

Thermal conditions for geothermal energy exploitation in the Transcarpathian depression and surrounding units

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Abstract: The contribution presents the results acquired both by direct cognitive geothermic methods and by modelling approaches of the lithosphere thermal state in the region of the Transcarpathian depression and surrounding units. The activities were aimed at the determination of the temperature field distribution and heat flow density distribution in the upper parts of the Earth's crust within the studied area. Primary new terrestrial heat flow density map was constructed from values determined for boreholes, from their interpretations and from newest outcomes of geothermal modelling methods based on steady-state and transient approaches, and also from other recently gained geophysical and geological knowledge. Thereafter we constructed the maps of temperature field distribution for selected depth levels of up to 5000 m below the surface. For the construction we have used measured borehole temperature data, the interpolation and extrapolation methods, and the modelling results of the refraction effects and of the influences of source type anomalies. New maps and other geothermic data served for the determination of depths with rock temperatures suitable for energy utilization namely production of electric energy minimally by the binary cycles. Consequently the thermal conditions were used to identify the most perspective areas for geothermal energy exploitation in the region under study.

Key words: Outer Carpathians, Transcarpathian depression, Pannonian basin, geothermal energy, temperature field model, terrestrial heat flow density

1. Introduction

The studied area is situated in the north-eastern part of the Carpathian-Pannonian region. The central part of the area is formed by the Transcarpathian depression unit which represents the most promising region for

exploitation of geothermal energy in both Slovakia and Ukraine. This unit is the thermally most active area in both mentioned countries (Kráľ et al., 1985; Franko et al., 1986; Franko et al., 1995; Gordienko et al., 2004; Kutas. 2014). The separate sub-areas of the Transcarpathian depression (East Slovakian Basin, Mukachevo Basin and Solotvino Basin) also belong to the most explored regions concerning the density of geothermal measurements as well as structural knowledge because of massive gas/oil prospecting. The study area marked in Fig. 1 also contains the high thermally active units of the Pannonian Basin located southwest of the Transcarpathian depression (Dövényi et al., 1983; Lenkey et al., 2002). From geothermal measurements and from newest outcomes of geophysical methods we can conclude that some inner parts of the Outer Carpathian Flysch also have sufficiently interesting thermal conditions (heat flow density, temperature distributions with depth) for utilization of the geothermal energy (Franko et al., 1986;

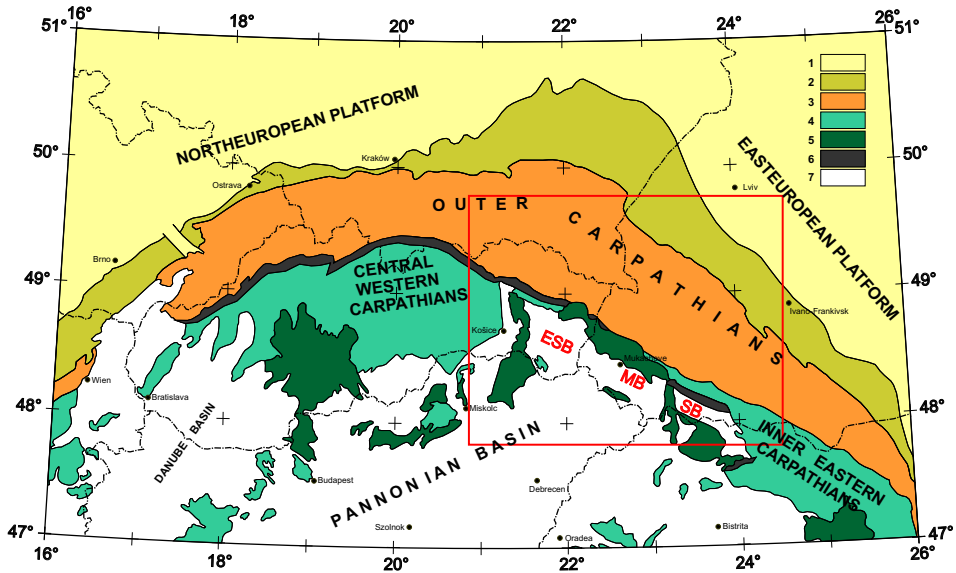


Fig. 1. Position of the studied area in the north-eastern part of the Carpathian-Pannonian region. Basic tectonic map was modified after Kováč, (2000). Structure description: 1 – European platform, 2 – Foredeep units, 3 – Alpine – Outer Carpathian Flysch Belt, 4 – Inner Alpine-Carpathian units, 5 – Neogene volcanites on the surface, 6 – Pieniny Klippen Belt, 7 – Neogene and Quaternary sediments. Transcarpathian depression subunits: ESB – East Slovakian Basin, MB – Mukachevo Basin, SB – Solotvino Basin.

Franko et al., 1995; Majcin et al., 2014). The thermal activity of the Outer Carpathian units rapidly decreases in the direction toward the European Platform (*Gordienko and Zavgorodnyaya, 1996; Gordienko et al., 2004; Kutas, 2014*). The Carpathian geological units characterized by relatively low thermal activity extend to the studied area both from the west (Central and Inner Western Carpathian units) and from the east (Inner Eastern Carpathian units) (*Franko et al., 1995; Kutas, 2014*).

Our contribution aims to determine the thermal conditions for the geothermal energy utilization for the electric energy production within the region of study. That means that it is necessary to estimate depths where rock temperatures suitable for production of the electric energy minimally by the binary cycle technology. Theoretically, the reservoir temperatures of about 130 °C are sufficient for this purpose. However, for the reasonable economic exploitation of the geothermal energy it is necessary to consider the subsurface temperatures at the level of 160 °C. The perspective areas are separated by the criteria of the technical accessibility of the deep geothermal energy sources.

This contribution arises from the knowledge provided in *Franko et al., (1986)* and in *Franko et al. (1995)*. It enhances the results both by enlargement of the studied area to the whole Transcarpathian depression and surrounding units and by application of the newest data obtained mainly from geothermal modelling approaches.

2. Methods and results

The main methodological framework of our contribution is based on three coupled and sequential activities:

1. The determination of the terrestrial heat flow density distribution based on both measured data and supplementary data from modelling results.
2. The construction of the temperature distribution maps that portray the thermal state of the upper crust parts belonging to the Transcarpathian depression together with surrounding geological units.
3. The analysis of the thermal conditions for the exploitation of the geothermal energy for the electric energy production.

Primarily the distributions of both temperatures and heat flow density were here determined by direct recognition methods with application of 1D analytical solutions of heat transfer equation in interpolations, extrapolations, and comparative analyses of data (*Franko et al., 1995; Buntebarth, 1984; Kutas et al., 1989*). The basic interpretation of the geothermic data were also complemented by the results of the geothermal modelling approaches. The numerical calculations of the temperature fields for tectonothermal interpretations were carried out for both the steady state and transient regime of the heat transfer equation. Derived math-physical tasks in bounded 2D/3D areas were solved by means of finite difference methods (*Majcin, 1982*) and/or by finite element approaches (using the COMSOL Multiphysics® modelling software with the Heat Transfer Module). For both the interpretation of measured data in boreholes and geothermic models of local structures, we used in preference the existing thermal conductivity parameters and heat productions determined from core samples. Otherwise we utilized the mean values for the lithological (eventually also stratigraphic) aggregates of rock complexes (*Vaňková et al., 1979; Král et al., 1985; Jančí and Král, 1986; Husák, 1986; Jančí and Král, 1990; Jančí, 1992; Majcin, 1993; Kutas and Gordienko, 1971; Kutas et al., 1989; Grytsik et al., 2007; Kutas, 2014*).

Moreover, we have utilized both the qualitative and quantitative analyses as well as methodical conclusions from refraction effects study carried out on the contrast conductivity structures together with consideration of the earth's surface topography (*Majcin, 1992; Majcin and Polák, 1995; Hvoždara, 2008; Jaupart and Mareschal, 2011; Majcin et al., 2012; Hvoždara and Majcin, 2013* and others).

The determined terrestrial heat flow density data, interpretations and constructed distributions for the studied area became the basic building information for our map. We used the data from international “Global heat flow database of IASPEI” and local data from countries lying in studied region. The heat flow data and borehole temperature distributions from the Slovak part were published in plenty of partial studies and summarized in publications (*Král et al., 1985; Rudinec, 1989; Král, 1991; Čermák et al., 1992* and *Franko et al., 1995*). These publications also contain the interpretations of geothermic data in the form of the terrestrial heat flow density distribution, temperature distribution maps both at various depth levels and

on cross sections within the upper parts of the upper crust. The Ukrainian heat flow density and temperature distribution data were measured and evaluated in *Kutas and Gordienko (1971)*, *Buryanov et al. (1985)*, *Gordienko et al. (2002)*, *Gordienko et al. (2004)* and recently in *Kutas (2014)*. The set of the geothermal data of the Outer Carpathians area is completed by results from its Polish part (*Plewa et al., 1992*; *Gordienko and Zavorodnyaya, 1996*; *Karwasiecka and Bruszezwska, 1997*; *Wróblewska, 2007*; *Górecki, 2013*). The Hungarian heat flow density values determined by *Dövényi et al. (1983)* and *Dövényi and Horváth (1988)* were interpreted by *Lenkey et al. (2002)* and *Kovács et al. (2011)*. The subsurface temperature distribution maps from the Hungarian region were constructed in the project “*Altener II*” (*2005*). In addition, we have also utilised some synthetic works which tried to interconnect the selected geothermal data (most of them using the terrestrial heat flow data) over wider areas containing our studied region (e.g. *Čermák and Hurtig, 1979*; *Hurtig et al., 1992*; *Lenkey et al., 2002*; *Wybraniec, 2008*).

The geothermal modelling results along the profiles crossing the studied geological units of the Western Carpathians provide very important interpretation information about both the temperature and heat flow density distributions in the lithosphere, and moreover, regarding the relationship of geothermal data with structures and tectonics. The models calculated in a steady state regime were made by *Bielik et al. (1991)*, *Majcin (1993)* and others. The results of the geophysical integrated modelling approaches applied within the studied region were presented in *Dérerová et al. (2006)*, *Bielik et al. (2010)*, *Hlavňová et al. (2015)*. Moreover the transient 2D models along the profiles crossing the Carpathian arc and main local structures (*Kutas et al., 1989*; *Majcin and Tsvyashchenko, 1994*; *Tarasov et al., 2005*; *Majcin et al., 2014* and *Kutas, 2014*) deal with the recent tectono-thermal history of the region. They were based on the most recent geological and geophysical knowledge. The construction of result maps is also based on the specialized analyses of the geothermal data in relation both to structure of the lithosphere and to tectonic events (*Kutas, 2011*; *Majcin et al., 2014*; *Kutas and Majcin, 2014*; *Kutas, 2014*).

The complete model of the thermal state of the upper parts of the lithosphere of the Transcarpathian depression as well as neighbouring geological units is represented both by the map of the terrestrial heat flow density

(THFD) distribution (Fig. 2) and by the distributions of the temperature at selected depths of 2000, 3000, 4000 and 5000 m below the surface (in Figs. 3a, 3b, 3c, and 3d). In the process the heat flow map served as one of the basic source materials for the calculation and interpretation of temperature distribution.

The determined heat flow density values for boreholes within the studied area come from interval of 35–130 mW/m². In general, the THFD declines across the structures of the Carpathian arc from values greater than 100 mW/m² in the Transcarpathian depression sub-basins to the common values of 40–50 mW/m² observed in the European platform.

The Transcarpathian depression is characterized by heat flows with density values greater than 80 mW/m². Smaller values were determined only locally. A more marked anomaly with terrestrial heat flow densities around 70 mW/m² exists only in the eastern part of the Mukachevo Basin – in the

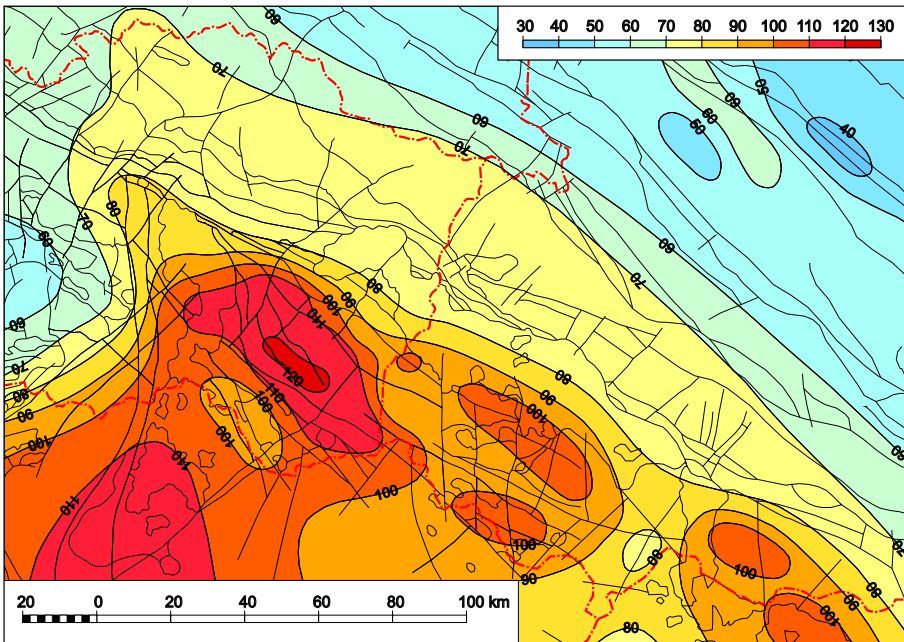


Fig. 2. Terrestrial heat flow density distribution [mW/m²] within the Transcarpathian depression and surrounding units. Basic scheme of structure boundaries and faults constructed from maps of *Lexa et al. (2000)* and of *Kruglov and Gurskij, 2007*.

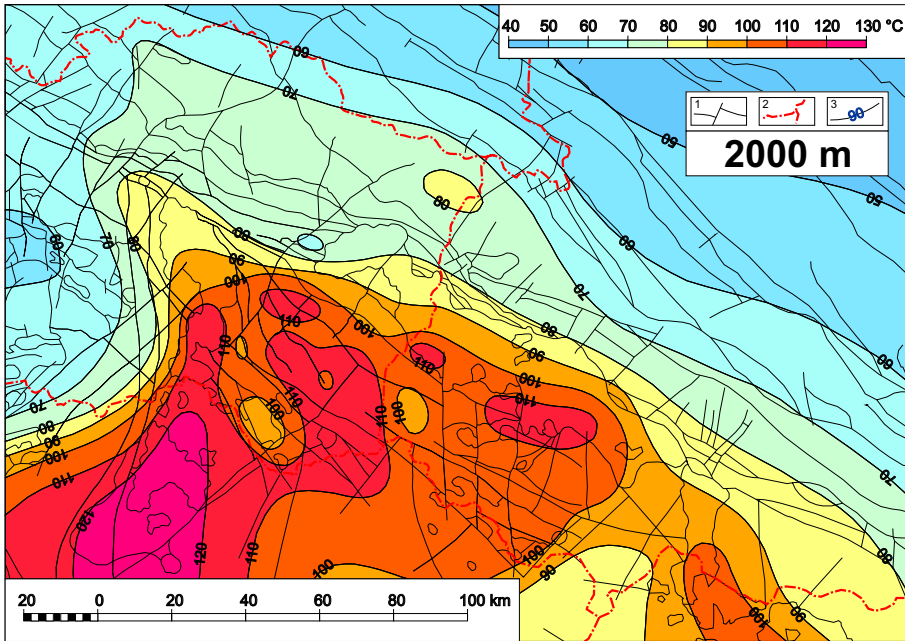


Fig. 3a. Temperature distribution map at the depth of 2000 m below the surface. Basic scheme of structure boundaries and faults constructed from maps of *Lexa et al. (2000)* and of *Kruglov and Gurskij (2007)*. Temperature isoline values in [°C].

Vinohradiv area. The thermal activity of separate sub-basins has the global tendency to decrease from the northwestern East Slovakian Basin toward the southeastern Sotvino Basin. The western most part of the Transcarpathian depression has a compact, centred, nearly rhomboid-shaped area with THFD values greater than 110 mW/m^2 . The region of increased heat flows belongs to the Trebišov Basin equivalent to the eastern part of the East Slovakian Basin. The Mukachevo and Sotvino basins contain only relatively delimited areas with the THFD greater than 100 mW/m^2 . The greatest heat flow values in the Mukachevo Basin are situated in the northern part (line Uzhhorod-Mukachevo) and along the Peri-Pannonian fault system.

Southwesterly from the Transcarpathian depression the changes of heat flow are relatively small. Usually they keep the background values typical for adjacent parts of the Transcarpathian depression that is to say 90–

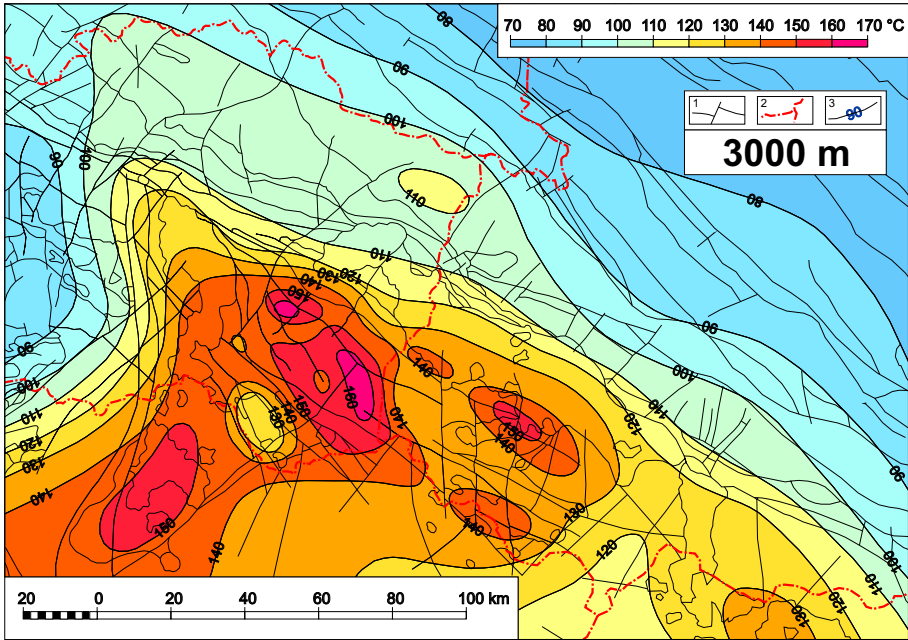


Fig. 3b. Temperature distribution map at the depth of 3000 m below the surface. Explanation in Fig. 3a.

100 mW/m². The greatest decrease of THFD occurs in the contact region between the Trebišov Basin and Slovakian Zemplínske vrchy Mts.

The second pre-selected area of our interest – the inner parts of the Outer Carpathians, is located to the north of the Transcarpathian depression. The heat flows are characterized here by values about or more than 70 mW/m². The related isoline of THFD was recently shifted to the north according the last tectono-thermal interpretations (Majcin et al., 2014 and others). On the other side, we suppose that in the Outer Carpathian Flysch area, bounded by isoline 70 mW/m², relatively small localities exist with values below the mentioned value. They should be caused mainly by refraction effects on contrasting structures and/or by hydrological phenomena. In the outer part of the Outer Carpathians the heat flows decrease to values of around 40–50 mW/m².

The terrestrial heat flow density distribution in the region under study predicts the selection results of regions suitable for the utilization of geother-

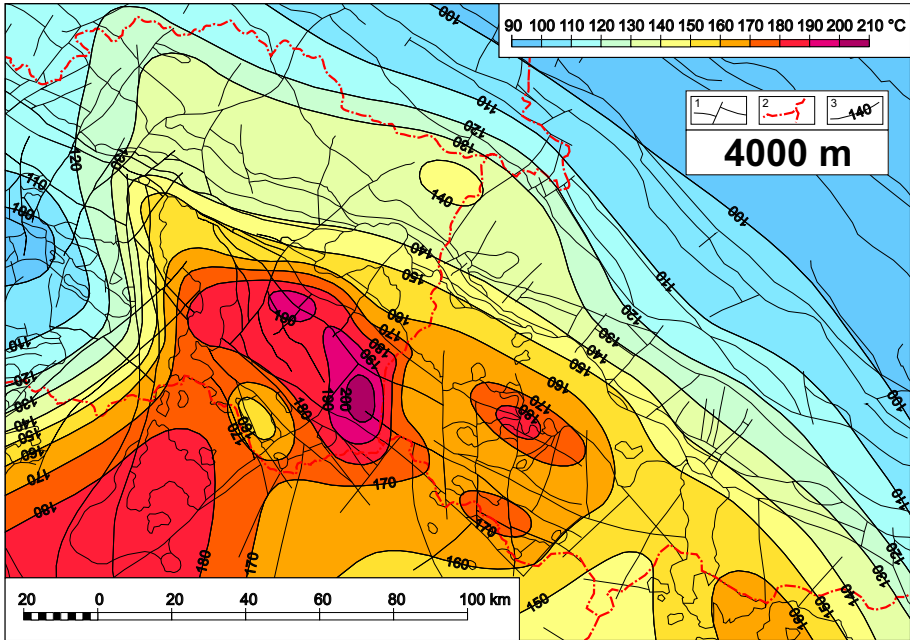


Fig. 3c. Temperature distribution map at the depth of 4000 m below the surface. Explanation in Fig. 3a.

mal energy in the electric power production because for the most active regions characterized by THFD values it is supposed the required temperatures of 160 °C (or 130 °C) are closer to the Earth’s surface. However, the lateral inhomogeneity of subsurface parts of the Earth’s crust (depths up to 6 km from surface) as well as a lot of phenomena influenced by the refraction effects and/or source type effects, make it necessary to carry out direct determination of depth temperatures by direct measurements or by modelling approaches and thereafter to construct the output distribution maps.

Even now, from maps of temperature distributions in separate depth levels under the surface (Figs. 3a, 3b, 3c, 3d) it is possible to reveal the areas with the geothermal source thermal conditions suitable for electricity production by binary cycles. The maps for the depths of 2000 m and 3000 m indicate that the temperatures over 160 °C exist between these two levels both in the eastern and northern parts of the Trebišov Basin (Ptruckša-

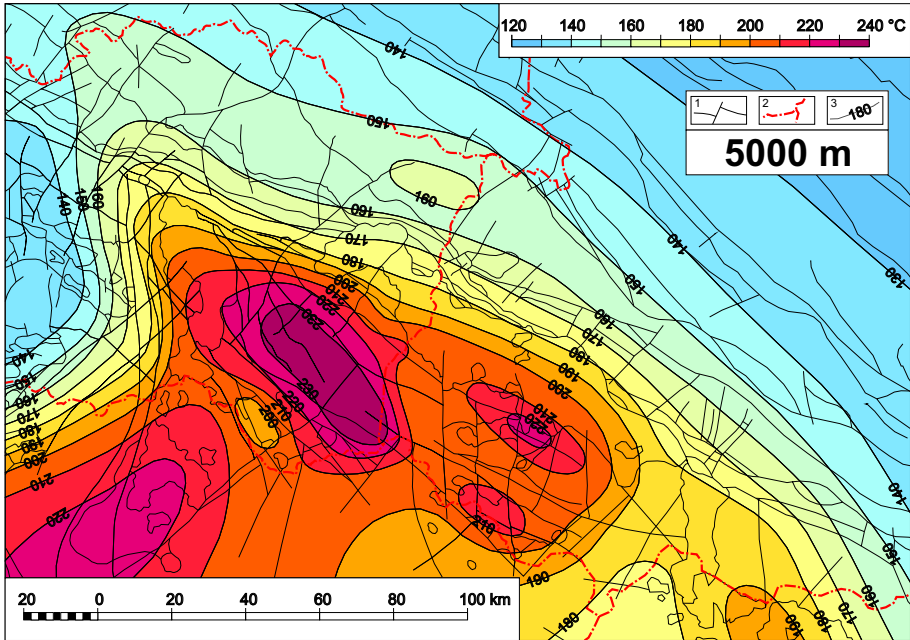


Fig. 3d. Temperature distribution map at the depth of 5000 m below the surface. Explanation in Fig. 3a.

Stretava and Pozdišovce-Trhovište). Closely under the depth of 3000 m the areas near Mukachevo and a bit deeper in the Beregovo area (both from Mukachevo Basin) are joined in the perspective localities group. In the East Slovakian Basin the compact area (the prevailing part of Trebišov Basin) with suitable conditions is formed between the depth levels of 3000 m and 4000 m below the surface. According to the temperature distribution estimations, the wider region around the Hungarian Zempleni-hegyseg Mts. becomes a part of the promising areas in a crustal layer between the mentioned depths. At depths of 4000 m the reservoir temperatures higher than 160 °C are anticipated also in the Solotvino Basin. At the depth level of 5000 m, which is considered technically acceptable for borehole drilling activities, the separated perspective areas cover the whole Transcarpathian depression and some regions of the inner parts of the Outer Carpathians. We suppose the surroundings of the borehole Zboj (in the Outer Carpathians) and probably some additional localities along the axis of the Carpathian

Conductivity Anomaly Zone reach the temperatures of $160\text{ }^{\circ}\text{C}$ or greater at depths up to 5000 m below the surface.

The selected regions with geothermal reservoir temperature of $160\text{ }^{\circ}\text{C}$ are more precisely processed and displayed in the map shown in Fig. 4a. The depth distributions of promising areas for reasonable economic exploitation of the geothermal energy by binary cycle technology are plotted with the step of 500 m. The second map (in Fig. 4b) provides the isobaths for the reservoir temperature of $130\text{ }^{\circ}\text{C}$ and accordingly wider areas (in relation to previous map), but only with theoretical applicability for electricity production. This map is useful for estimation of the use of geothermal sources with a lower requirement for temperatures on the Earth's surface, for example, heating of buildings. The smallest depths (2000–2500 m below surface) with a required temperature of $130\text{ }^{\circ}\text{C}$ are found both in the East Slovakian Basin

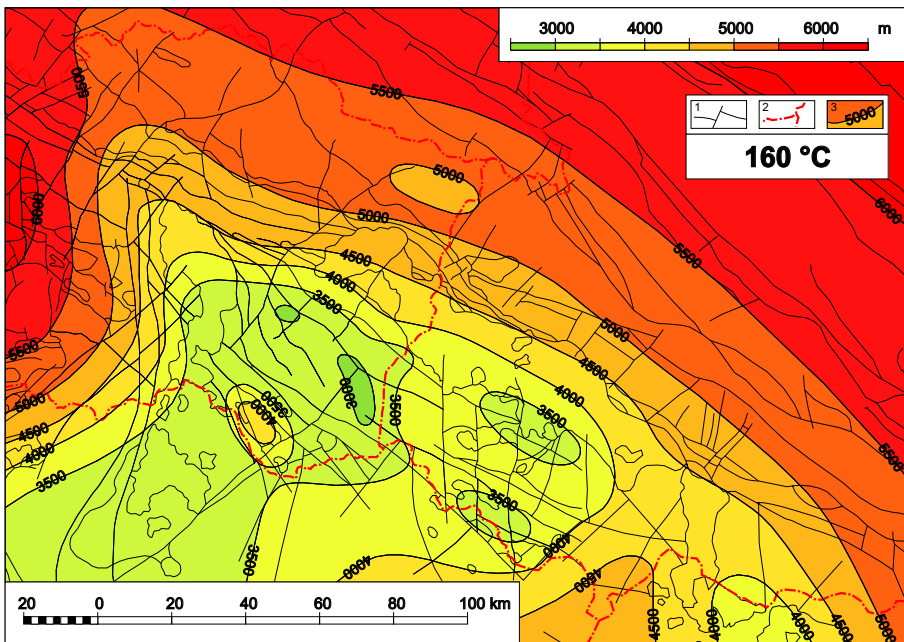


Fig. 4a. Depth distribution with the reservoir temperature $160\text{ }^{\circ}\text{C}$ for effective application of the binary cycle power plant technology in the Transcarpathian depression and in surrounding units. Basic scheme of structure boundaries and faults constructed from maps of Lexa et al. (2000) and of Kruglov and Gurskij (2007). Depth isoline values in [m].

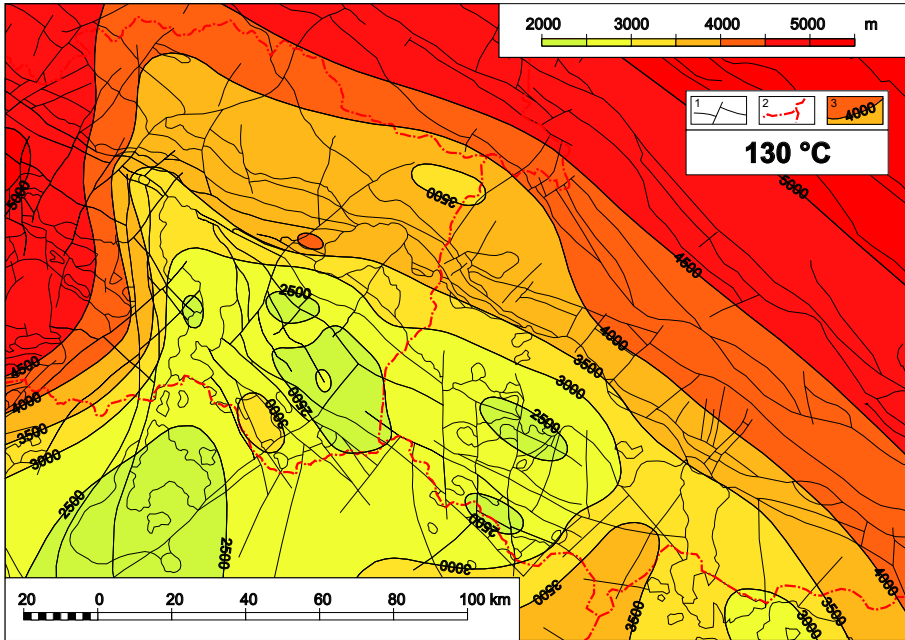


Fig. 4b. Depth distribution with the reservoir temperature 130 °C for theoretical application of the binary cycle power plant technology in the Transcarpathian depression and in surrounding units. Explanation in Fig. 4a.

(central and northern part of the Trebišov Basin, surroundings of Ďurkov in the Košice Basin) and in the Mukachevo Basin (local areas of Mukachevo and Beregovo). Such temperatures for the Solotvino Basin are supposed to be at depths of about 3000 m.

3. Conclusion

The main activities of our contribution were concentrated on the analysis of thermal conditions for geothermal energy exploitation and construction of related map outputs. The map containing the selected areas for reasonable economic application of technologies producing electricity by binary cycle (i.e. the geothermal source areas with the reservoir temperatures equal or

higher than 160 °C) is the most important result. It shows that practically the whole Transcarpathian depression has the required temperatures at depths of up to 5000 m depth from the surface. This means, that the deep source areas are accessible by the usual technical means and technologies for drilling boreholes. Such suitable thermal conditions also exist in some areas located in the inner part of the Outer Carpathians. The East Slovakian Basin is covered by areas with the best thermal conditions. In contrast, the conditions in the Solotvino Basin are conspicuously weaker. The supplementary constructed map for the reservoir temperatures of 130 °C provides the upper depth boundary for theoretical applicability of binary cycle technologies for electricity production or the depth distribution for the utilization of technologies with smaller input temperature requirements. The maps and analyses are applicable both for classic hydrothermal source types and for petrothermal sources with supposed enhanced geothermal system utilization.

The partial results represented by the terrestrial heat flow density distribution map and the temperature distribution maps at various selected depth levels below the surface in the Transcarpathian depression and surrounding units have great importance for the appraisal of the upper crust thermal state, for the construction of lithospheric models and for the interpretation of the structure and tectonics of the studied region. The interpretation of geothermal as well as other geophysical and geological data in state border regions was the part of the work allowing important reconnection both of measured geothermal inputs and of modelling results. Finally the study's results may contribute to more detailed evaluation of all parts of the lithosphere at more precise map scales. Moreover, these results can be used as the check parameters for both the geothermal and integrated modelling approaches and the solution of inverse problems in the geothermics and other geosciences as well.

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