DE GRUYTER
OPEN

Contributions to Geophysics and Geodesy Vol. 47/1, 2017 (1–22)

Deep geothermal sources for electricity production in Slovakia: thermal conditions

Dušan MAJCIN[1], Miroslav KRÁL[2], Dušan BILČÍK[1], Martin ŠUJAN[3], Andrea VRANOVSKÁ[4]

[1] Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovak Republic; e-mail: dusan.majcin@savba.sk

[2] Thermex, Bernolákova 5678/82A, Pezinok, Slovak Republic

[3] AB-geo, Račianska 25, 831 02 Bratislava, Slovak Republic

[4]HG Service, Bieloruská 64, 821 06 Bratislava, Slovak Republic

Abstract: The contribution presents the results of geothermic interpretation approaches applied to measured geothermal data and is focused to determination of the thermal conditions both for application of classic hydrothermal sources exploitation and specialized EGS technologies for electricity production in the region of Slovakia and adjacent areas. Primarily, the heat flow density data and the temperature distribution measurements in boreholes were interpreted by classic 1D interpolation and extrapolation methods. New terrestrial heat flow density map for the studied area was constructed using the values determined in boreholes, their interpretations, the newest outcomes of geothermal modelling methods based both on steady-state and transient heat transfer approaches, and on other recently gained geoscientific knowledge. Thereafter, we constructed the maps of temperature field distribution for selected depth levels up to 6000 m below the surface and the final map of the isothermal surface depths for the reservoir temperature of 160 °C. This final map serves for the appraisal of the effective application of the binary cycle power plant technology in Slovakia in terms of thermal conditions.

Key words: Western Carpathians, geothermic interpretations, geothermal energy, hot dry rock, enhanced geothermal system

1. Introduction

The temperature of the acquired liquid medium on the Earth's surface represents the basic determining criterion of the geothermal energy utilization for a wide spectrum of approaches, namely the classic hydrothermal systems, the hot wet rock (HWR) systems, and the pure petro-thermal systems based on the hot dry rock (HDR) concept. In recent times the evaluation of the

doi: 10.1515/congeo-2017-0001

regions of the potential geothermal energy sources is made mainly according to temperatures required for the electric energy production minimally by binary cycles (Kalina cycle, Organic Rankine cycle or others). This responds to the criterion of the minimal reservoir temperature. Sustainability and restorability of the thermal conditions in the geothermal source throughout its utilization is also an important factor for the appraisal of the source area. It results mostly from the high regional heat flow density values and/or from the sufficient heat capacity of the local geological structure with higher heat production.

The second criterion for the classification of geothermal regions has a technical and economic nature. It is represented by the depth at which the required reservoir temperature is safely and effectively reachable by present day drilling methods. Nowadays the depth of 5000 m is considered the maximum reasonable value.

The third criterion for the utilization of geothermal sources of the HDR or the HWR type is related both to the structural and lithological conditions suitable for creation of the artificial underground heat exchanger as a part of the enhanced geothermal system (EGS).

The studied region of Slovakia (Fig. 1) is situated in the northern part of the Carpathian-Pannonian region. The great part of this region belongs to one of the very promising parts of Europe suitable for geothermal energy exploitation (*Hurtig et al., 1992; Geoelec, 2013; 2016*).

Activities related to geothermal energy source prospecting in Slovakia were devoted to some selected localities, but comprehensive studies of the whole area of Slovakia have also been published. The existing knowledge was concentrated and analysed mainly in the Atlas of geothermal energy of Slovakia (*Franko et al., 1995*). This important publication presents a summary of the research results from a period of more than two decades of the authors and other scientists working in this subject field as well. Among other problems it also evaluates the thermal, geological and hydrological conditions for geothermal energy, thermal capacity of sources and defines a basic selection of regional to separate source areas. The atlas, mentioned above, becomes the data and cartographic basis for subsequent geothermal energy studies in the region of Slovakia. The prospection and applications were aimed mainly at hydrothermal sources (*Král et al., 1985; Franko et al., 1986; Franko et al., 1995; Remšík and Bodiš, 2010; Fendek*

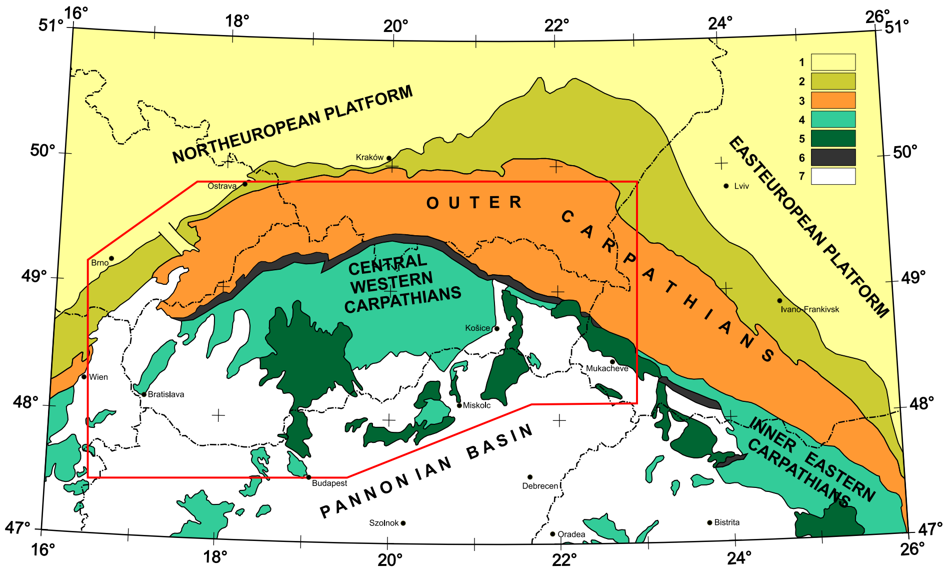

Fig. 1. Position of the studied area in the northern part of the Carpathian-Pannonian region. Basic tectonic map was modiffied after *Kováč (2000)*. Structure description: 1 – European platform, 2 – Foredeep units, 3 – Alpine – Outer Carpathian Flysch Belt, 4 – Inner Alpine-Carpathian units, 5 – Neogene volcanites on the surface, 6 – Pieniny Klippen Belt, 7 – Neogene and Quaternary sediments.

et al., 2011 and plenty of other publications from partial geothermal localities in Slovakia). The research activities in Slovakia were less focused on the problems of obtaining energy by the HDR and HWR approach. Beside some methodologically and technically specialized works (*Zembjak, 1989; Vranovská, 1993; Masaryk, 2009*) various local analyses were accomplished. They were related mainly to the Beša-Čičarovce structure (*Franko et al., 1986; Rudinec, 1989; Franko et al., 1995; Masaryk, 2008*). In the recent years some projects of geothermal energy exploitation by EGS systems were prepared in localities of both the Danube Basin and East Slovakian Basin, but they have not been implemented up to now.

Our contribution aims to determine the thermal conditions for the geothermal energy utilization in the electric energy production within Slovakia and adjacent areas. That means it is necessary to estimate the depths where rock temperatures are suitable for production of electric energy minimally by the binary cycle technologies. Theoretically, the reservoir temperatures of about 130 °C are sufficient for this purpose. However, for the reasonable economic exploitation of geothermal energy it is necessary to consider the subsurface temperatures at the level of 160 °C.

2. Methods

This contribution arises from the knowledge provided in *Franko et al. (1986)* and in *Franko et al. (1995).* It enhances the results both by the enlargement of the studied area (Slovakia) and by application of the newest geothermal data, structural and tectonic knowledge, and results from geothermal modelling approaches.

The connection with the above mentioned publications also exists in the methodological field. The starting models of the thermal state of the upper parts of the upper crust were constructed from the actual geothermal measured data and by the application of methodical principles utilized in the "Atlas of geothermal energy of Slovakia" (*Franko et al., 1995*). Both the interpolation and the "short distance" extrapolation methods based on 1D solutions of the heat transfer problem in heterogeneous media were used as a basic approach. We constructed the starting geothermal models using these methods. Similarly to the paper (*Majcin et al., 2016*) these models were supplemented by existing results of the geothermal modelling made for the studied region both for steady state (*Čermák and Bodri, 1986; Bielik et al., 1991; Majcin, 1993*) and transient thermal regimes (*Kutas et al., 1989; Majcin and Tsvyashchenko, 1994; Majcin et al., 1998; Tarasov et al., 2005; Majcin et al., 2014; Kutas, 2014; Majcin et al., 2015*) approaches and by so-called integrated modelling approaches (*Zeyen et al., 2002; Dérerová et al., 2006, 2012, 2014; Bielik et al., 2010; Grinč et al., 2014; Hlavňová et al., 2015*).

When finalizing the geothermal models we utilized both the qu alitative and quantitative analyses as well as methodical conclusions from study of refraction effects 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) and additional models of temperature fields for structures approximating the real conditions in the Western Carpathians and surrounding units.

The mathematical-physical problems solved within the contribution (Fig. 2) can be universally described by a heat conduction equation and additional conditions:

$$c\rho \, \frac{\partial T}{\partial t} = \operatorname{div}\left(k \operatorname{grad} T\right) + A \,, \tag{1}$$

$$T(x, y, z_S, t) = T_S(x, y, t) \,, \tag{2a}$$

$$k \, \frac{\partial T}{\partial z}\Big|_{z=z_S} = q_S(x, y) \,, \tag{2b}$$

$$k \, \frac{\partial T}{\partial x}\Big|_{x=0} = 0 \quad \text{and} \quad k \, \frac{\partial T}{\partial x}\Big|_{x=L} = 0 \,, \tag{3a}$$

$$k \, \frac{\partial T}{\partial y}\Big|_{y=0} = 0 \quad \text{and} \quad k \, \frac{\partial T}{\partial y}\Big|_{y=M} = 0 \,, \tag{3b}$$

$$T(x, y, z_H, t) = T_H(x, y, t) \,, \tag{4a}$$

$$k \, \frac{\partial T}{\partial z}\Big|_{z=z_H} = q_H(x, y) \,, \tag{4b}$$

$$T(x, y, z, 0) = T_0(x, y, z) \,, \tag{5}$$

where $T(x, y, z, t)$ is the temperature at the point $X(x, y, z)$ and the time t, $k(x, y, z)$ is the thermal conductivity coefficient in the point X, $c(x, y, z)$ is the specific heat coefficient, $\rho(x, y, z)$ is density, $A(x, y, z)$ is the heat production coefficient, $z_S(z_H)$ is the vertical coordinate distribution for upper (lower) model boundary, $T_S(x, y, t)(T_H(x, y, t))$ is the temperature distribution at upper (lower) model boundary at the time t, $q_S(x, y)(q_H(x, y))$ is the vertical component of the heat flow density distribution at upper (lower) model boundary, L, M are the horizontal dimensions of model in direction x, y and $T_0(x, y, z)$ is the initial temperature distribution within the model for transient heat transfer problem.

The configuration of additional conditions (2a)–(5) depends on the type of solved problem. Practically all model problems contain lateral boundary conditions with zero lateral heat flow density in x or y direction (3a), (3b) on the sufficiently distant boundaries from the region under study. The thermal continuity conditions (for both temperature distribution and heat

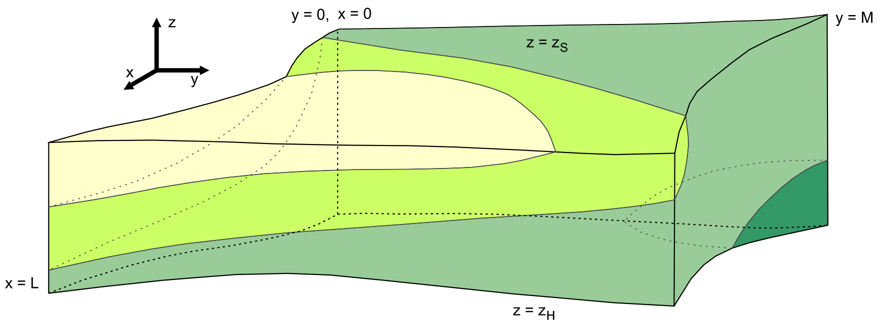

Fig. 2. General 3D model for heat transfer problems.

flow densities) are fulfilled in all models and in the utilized numerical approaches.

The refraction problems used the temperature distribution on the surface (2a) and simple distribution (constant or linear in any direction to describe regional trend) of the vertical component of heat flow density at the lower boundary (4b). The lower boundary of refraction problems is usually equal to a plane placed at the determined depth ($z_H = H$).

The direct problems of steady state heat transfer in real world conditions are solved with surface condition (2a) and with condition (4a) or (4b) at the lower boundary. The direct transient problems use the condition (5) as the initial temperature distribution within the model. The inverse geothermal problems use the heat flow density distribution as the main model quality parameter. The measured data and calculated model data are compared. For some special cases we also utilized model temperature distributions for interpretation of known data. The temperature distributions within the model in transient regime were also utilized for model acceptability in relation to various geological thermometers, volcanism development and with additional calculations also for tectonic evolution events influencing the thermal state of the lithosphere (e.g. thermal subsidence, rheology, . . .).

The numerical calculations of the temperature fields for geothermal and tectono-thermal 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 and/or by finite element approaches (using the COMSOL Multiphysics® modelling software with the Heat Transfer Module). The finite difference methods were programmed by the authors. The method of the steepest descent (*Samarskii and Nikolaev, 1978*) with alternating direction sweeping algorithm was utilized for the solution of grid equations in steady state heat transfer problems (*Majcin, 1982*).

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; Husák and Král, 1986; Jančí and Král, 1990; Jančí, 1992; Majcin, 1993; Kutas and Gordienko, 1971; Kutas et al., 1989; Grytsik et al., 2007; Kutas, 2014*).

The determined terrestrial heat flow density (THFD) data, interpretations and constructed distributions for the studied area became the basic building information for our map. We used the data from the international *"Global heat flow database of IASPEI" (2011)* and local data from countries lying in the studied region. The heat flow density data and borehole temperature distributions from the Slovak and Czech part were published in plenty of partial studies and summarized in publications (*Čermák, 1979; 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 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 projects *"Altener II" (2005)* and in the *"Transenergy" (2013)* project with data from studied regions of Slovakia and Austria as well. The heat flow density distribution map for the Danube basin was taken from an interpretation made in *Majcin et al. (2015).*

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 resultant maps for the Transcarpathian depression and surrounding units constructed in *Majcin et al. (2016)* were included in our current contribution. The set of the geothermal data in the studied region is completed by the results from its Polish part (*Majorowicz and Plewa, 1979; Plewa et al., 1992; Gordienko and Zavgorodnyaya, 1996; Karwasiecka and Bruszewska, 1997; Wróblewska, 2007; Górecki, 2013*).

In addition and as complementary information, we have utilized the results of some synthetic works which tried to interconnect the selected geothermal data (most of them using the terrestrial heat flow density 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 complete model of the depth distribution for the 160 °C temperature isosurface was constructed both from the terrestrial heat flow density map and from the supporting maps of the temperature distributions at selected depths of 2000, 3000, 4000, 5000 and 6000 m below the surface (selection depends on the thermal activity of the concrete area of the region under study). We used the data from 396 deep boreholes for supporting temperature maps in the region of Slovakia. Some work maps used for construction of the final map will be presented in the results part.

The terrestrial heat flow density plays the role of basic indicator for the appraisal of the geothermal suitability of geological structures for utilization of energetic potential accumulated in the upper crust.

3. Results

The Slovak THFD values, used here for the analyses, were determined in 155 boreholes. The data represent practically all the basic structural-tectonic units of the Western Carpathians and the northern offsets of the Pannonian Basin as well. The constructed terrestrial heat flow density distribution map is shown in Fig. 3 together with the main surface structural boundaries and faults.

The determined heat flow density values for boreholes within the studied area of Slovakia span the interval of 40–130 mW/m^2 (Table 1). In general, the THFD increases across the structures of the Carpathian arc from the outer Carpathian units toward the Pannonian basin units.

The greatest heat flow (values of THFD greater than 120 mW/m^2) ex-

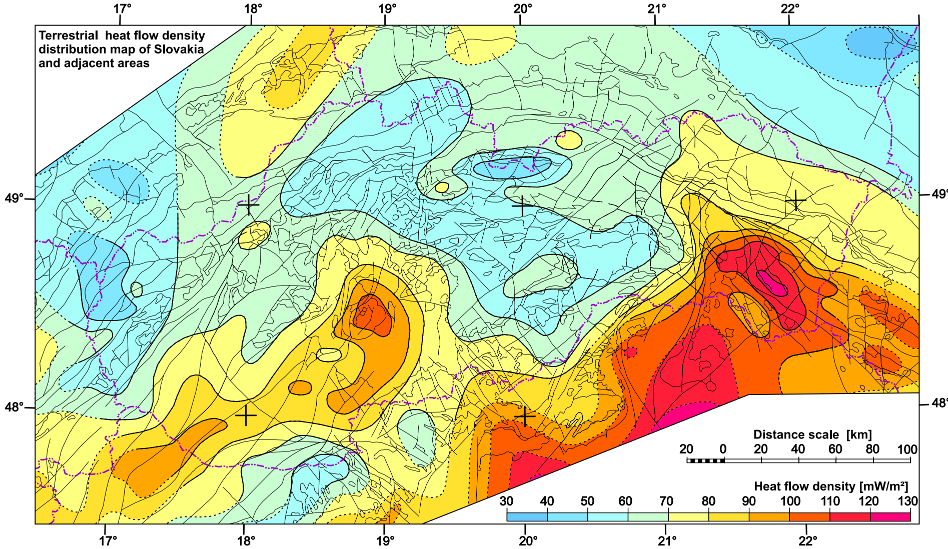

Fig. 3. Terrestrial heat flow density distribution [mW/m^2] in the Slovakia and adjacent area. Basic scheme of surface structure boundaries and faults (*Lexa et al., 2000*).

ists in the eastern part of the East Slovakian Basin – Trebišov Depression. Values greater than 100 mW/m^2 were observed in the prevailing part of this basin. Heat flow density over 100 mW/m^2 is also typical for the central part of the Central Slovakian Neovolcanics. THFD values greater than 90 mW/m^2 were determined in Gabčíkovo Depression in the central part of the Danube Basin. The smallest heat flow densities with mean value of 55.0 $\pm$ 10.2 mW/m^2 characterize the thermal state in the area of the Vienna Basin. The terrestrial heat flow densities below the value of 60 mW/m^2 were also observed in the western part of the Outer Carpathian Flysch Belt and moreover they are typical for the Tatra Mts. as well as for mountain regions in the Central part of Slovakia. The eastern part of the Outer Flysch Zone is characterized by THFD values between 70 and 80 mW/m^2. In other regions of Slovakia, the thermal activity is average with the heat flow density data predominantly within the range of 60 – 70 mW/m^2.

The final map of the terrestrial heat flow density distribution in Slovakia and adjacent areas predicts the selection results of regions suitable for the utilization of geothermal energy in the electric power production. It deter-

Table 1. Heat flow density values in the region of Slovakia. **N** – number of data, q_{min} – minimal value, q_{max} – maximal value, q_{mean} – mean heat flow density value and standard deviation for selected geological unit.

Geological unit	**Heat flow density (mW/m²)**			
	N	q_{min}	q_{max}	q_{mean}
Danube Basin	48	61.0	99.0	77.3 ± 9.1
Trebišov Depression	30	82.1	121.6	110.9 ± 9.5
South Slovakian Basin	4	59.9	63.4	62.2 ± 1.6
Vienna Basin	11	40.6	69.0	55.0 ± 10.2
Horná Nitra Depression	11	70.2	84.4	79.2 ± 4.6
Turiec Depression	2	54.6	72.3	63.5 ± 12.5
Bánovce Depression	3	55.1	61.8	58.4 ± 3.4
Prešov Depression	6	87.6	114.9	105.2 ± 11.6
Moldava Depression	1	–	–	87.9
Central Slovakian Neovolcanics	11	74.0	108.0	91.7 ± 12.3
Vihorlat Neovolcanics	2	73.3	91.4	82.4 ± 12.8
Žilina – Rajec Depression	2	51.5	54.1	52.8 ± 1.8
Liptov Depression	5	52.0	71.7	62.0 ± 8.3
Paleogene of Orava region	1	–	–	69.4
Paleogene of Šariš region	3	65.4	66.6	65.8 ± 0.7
Poprad Depression	3	65.5	69.3	66.8 ± 2.2
Spišská Magura Mts.	2	61.8	77.0	69.4 ± 10.7
Gemeric Unit	2	50.7	67.0	58.9 ± 11.5
Veporic Unit	1	–	–	68.3
Core mountains & Pieniny Klippen Belt	4	52.7	79.8	67.4 ± 11.2
Outer Flysch Belt	3	41.9	72.5	57.1 ± 15.3

mines mainly the parameters of thermal renewability of source areas.

Some constructed supporting maps of the temperature distributions in the most important regions and in selected depths are displayed on the maps in Fig. 4. The depth distributions of promising areas for reasonable economic exploitation of the geothermal energy by the binary cycle technology (reservoir temperatures of 160 °C) are plotted with the step of 500 m (Fig. 5).

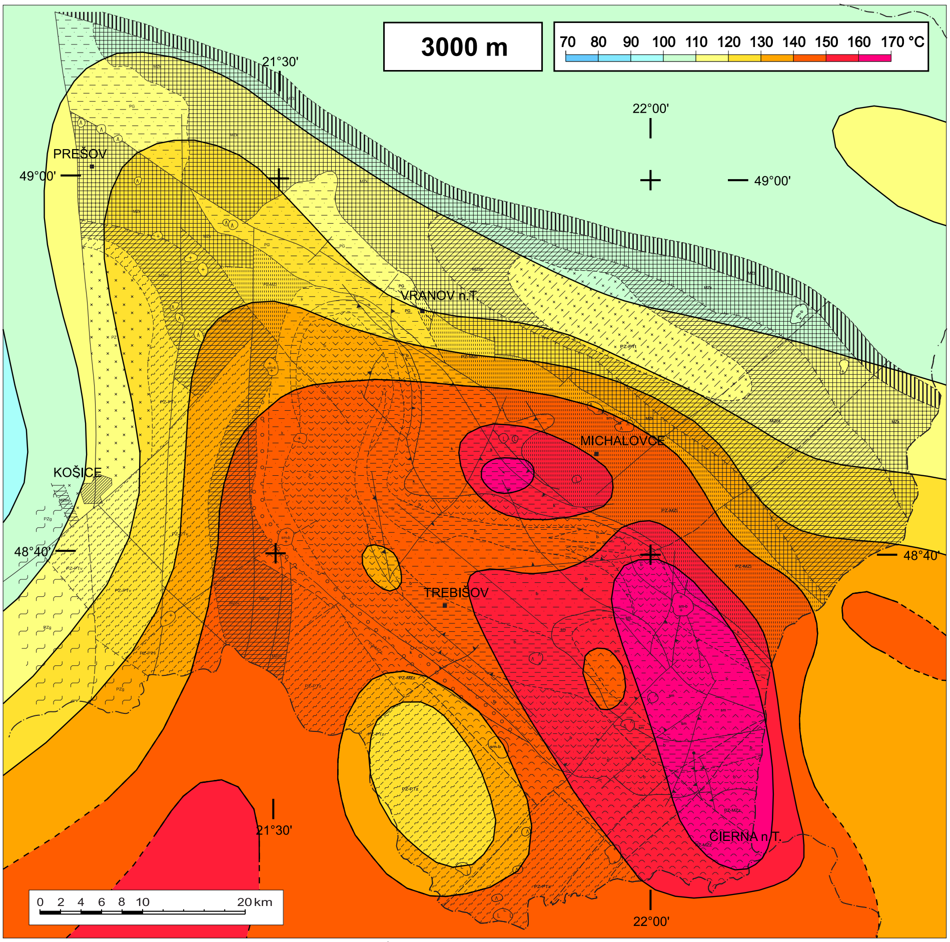

Fig. 4a. The temperature distribution at the depth level of 3000 m in the East Slovakian Basin.

The East Slovakian Basin with the flanking Prešov Depression is the most perspective area in the region of Slovakia regarding the thermal conditions. In the prevailing part of this structure the temperature of 160 °C is reachable at depths of up to 4000 meters. In the central part of the Trebišov depression the depths of the considered temperature isoplane would be smaller than 3500 m. Furthermore, in the SE part of the Trebišov Depression the isosurface depth is supposed up to 3000 m. This was confirmed

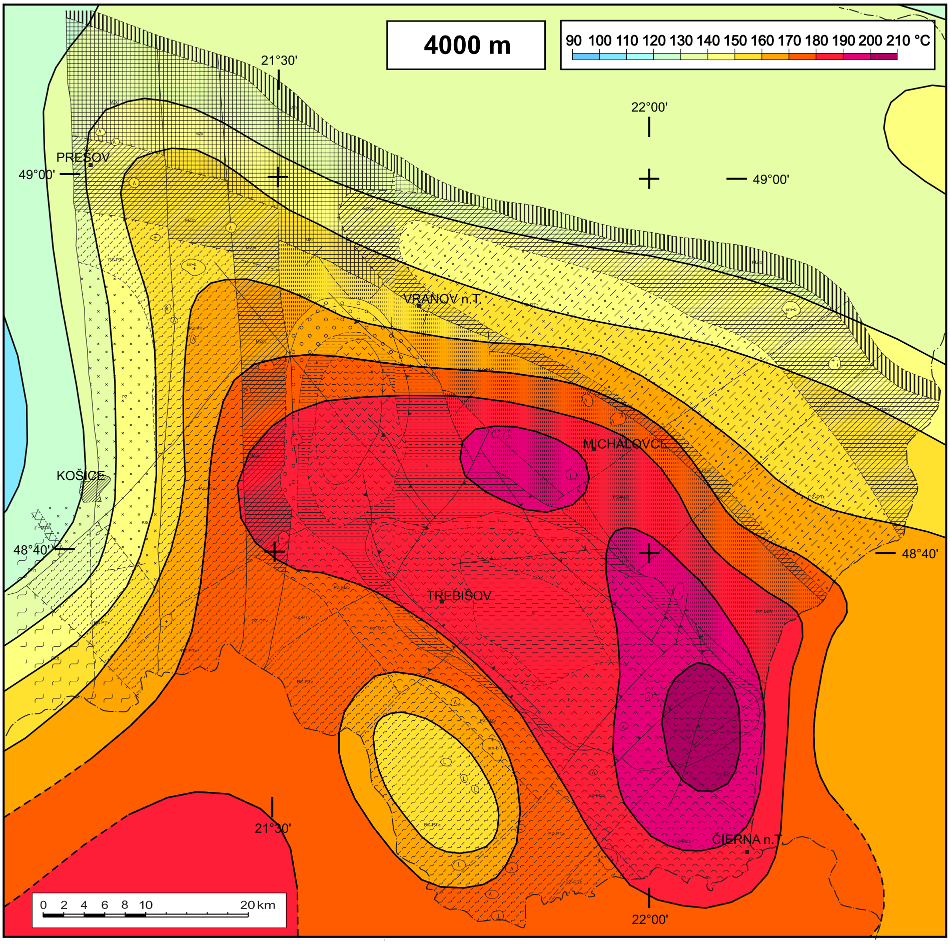

Fig. 4b. The temperature distribution at the depth level of 4000 m in the East Slovakian basin.

by direct temperature measurements in deep boreholes in the structures of Ptrukša and Stretava. High quality temperature conditions also exist in the Mukatchevo Basin and are manifested mainly on the NE and SW borders of the basin.

The temperature of 160 °C is reachable at the depth of 4000 m or less also in the central part of the Danube Basin both in Slovakia and Hungary. From the technological and economic point of view it is also possible to con-

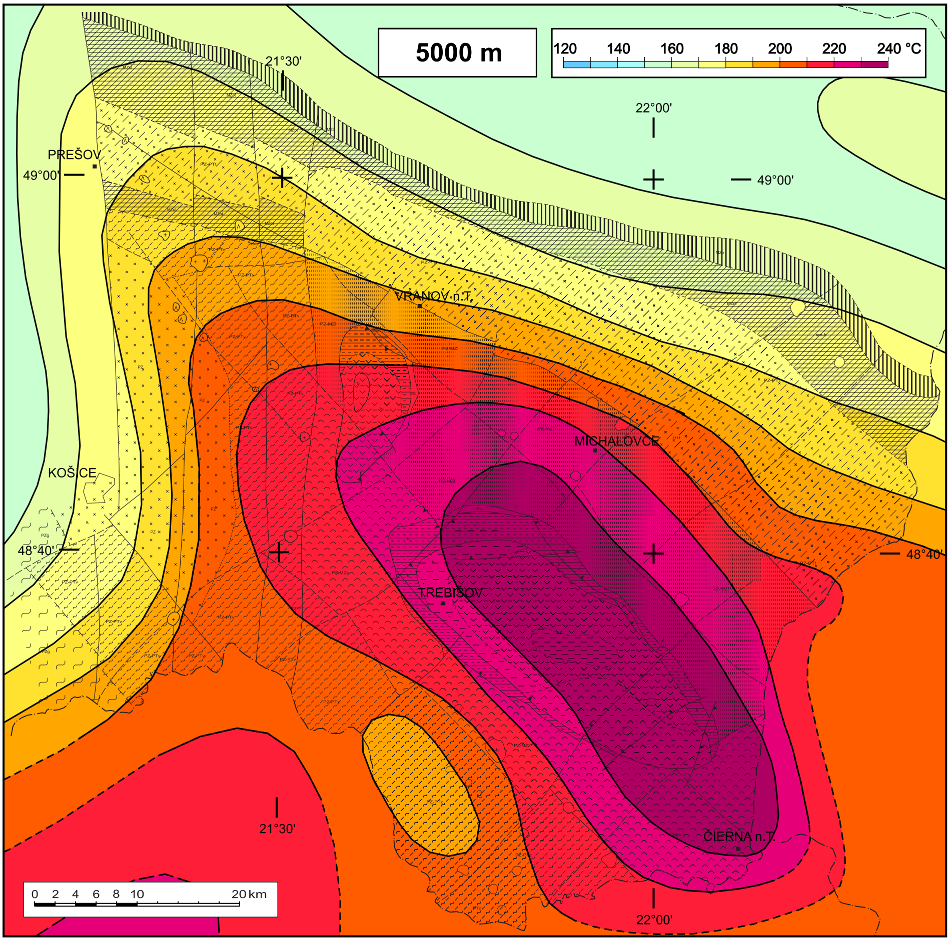

Fig. 4c. The temperature distribution at the depth level of 5000 m in the East Slovakian Basin.

sider regions with 160 °C temperature existing at depths of up to 5000 m. This condition is fulfilled at the substantial part of Slovakia. It includes particularly the southern parts of western and central Slovakia (except the Komarno High Block formation area) and the broad area of eastern Slovakia. Here it is also necessary to mention the central part of the Vienna basin, central area of the Central Slovakian Volcanics together with the Žiar Depression, and the partial areas along the axis of the Carpathian Conduc-

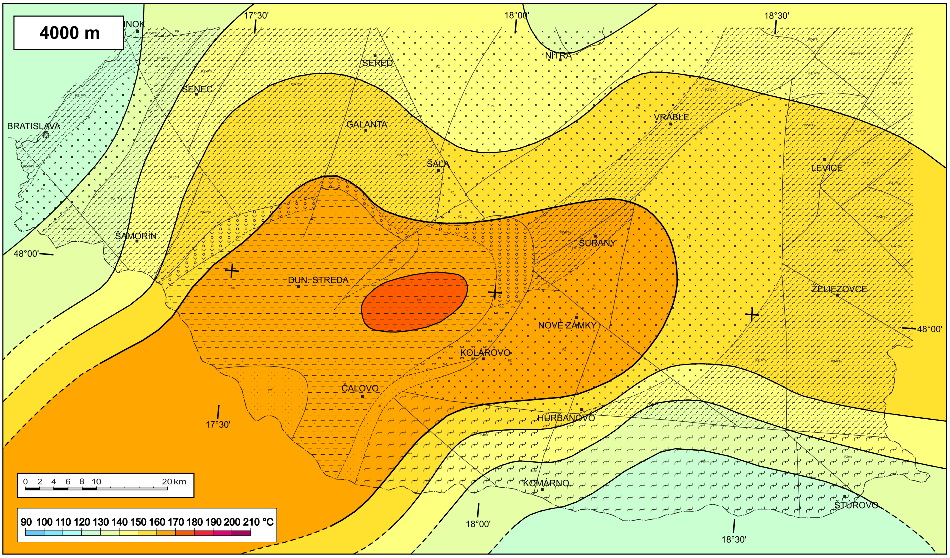

Fig. 4d. The temperature distribution at the depth level of 4000 m in the Danube Basin.

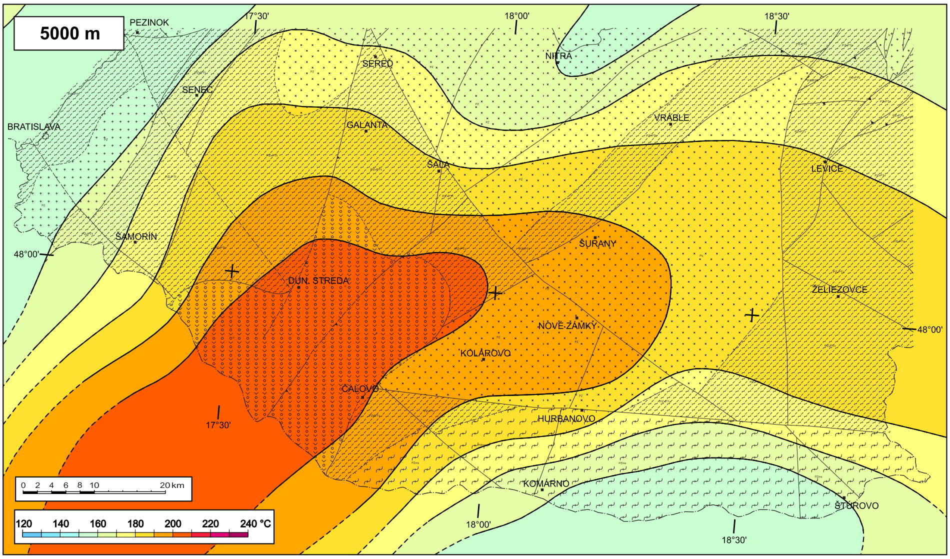

Fig. 4e. The temperature distribution at the depth level of 5000 m in the Danube Basin.

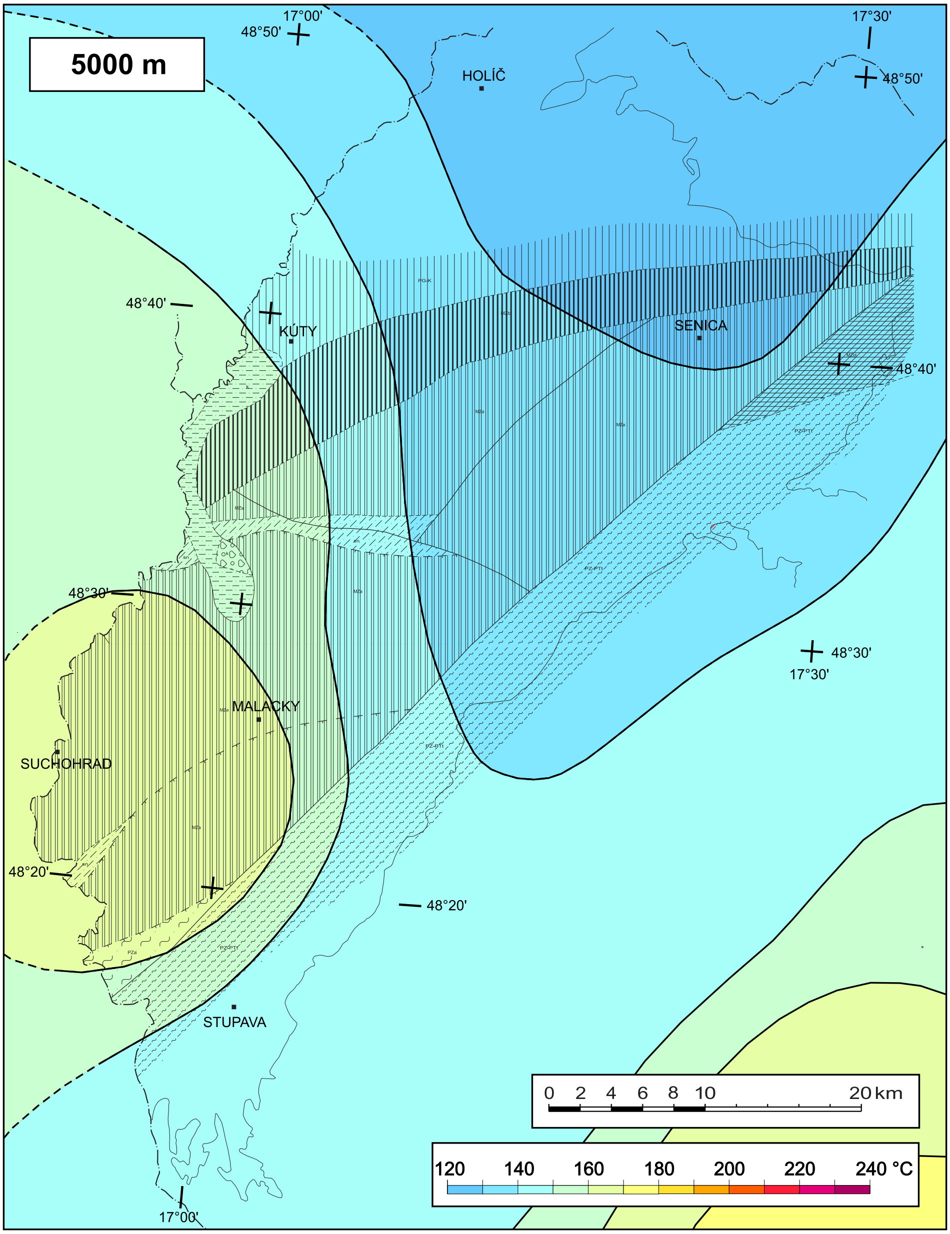

Fig. 4f. The temperature distribution at the depth level of 5000 m in the Vienna Basin.

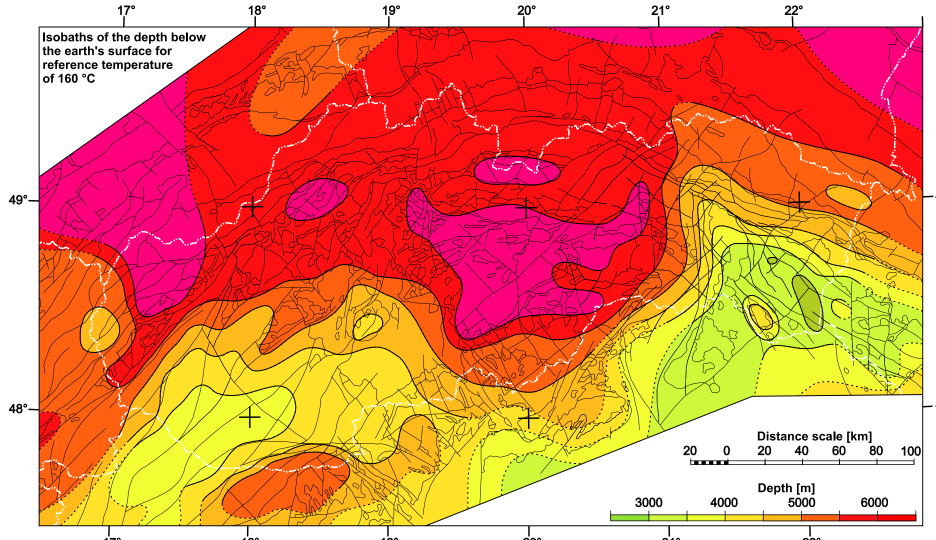

Fig. 5. Depth distribution with the reservoir temperature 160 °C for effective application of the binary cycle power plant technology in Slovakia and adjacent areas. Basic structural scheme (*Lexa et al., 2000*). The depths of the isothermal surface are plotted with the isoline step of 500 m.

tivity Zone in the most Eastern part of the Outer Carpathian Flysch.

The Western Carpathian mountain ranges of central and northern Slovakia, the Inner Carpathian Palaeogene depressions, and also the NW part of Slovakia are not considered promising areas for the exploitation of geothermal energy for electricity production. The temperature of 160 °C will be reached there only at depths exceeding 5500–6000 m.

4. Conclusion

Slovakia is one of the promising areas for the exploitation of geothermal energy in the form of hydrothermal sources and also as the hot dry/wet rock sources. The region is characterized by complicated tectonic evolution and a resultant structure with relatively high thermal activity. In consequence, the applied geothermal interpretation methods utilize both stationary and transient heat transport modelling approaches. The 1D modelling methods

(*Franko et al., 1995*) were applied mainly for interpretation of data measured in boreholes (interpolations between measurements and extrapolation for short distance). The main geothermal modelling approaches solve the problems in real 2D/3D environment and in both regimes: steady state and transient. The math-physical problems are solved by numerical approaches of finite difference method and finite element method.

The final constructed map provides the information that the terrestrial heat flow density varies typically within the interval of 50–120 mW/m^2 with some extreme values outside this range. Our contribution presents the new map of THFD distribution for the studied region of Slovakia and surrounding areas based both on measured and modelling results.

The heat flow density values in localities suitable for geothermal energy exploitation from the thermal and technical point of view are normally higher than 90 mW/m^2. The new THFD map, temperature distribution in boreholes, their interpretation, newest outcomes of geothermal modelling methods, and other recently gained geoscientific knowledge were used for the construction of the temperature distribution maps at various depth levels below the Earth's surface and finally, for the isothermal surface of the geothermal source temperature 160 °C. This map provides the basis for selection of source areas for technologically and economically convenient utilization of the geothermal energy for electricity production minimally by application of binary cycles technologies. The perspective regions both for classic hydrothermal source types and for petrothermal sources with 160 °C deep source temperature existing at depths of up to 5000 m include a substantial part of Slovakia. However, it is not reasonable to exclude other regions with lower temperatures at the depth of 5000 m because they could be utilized for other energy purposes such as heating. The final depth distribution map for the temperature of 160 °C will be used for further selection of suitable areas according to other criteria most of them by the lithological content of structures at determined depths or in other words whether the media are suitable for construction of artificial underground heat exchangers as a part of the enhanced geothermal system application.

Both the heat flow density and temperature distributions constructed in our paper contribute to the enhancement of knowledge about the thermal state and energy balance of the lithosphere in the Western Carpathians and surrounding geological units. Moreover, these results can be used as the check parameters both for the classic geothermal, integrated, and tectonothermal modelling approaches and for the solution of inverse problems in the geothermics and other geosciences as well.

Acknowledgements. The authors are grateful for partial support of the work by the APVV agency by means of project APVV-0724-11 and the Slovak Grant Agency VEGA by means of projects 2/0042/15 and 1/0141/15.

References

Bielik M., Alasonati-Tašárová Z., Zeyen H., Dérerová J., Afonso J. C., Csicsay K., 2010: Improved geophysical image of the Carpathian-Pannonian basin region. Acta Geod. Geoph. Hung., **45**, 3, 284–298.

Bielik M., Majcin D., Fusán O., Burda M., Vyskočil V., Trešl J., 1991: Density and geothermal modelling of the Western Carpathian Earth's crust. Geologica Carpathica, **42**, 6, 315–322.

Buryanov V. B., Gordienko V. V., Zavgorodnyaya O. V., Kulik S. N., Logvinov I. M., 1985. Geophysical Model for the Tectonosphere of the Ukraine. Naukova Dumka, Kiev, 1–212 (in Russian).

Čermák V., 1979: Review of Heat Flow in Czechoslovakia. In: Čermák V. and Rybach L. (Eds.): Terrestrial Heat Flow in Europe. Springer-Verlag, Berlin Heidelberg, 152–160.

Čermák V., Bodri L., 1986: Two-dimensional temperature modelling along five east European geotraverses. In: Čermák V. (Ed.): Geophysical Fields, Their Nature and Geological Interpretation. J. of Geodynamics, **5**, 133–163.

Čermák V., Hurtig E., 1979: Heat Flow Map of Europe. In: Čermák V. and Rybach, L. (Eds.): Terrestrial Heat Flow in Europe. Springer-Verlag, Berlin Heidelberg (Enclosure map).

Čermák V., Král M., Kubík J., Šafanda J., Krešl M., Kuferová L., Jančí J., Lizoň I., Marušiak I., 1992: Subsurface temperature and heat flow density maps on the territory of Czechoslovakia. In: Hurtig V., Čermák V., Haenel R., Zui V. L. (Eds): Geothermal Atlas of Europe. Hermann Haack, Geogr.-Kart. Anstalt, Gotha, 21–24.

Dérerová J., Bielik M., Pašiaková M., Kohút I., Hlavňová P., 2014: Calculation of temperature distribution and rheological properties of the lithosphere along transect II in the Western Carpathian-Pannonian Basin region. Contrib. Geophys. Geod., **44**, 2, 149–160.

Dérerová J., Kohút I., Bielik M., Bošanský M., Porubčanová B., 2012: Calculation of temperature distribution and rheological properties of the lithosphere along transect I in the Western Carpathians. Contributions to Geophysics and Geodesy, **42**, 4, 345–356.

Dérerová J., Zeyen H., Bielik M., Salman K., 2006: Application of integrated geophysical modeling for determination of the continental lithospheric thermal structure in the Eastern Carpathians. Tectonics, **25**, 3, TC3009, doi: 10.1029/2005TC001883.

Dövényi P., Horváth F., 1988: A review of temperature, thermal conductivity, and heat flow data from the Pannonian Basin. In: Royden L. H. and Horváth F. (Eds.): The Pannonian Basin, a Study in Basin Evolution, Amer. Assoc. Petr. Geol. Mem., **45**, 195–233.

Dövényi P., Horváth F., Liebe P., Gálfi J., Erki I., 1983: Geothermal conditions of Hungary. Geophys. Transactions, **29**, 1, 3–114.

Fendek M., Bágelová A., Fendeková M., 2011: Geothermal energy world-wide and in Slovakia. Podzemná voda, **XVII**, 1, 74–83 (in Slovak).

Franko O., Fusán O., Král M., Majcin D., 1986: Distribution of high and middle temperature geothermal waters and hot dry rock in Slovakia. In: Geothermal energy of Slovakia and their utilization. Dionyz Stur Institute of Geology, Bratislava, 81–92 (in Slovak).

Franko O., Fusán O., Král M., Remšík A., Fendek M., Bodiš D., Drozd V., Vika K., 1995: Atlas of Geothermal Energy of Slovakia. Dionyz Stur Institute of Geology, Bratislava, 1–194.

Geoelec, 2013: A prospective study on the geothermal potential in the EU. Electronic source: http://www.geoelec.eu/wp-content/uploads/2011/09/D-2.5-GEOELEC-prospective-study.pdf.

Geoelec, 2016: Geothermal Potential for Electricity Generation for the EU. 2016. Interactive GIS map. Electronic source: http://www.thermogis.nl/geoelec/ThermoGIS_GEOELEC.html.

Global heat flow database of the International heat flow commision of the International Association of Seismology and Physics of the Earth's Interior, 2011. University of North Dakota. Electronic document: http://www.heatflow.und.edu/index2.html.

Gordienko V. V., Gordienko I. V., Zavgorodnyaya O. V., Logvinov I. M., Tarasov V. N., Usenko O. V., 2004: Geothermal atlas of Ukraine. Korvin Press, Kiev. 1–61 (in Russian).

Gordienko V. V., Gordienko I. V., Zavgorodnyaya O. V., Usenko O. V., 2002: A thermal field of territory of Ukraine. Znannya. Kiev. 1–170 (in Russian).

Gordienko V. V., Zavgorodnyaya O. V., 1996: Estimation of heat flow in Poland. Acta Geophysica Polonica, **44**, 2, 173–180.

Górecki B., 2013: Geothermal atlas of the Eastern Carpathians. Goldruk, Krakow, 1–791 (in Polish with English resume).

Grinč M., Zeyen H., Bielik M., 2014: Automatic 1D integrated geophysical modelling of lithospheric discontinuities: a case study from Carpathian-Pannonian Basin region. Contributions to Geophysics and Geodesy, **44**, 2, 115–131.

Grytsik I., Kurovets I., Osadchyi V., Prykhodko O., 2007: Current state of studying heat conductivity of hydrocarbon reservoir rocks. Geologiya i geohimiya goryuchih kopalin, **3**, 43–48 (in Ukrainian).

Hlavňová P., Bielik M., Dérerová J., Kohút I., Pašiaková M., 2015: A new lithospheric model in the eastern part of the Western Carpatians: 2D integrated modelling. Contributions to Geophysics and Geodesy, **45**, 1, 13–23, doi: 10.1515/congeo-2015-0010.

Hurtig V., Čermák V., Haenel R., Zui V.l., 1992: Geothermal Atlas of Europe. Hermann Haack, Geogr.-Kart. Anstalt, Gotha (Enclosure maps).

Husák Ľ., 1986: Density and radioactivity of rocks of Inner Western Carpathians. Manuscript, Geofond, Bratislava, 1–124 p. (in Slovak).

Husák Ľ., Král M., 1986: Radioactivity contribution of Western Carpathian rocks to heat flow (Podiel rádioaktivity hornín Západných Karpát na tepelnom toku). In: Geothermal energy of Slovakia and their utilization. Dionyz Stur Institute of Geology, Bratislava, 31–37 (in Slovak).

Hvoždara M., 2008: Refraction effect in the heat flow due to 3-D prismoid, situated in two-layered Earth. Contrib. Geophys. Geod., **38**, 4, 371–390.

Hvoždara M., Majcin D. 2013: Geothermal heat flux anomaly due to a 3D prismoid situated in the second layer of a three-layered Earth. Contrib. Geophys. Geod., **43**, 1, 39–58.

Jančí J., 1992: Rock thermophysical parameters of East Slovakian Basin, measurement methods and utilization in geothermal exploration. Thesis. Department of applied and environmental geophysics Faculty of natural sciences, Comenius University, Bratislava, 1–154 (in Slovak).

Jančí J., Král M., 1986: Thermal conductivity of rocks in Western Carpathians (Tepelná vodivosť hornín v Západných Karpatoch). In: Geothermal energy of Slovakia and their utilization. Dionyz Stur Institute of Geology, Bratislava, 25–30 (in Slovak).

Jančí J., Král M., 1990: Thermophysical parameters of rocks and soils. Manuscript, Geofond, Bratislava, 1–15 (in Slovak).

Jaupart C., Mareschal J. C., 2011: Heat Generation and Transport in the Earth. Cambridge University Press, 464 p.

Karwasiecka M., Bruszewska B, 1997: Surface heat flow density in the region of Poland. Centralne Archivum Geologiczne, Warszawa, Manuscript 21/98 (in Polish).

Kováč M., 2000: Geodynamic, paleogeographic and structural development of the Carpathian-Pannonian region in Miocene. Veda, Bratislava, 1–202 (in Slovak).

Kováč M., Synak R., Fordinál K., Joniak P., Tóth C., Vojtko R., Nagy A., Baráth I., Maglay J., Minár J., 2011: Late Miocene and Pliocene history of the Danube Basin: inferred from development of depositional systems and timing of sedimentary facies changes. Geologica Carpatica, **62**, 6, 519–534, doi: 10.2478/v10096-011-0037-4.

Král M., 1991: Neogene basins of Western Carpathians – geothermal model of the East Slovakian Basin (Neogénne panvy Západných Karpát – geotermálny model východoslovenskej panvy). MS Geofond Bratislava (in Slovak).

Král M., Lizoň I., Jančí J., 1985: Geothermal exploration of SSR (Geotermický výskum SSR). Manuscript, Geofyzika Bratislava, 1–116 (in Slovak).

Kutas R. I., 2014: Heat flow and geothermal crustal model of the Ukrainian Carpathians. Geophysical Journal, Kiev, **36**, 6, 3–27 (in Russian).

Kutas R. I., Gordienko V. V., 1971: Thermal field of Ukraine. Naukova Dumka, Kiev, 1–141 (in Russian).

Kutas R. I., Tsvyashchenko V. A., Korchagin I. N., 1989: Modelling thermal field of the continental lithosphere. Naukova Dumka, Kiev (in Russian).

Lenkey L., Dövényi P., Horváth F., Cloetingh S. A. P. L., 2002: Geothermics of the Pannonian basin it's bearing on the neotectonics. EGU Stephan Mueller Special Publication Series, **3**, 29–40.

Lexa J., Bezák V., Elečko M., Mello J., Polák M., Potfaj M., Vozár J., 2000: Geological map of the Western Carpathians and adjacent area, 1:500000. Geological Survey of Slovak Republic.

Majcin D., 1982: Mathematical models of stationary heat conduction. Contrib. Geophys. Instit. Slov. Acad. Sci., **13**, 135–151.

Majcin D., 1992: Refraction of heat flow on the near-surface structures with thermal conductivity contrast. Contrib. Geophys. Instit. Slov. Acad. Sci., **22**, 67–80.

Majcin D., 1993: Thermal state of the west carpathian lithosphere. Studia Geophysica & Geodætica, **37**, 4, 345–364.

Majcin D., Bilčík D., Hvoždara M., 2012: Refraction of heat flow on subsurface contrast structures – the influence both on geothermal measurements and interpretation approaches. Contrib. Geophys. Geod., **42**, 2, 133–159.

Majcin D., Bilčík D., Klučiar T., 2015: Thermal state of the lithosphere in the Danube Basin and its relation to tectonics. Contrib. Geophys. Geod., **45**, 3, 193–218.

Majcin D., Bilčík D., Kutas R. I., Hlavňová P., Bezák V., Kucharič Ľ., 2014: Regional and local phenomena influencing the thermal state in the Flysch belt of the northeastern part of Slovakia. Contrib. Geophys. Geod., **44**, 4, 271–292.

Majcin D., Dudášová V., Tsvyashchenko V. A., 1998: Tectonics and temperature field along the Carpathian profile 2T. Contrib. Geophys. Geod., **28**, 107–114.

Majcin D., Kutas R., Bilčík D., Bezák V., Korchagin I., 2016: Thermal conditions for geothermal energy exploitation in the Transcarpathian depression and surrounding units. Contrib. Geophys. Geod., **46**, 1, 33–49.

Majcin D., Polák Sz., 1995: Refraction of heat flow near the border of the sedimentary basins with topography. Contrib. Geophys. Instit. Slov. Acad. Sci., **25**, 99–112.

Majcin D., Tsvyashchenko V. A., 1994: The influence of magmatism on the thermal field in northern part of Transcarpathian depression. Contrib. Geophys. Inst. SAS, **24**, 72–86.

Majorowicz J., Plewa S., 1979: Study of Heat Flow in Poland with Special Regard to Tectonophysical Problems. In: Čermák V. and Rybach L. (Eds.): Terrestrial Heat Flow in Europe. Springer-Verlag, Berlin Heidelberg, 240–252.

Masaryk M., 2008: Energetic potential of dry rock geothermal heat in the region of Slovakia and the utilization for electric energy production (Energetický potenciál geotermálneho tepla suchých hornín na území Slovenska a jeho využitie pre výrobu elektrickej energie). Slovak University of Technology, Bratislava, 20 p., ISBN: 978802273090 (in Slovak).

Masaryk M., 2009: Utilization of geothermal sources for electric energy production (Využitie geotermálnych zdrojov na výrobu elektrickej energie). Bratislava, SF STU, 24 p., ISBN: 978-80-227-3089-1 (in Slovak).

Plewa M., Plewa S., Poprawa D., Tomaś A., 1992: Poland. In: Hurtig E. et al.: Geothermal Atlas of Europe. Hermann Hack Verlagsgesellschaft; Geographisch-Kartographische Anstalt, 57–59.

Project report "Altener II", 2005: Intergated Feasibility Study on Geothermal Utilisation in Hungary. Geothermal Power Project Altener II 4.1030/Z/02-045. Electronic publication: http://www.geothermalcommunities.eu.

Project report "Transenergy", 2013: Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia. Electronic publication: http://transenergy-eu.geologie.ac.at.

Remšík A., Bodiš D., 2010: Geothermal waters, situation and possibilities of their utilization in Slovakia (Geotermálne vody, stav a možnosti využitia na Slovensku). ŠGÚDŠ, Bratislava, Manuscript, 19 p. (in Slovak), Electrinic source: http://www.rokovania.sk/File.aspx/ViewDocumentHtml/Mater-Dokum-120135?prefixFile=m_.

Rudinec R., 1989: Crude oil, Natural Gas and Geothermal energy Resources in Eastern Slovakia (Zdroje ropy, zemného plynu a geotermálnej energie na východnom Slovensku). Alfa, Bratislava, 1–162 (in Slovak).

Samarskii A. A., Nikolaev E. S., 1978: The methods for solution of grid equations. Nauka, Moscow, 1–592 (in Russian).

Tarasov V., Gordienko V., Gordienko I., Zavgorodnyaya O., Logvinov I., Usenko O., 2005: Heat Field, Deep Processes and Geoelectrical Model of East Carpathians. In: Proceedings of World Geothermal Congress 2005 Antalya, Turkey.

Vaňková V., Bartošek J., Chlupáčová M., Matolín M., 1979: Radioactivity and heat production of rocks from the Bohemmian Massif and the Westerrn Carpathians. In: Geodynamic Investigation in Czechoslovakia. Veda, Bratislava, 257–263.

Vranovská A. 1993: Selection principles of localities suitable for exploitation of heat of hot rocks (Princípy výberu lokalít vhodných na exploatáciu tepla suchých hornín). Geologické práce, Správy 98, GÚDŠ, Bratislava, 21–28 (in Slovak).

Wróblewska M., 2007: The thermal regime in deep lithosphere in the region of Polish Carpathians. Geologia, **33**, 4/1, 237–246 (in Polish).

Wybraniec S., 2008: Heat flow density. Central Europe. Manuscript (in Polish).

Zembjak O., 1989: The feasibility of hot dry rock exploitation (Možnosti ťažby tepla suchých hornín). Geologické práce. Správy 88, GÚDŠ, Bratislava, 137–146 (in Slovak).

Zeyen H., Dérerová J., Bielik M., 2002: Determination of the continental lithosphere thermal structure in the western Carpathians: Integrated modelling of surface heat flow, gravity anomalies and topography. Phys. Earth Planet. Inter., **134**, 89–104.