manifestations of positive and negative character were identified.

There is also a deformation of the thermal field across Kryvyi Rih structure. It is noted that in the central part (borehole 19 925) there is an intensive negative local anomaly, which is not related to the change in the thermal properties of rocks, because the adjacent borehole (22 350) encountered similar rocks, but has a completely different thermal background. The presence of this anomaly may be explained by the existence of a large fault tectonic zone here with predominant movements of the surface cooled waters down. The showing of a negative anomaly that is seen at the depth from the western side is an important feature of this schematic section (see Fig. 5). Spatially it coincides with a massif of the Archean granitoids.

This granitoid massif caused the arched vertical bending of the western side of the Kryvyi Rih structure, acting as a cold apron [Sheremet, 2011]. The thick ancient metamorphic weathering crust on the Archaean granitoids, that is crossed twice by Kryvyi Rih SD-8, evidences the fact that this was a very cold contact.

It is difficult to overestimate the knowledge gained about the intensity and variability of regional and local components of the underground thermal field for solving a number of geological, geophysical and mining tasks.

The quality of iron-ore raw materials, which is very dependent on the ratio of unoxidized and oxidized iron-ore minerals, is a significant problem in Kryvyi Rih basin. Current oxidation processes are closely related to the oxidative-reducing potential of groundwater, the value of which, in turn, depends on the temperature. Thus, the temperature factor should be taken into account when conducting geological and geophysical studies of the current oxidative processes development.

The determining of the underground temperature background values along the Saksagan iron-ore strip is also of a great practical importance for mining specialists and mine developers. Data about the actual temperature values and their changes with the growth of the depths are very important, as operations are already being conducted at depths below 1500 m. In the long run, the depths of the mining operations will increase.

Previous studies discovered quite active neotectonic movements within the Kryvbas and its frames [Mechnikov, 2009; Mechnikov, Volkov, 2013]. There exists a widely developed scientific point of view stating the fact that areas of increased neotectonic activity are closely associated with regions of a differential thermal background [Morgan, 1978]. A detailed coverage of neotectonic movements is topical for the Kryvbas, since they lead to local earthquakes of little intensity so far, together with active deep mining developments using blasting. Data of temperature studies can help in solving this problem when identifying the most activated sites and zones.

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The data from thoroughly selected 46 deep exploration boreholes drilled along the Saksagan iron-ore stripe located in the Kryvbas and a transverse section of the stripe, which included results of studies conducted in the Kryvyi Rih super-deep borehole SD-8, have served as the data bank for analyzing and calculating the temperature background parameters. The methodical procedures for ordinary measurements averaging, determining and generalizing temperature values and other thermal background parameters were given. The distribution of temperature along the strike of the Saksagan iron-ore stripe from the south-west to the north-east within the depth range from 0 m to 2000 m was shown. The whole territory of the Saksagan iron-ore stripe from the Rodina Mine in the south was divided into 7 sites, approximately equal in area, each of sites contained at least 4 boreholes. The area-averaged and the depth-averaged data were calculated for each of the sites. The averaging depth range was 500 m. The pattern of the anomalous isotherms has shown the anomalous field to be very diverse, and can be defined as the alternation of negative and positive thermal fields, complicated by local anomalies in the northern direction. The characteristic of the geothermal gradient after the averaged data of 46 deep boreholes drilled along Saksagan iron-ore stripe was given. The given data allow us to state about high variations of GTG values. The obtained results will be greatly appreciated in interpreting the features of the overall structure of the Kryvbas, especially its western side and the central part tectonics, by hydrogeological and mining services in view of further deepening of the mines. The temperature data will help in determining areas and zones of neotectonic and seismic activation.

Key words: underground temperature background, geothermal gradient, Saksagan iron-ore stripe.

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