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Distribution Modeling of Thermal Field Parameters in the Polish Eastern Carpathians Based on Geophysical Data

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ABSTRACT

The scarce information on thermal parameters of rock formations in the Polish Eastern Carpathians together with irregularly spaced and distant wells where these parameters were properly measured impede construction of credible maps of thermal field distribution. Statistical methods of geometrical interpolation (e.g., kriging) appear to be insufficient for that purpose. Therefore, it is reasonable to apply computer modeling, which involves known rock formations properties to modify the geothermal field pattern. The following paper presents an attempt to interpolate the thermal field maps using the correlations between rock formations parameters and seismic, gravity, and geoelectric data. The correlation between seismic P-wave velocity and thermal conductivity of sedimentary rocks enabled us to construct 3D/2D models of thermal conductivity of sedimentary rocks in the Earth crust based on velocity distribution derived from the tomography inversion for prestack depth migration (PreSDM).

Both the temperature/gravity anomalies and temperature/electric resistivities correlations were analysed with the grid-based interpolation of the rock formations parameters established for wells and their neighborhood. The correlation coefficients were calculated for mean temperatures at various depths and for heat flows related to residual and regional gravity anomalies, and resistivities obtained from magnetotelluric sounding data interpretation. The relationships between these parameters are shown in a tabular form as linear correlation coefficients. Based on the established regression equations, we constructed the alternative maps of mean temperature distribution at selected depths. The developed approach to the construction of thermal maps is a proposal that needs further studies.

1. INTRODUCTION

The construction of credible maps of thermal field distribution within the Earth crust in the Eastern Polish Carpathians is impeded by both the scarce data on thermal properties of rock formations and by an irregular spacing, and distances between wells where thermal parameters were properly measured. Moreover, the statistical methods of geometrical interpolation (e.g. kriging) seem to be inadequate for that purpose. Therefore, it is useful to apply computer modeling of rock formations properties, which would modify the geothermal field pattern. In this paper we present an attempt to interpolate the thermal field distribution using correlations between these thermal parameters and seismic, gravity, and geoelectric data. The distribution of thermal parameters within a rock formation depends, among others, on porosity, permeability and petrographic features of rock framework. The same set of parameters determines the bulk density of rocks and significantly influences the diversity of both the velocity of elastic waves and the electric resistivity of rocks. The spatial distribution of bulk density of rocks results in the anomalies of gravity field. These regularities provide opportunities to use the gravity field, the velocity of seismic waves and the electric resistivity field of rock formations to correct and improve the accuracy of geothermal parameters maps including the temperatures and heat flow ones.

In the Polish Eastern Carpathians, the basic measurement data, which are necessary for determination of geothermal field pattern, are incomplete and irregularly spaced. Therefore, for the construction of maps, the application of computer modeling is useful, which includes the properties of rock formations influencing the distribution of geothermal field. In the following paper, we analyzed the values of thermal conductivity coefficient of rocks λ measured in the laboratory and used these values to construct the variability model of Earth heat flow density in the Polish Eastern Carpathians. The mean values of λ coefficient were then applied to the construction of recent thermal conductivity coefficient maps for the flysch formations. Such model, in turn, enabled us to draw the map of recent heat flow density based on the distribution of recent geothermal gradient. The established correlations between seismic P-wave velocity and thermal conductivity of sedimentary rocks gave rise to the construction of 3D/2D models of thermal conductivity of the sedimentary formations based on velocity distribution derived from the tomographic inversion for PreSDM.

The temperature/gravity anomalies and temperature/electric resistivities correlations were analysed with the grid-based interpolation of the set of parameters established for wells and their vicinities. The correlation coefficients were calculated for mean temperatures at various depths and for heat flow related to residual and regional gravity anomalies, and resistivities obtained from magnetotelluric sounding data interpretation. The relationships between the parameters are shown in a tabular form as linear correlation coefficients. Based on the established regression equations, we constructed alternative maps of average temperature distribution at selected depths. This newly developed approach to the construction of thermal maps is a proposal that needs further studies.

2. OUTLINE OF GEOLOGY

The Polish Eastern Carpathians are defined from the west by the Gorlice town meridian and are bordered from the south by the Slovak Carpathians and from the east by the Ukrainian Carpathians. This area belongs to the Outer Carpathians (Externides), which include the continuous claystone-sandstone successions with minor carbonates and pyroclastics (Bieda et al., 1963), all known as

"the Carpathian Flysch". The allochthonous, deep-marine, folded flysch formations are thrusted over the younger, Miocene sedimentary suite, which fills the Carpathian Foredeep (Fig. 1).

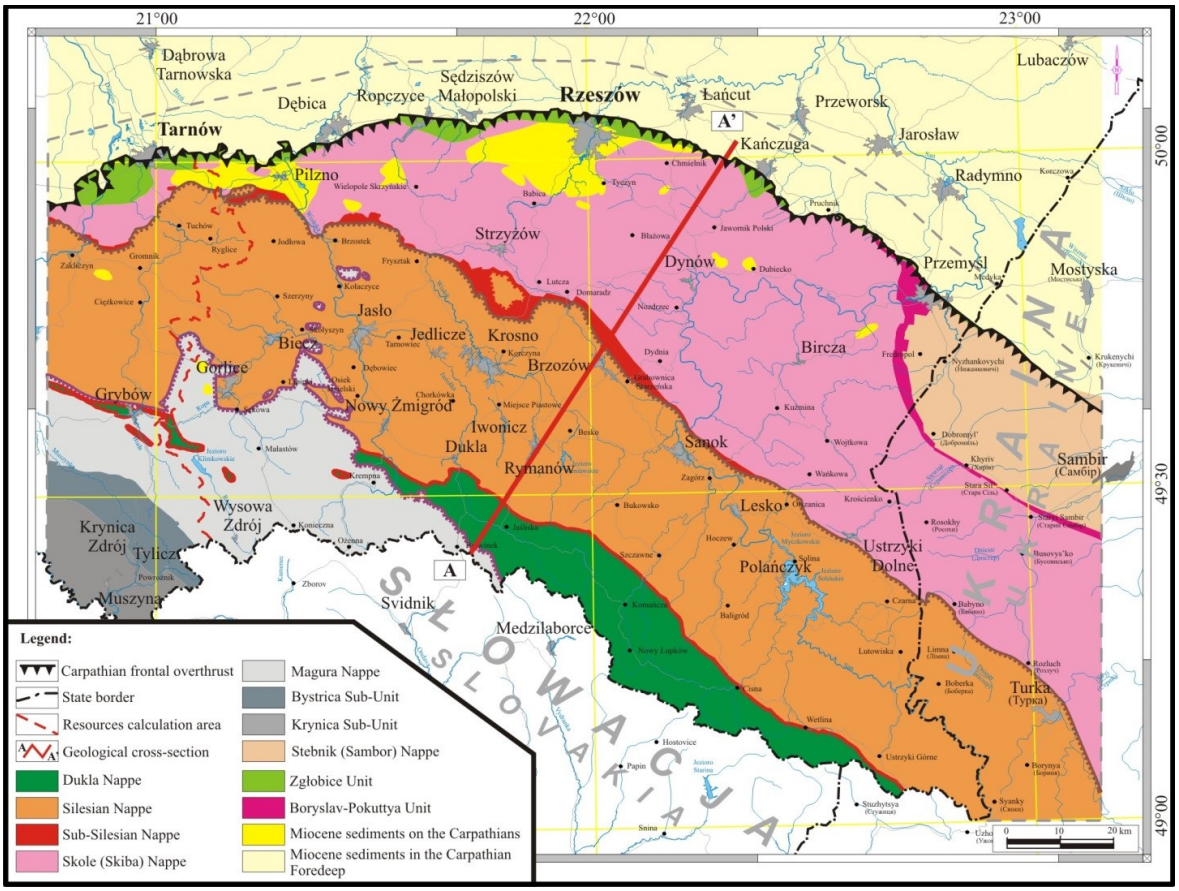


Figure 1: Geological-structural map of the Polish Eastern Carpathians based on: Żytko et al. (1989); Jankowski et al. (2004).

The folding of the Outer Carpathian sedimentary formations (including those building the Beskidy Mountains) took place at the final stages of the Alpine orogeny, in the Savian phase, i.e., at the break of the Paleogene and the Neogene (about 23 Ma ago). Precisely, the Outer Carpathians were folded and uplifted at the end of the Burdigalian due to collision between the European plate and both the Alcapa and the Tisa-Dacia terranes. Simultaneously, the overthrusting of the Carpathians to the north has commenced contemporaneously with the formation of the Carpathian Foredeep. The folded rock formations were separated from the basement, pushed to the north and thrusted as nappes over the sediments filling the foredeep formed at the front of the Carpathian Orogen. In the Polish Eastern Carpathians, three structural-facial groups were distinguished: Magura, Middle and Marginal. These units include a number of distinct nappes or structural-facial units, which reveal diversified lithostratigraphies and tectonic patterns. From the south to the north these are the Magura, Dukla, Silesian, Sub-Silesian, Skole (Middle Group) as well as Borysław-Pokucie, Stebnik and Zgłobice Nappes. The Magura Unit succession occupies mostly the western part of the Polish Flysch Carpathians. To the southeast both the range and the thickness of the Magura Unit are reduced and its front margin cuts the Polish-Slovakian state border in the area of the Jasionka River basin.

The eastern part of the Polish Flysch Carpathians is dominated by the Middle Group, which attains its maximum width in the San (Poland) and the Ondava (Slovakia) rivers basins. The characteristic feature of the Middle Group Nappes and units is the presence of the youngest flysch sediments (Oligocene-Early Miocene) known as the Menilite-Krosno Series (Jucha and Kotlarczyk, 1958). Its thickness reaches 3,000 meters in the Upper San River basin (Fig. 2).

The Marginal Group of the Eastern Carpathians includes the Borysław-Pokucie, Zgłobice and Stebnik Units (Gluško, 1968; Książkiewcz, 1972; Kuśmierek, 1984; 1990), which occupy the frontal part of the tectogen. Their ranges and thicknesses are radically reduced east from the so-called "Przemyśl sigmoid" (Świderski, 1952).

3. MODELING OF THERMAL FLOW DISTRIBUTION

The basic measurement data necessary for the construction of geothermal field distribution in the Polish Eastern Carpathians are incomplete and irregularly spaced. Hence, it is favourable to apply computer modeling methods using these properties of rock formations which modify the geothermal field pattern. In the following paper, we analyzed the values of thermal conductivity coefficient (λ) obtained from laboratory measurements and applied the results to the construction of variability model of the density of Earth heat flow in the Polish Eastern Carpathians. Our database included measurements made in 41 exposures and in 8 wells (Górecki, Kuśmierek et al., 2005-2009). For the same rock samples, porosity (φ) and propagation velocity of longitudinal waves (Vp) were measured in the laboratory.

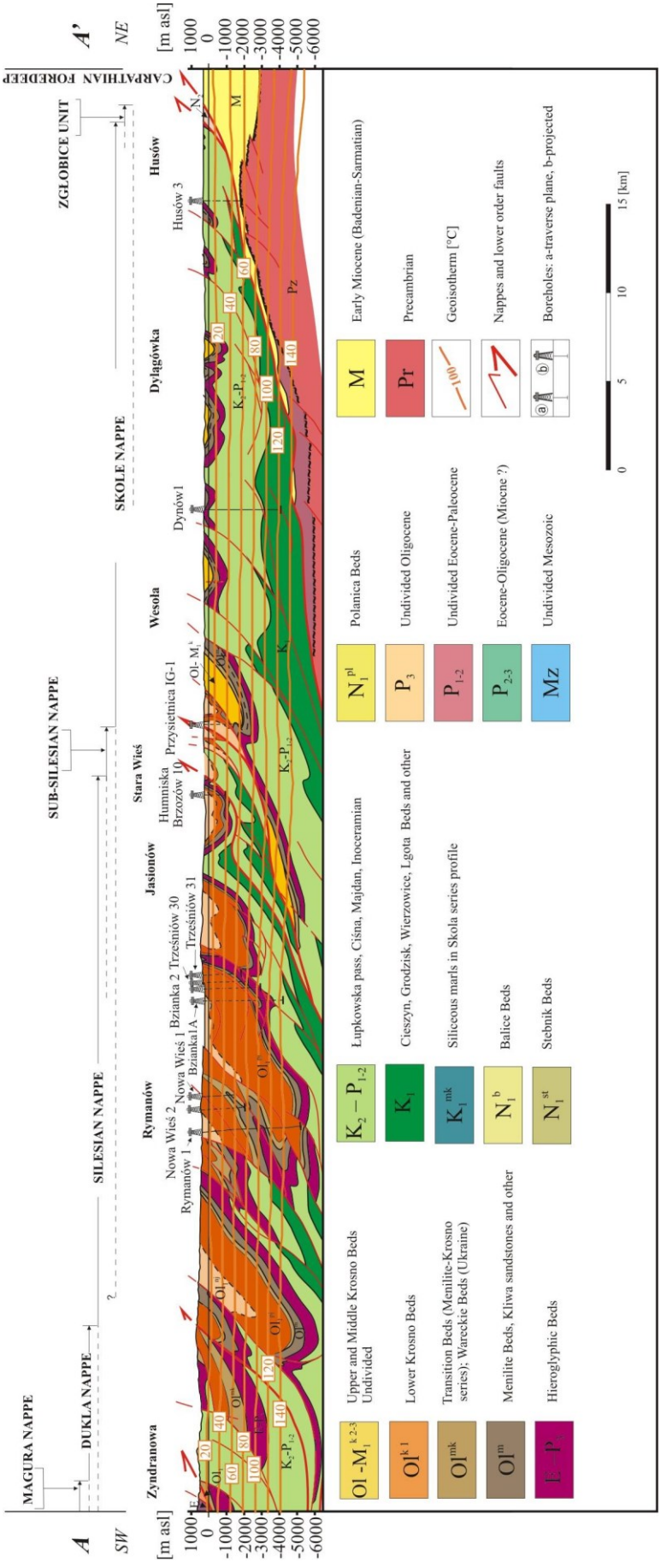


Figure 2: Geological cross-section Zyndranowa-Husów (A-A') in the area of the Polish Eastern Carpathians (modified from Kuśmierek, Baran and Golonka (2013)).

Based on the correlations between the thermal conductivity coefficient and the porosity values for sandstone and claystone lithotypes, thermal conductivity of rocks frameworks was determined. Additionally, by porosity estimation of rocks from the mechanical compaction curves, the λ coefficient was calculated for water-saturated sandstone-claystone successions varying in proportions between the lithologies.

Moreover, correlations were determined between the thermal conductivity coefficient and the velocity of longitudinal wave, which enabled us to calculate its values from acoustic logs in long depth intervals of wells (Fig. 3). Correlation indicating the linear increase of the λ coefficient with the increasing Vp values supports the applicability of the patterns of seismic waves velocities for prestack depth migration, at least at the stage of the control of λ parameter spatial interpolation process.

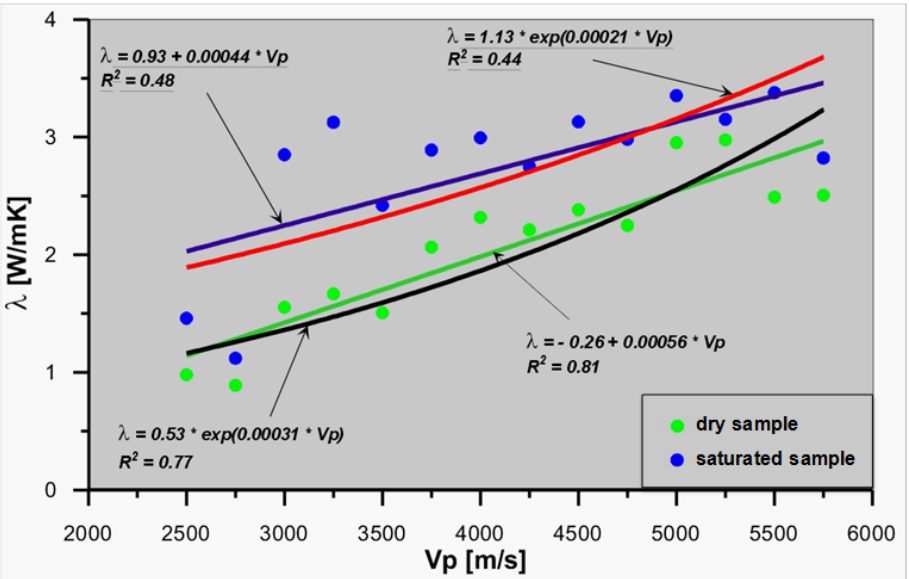


Figure 3: Cross-plot coefficient thermal conductivity vs. velocity of longitudinal wave.

Values of mean thermal conductivity coefficient were calculated separately for the Silesian and the Skole units, taking into account the stratigraphic subdivisions into the Lower Cretaceous, Upper Cretaceous, Eocene, Lower Oligocene and Upper Oligocene-Lower Miocene formations. Also, separate calculations were made for sandstones and claystones (including mudstones) due to diversified thermal properties of these rocks. Unfortunately, data from exposures and wells were very irregularly distributed and formed isolated clusters. Moreover, the number of samples appeared to be insufficient for construction of thermal conductivity coefficient maps for particular lithotypes. For further analyses, mean values of λ coefficient were taken, calculated separately for sandstones, and claystones-mudstones from stratigraphic members of the Silesian and Skole units. These values vary from 2.75 to 3.78 W/mK for sandstones and from 1.83 to 2.50 W/mK for claystones.

The mean λ coefficient values were applied to the construction of the maps of thermal conductivity coefficient for the whole flysch succession. The mean values were weighted by thicknesses of sandstones, claystones and particular stratigraphic units. Such variability model of thermal conductivity led us to the construction of density map of recent heat flow based on the Fourier's law of conduction and on distribution of recent geothermal gradient after Kuśmierek et al. (1991-1995). The obtained results show highest values, from 70 to over 75 mW/m^2 within the Silesian Unit along its boundary with the Dukla Unit as well as gradual decrease of the heat flow within the Skole Unit to the northeast, down to 50-55 mW/m^2 (Fig. 4).

The recognition of distribution of Earth heat flow density is crucial not only for geodynamic considerations but also for more practical applications related to hydrocarbon generation processes and to utilization of geothermal energy.

4. APPLICATION OF MAGNETOTELLURIC AND GRAVIMETRIC DATA TO THE CONSTRUCTION OF THERMAL FIELD PATTERN

Insufficient information on thermal parameters of rock formations in the Polish Eastern Carpathians together with irregular distribution of properly sampled wells and significant distances between them hamper the construction of maps credibly imaging the distribution of thermal field. As the statistical methods of geometric interpolation (e.g., kriging) appear to be inadequate, the construction of such maps requires the usage of additional parameters supporting the calculations. An alternative method supporting the interpolation can be the correlation of thermal parameters maps with the gravimetric and the geoelectric maps. Data contained in such distribution maps are practically continuous in the case of potential fields and are much better sampled in the case of magnetotelluric ones.

The analysis of above mentioned correlations was carried on with the interpolation grids or with the sets of parameters determined for particular wells and their vicinity. Correlations were calculated between mean temperatures at various depths and heat flow values, and residual, and regional gravity anomalies as well as electric resistivities interpreted from magnetotelluric soundings. Both the gravimetric and magnetotelluric parameters were selected in such a way, that, depending on assumed transformation parameters, they reflected the effects originating theoretically from particular depths or depth intervals. Degree of dependencies between analyzed parameters is presented in a table of linear correlation coefficients (Table 1).

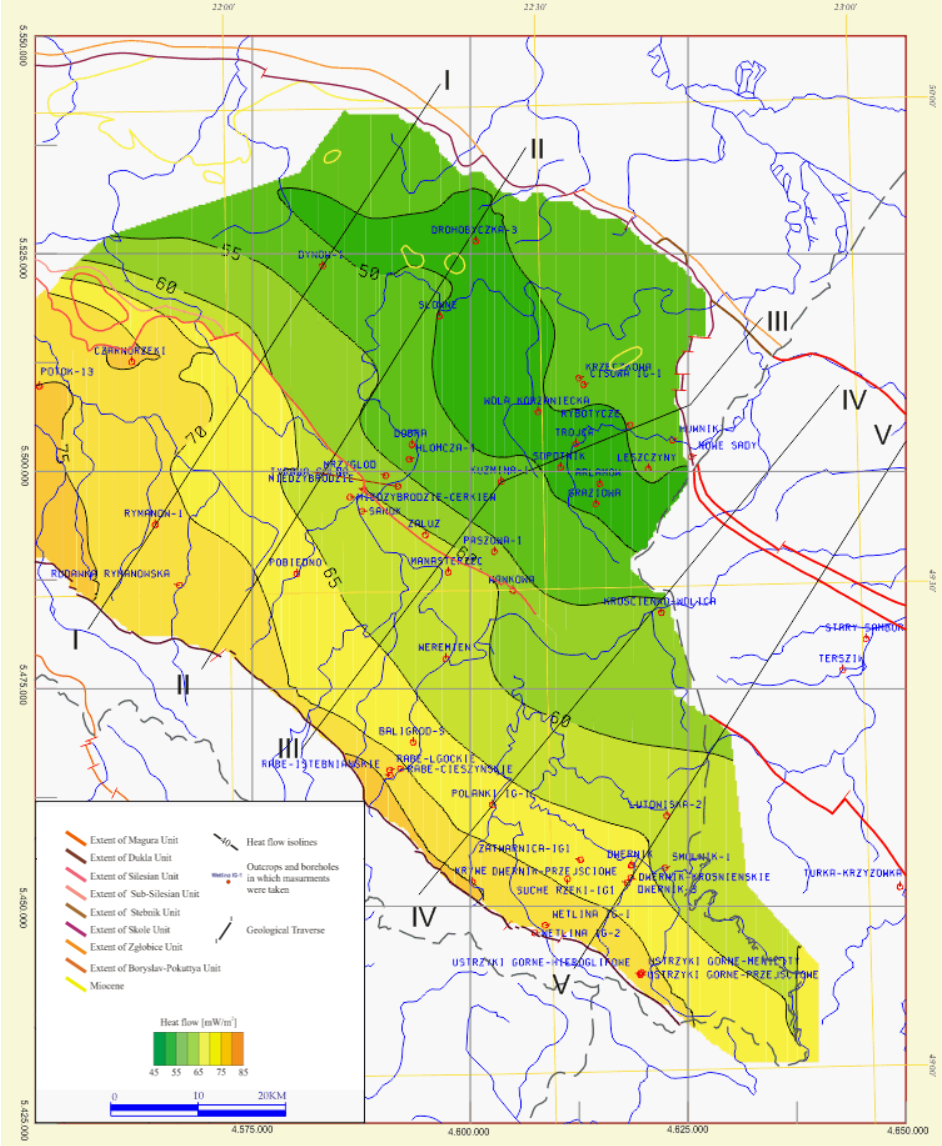


Figure 4: Map of heat flow distribution in Eastern part of Polish Carpathians.

Table 1: Correlation of the thermal parameter from boreholes and structural map of bottom flush with resistivity acc. Bostic transformation (1977).

		Electric resistivity according Bostick transformation at depth								
	Depth [m bsl]	**500**	**1000**	**1500**	**2000**	**2500**	**3000**	**4000**		
The temperature of the depth [°C]	**750**	0.71	0.78	0.79	0.48	0.35	0.28	0.16	**Correlation coefficient**	1.00
	1250	0.79	0.82	0.80	0.45	0.30	0.21	0.06		0.70
	1750	0.80	0.84	0.82	0.52	0.38	0.27	0.10		0.30
	2750	0.81	0.80	0.74	0.40	0.24	0.12	-0.06		0.00
	3250	0.80	0.78	0.71	0.40	0.24	0.12	-0.08		-0.30
	3750	0.80	0.78	0.71	0.40	0.23	0.10	-0.11		-0.70
Heat Flow		0.78	0.78	0.74	0.50	0.36	0.24	0.05		-1.00
The Base of Carpathian Overthrust		-0.84	-0.78	-0.63	-0.15	0.06	0.20	0.36		

The results of correlation analysis carried on with the interpolation grids revealed relatively low values of correlations coefficients for gravimetric data (below 0.3) and higher values for electric resistivity data in shallower depth intervals. However, if we limit the thermal parameters only to values determined in boreholes, the values of correlation coefficients increase for both the gravimetric and magnetotelluric data. The correlation plots show that the increasing values of particular parameter corresponds to the increasing or decreasing values of another parameter. Hence, we can assume the linear correlations between specific parameters although it must be emphasized that such dependencies may not (and, in fact, commonly do not) reflect the true causative-consecutive connections. Reduction of correlations to only the data from wells and elimination of outliers resulted in significant increase of correlation coefficient, particularly for gravimetric data.

The obtained linear regression equations enabled us to construct two alternative maps illustrating the distribution of mean temperatures at 1,250 meters below surface based upon distribution of electric resistivity, at 1,000 meters below surface (according to Occam's 1D inversion) and at approximate tracking depth <1,000 meters below surface for regional anomalies (Fig. 5-6). The developed methodology of thermal maps construction is a proposal which requires further improvements and studies, particularly the increased number of data used for correlations. Interesting problem will be also the development and implementation of corrections resulting from e.g., local peculiarities of density, resistivity and thermal parameters distribution patterns.

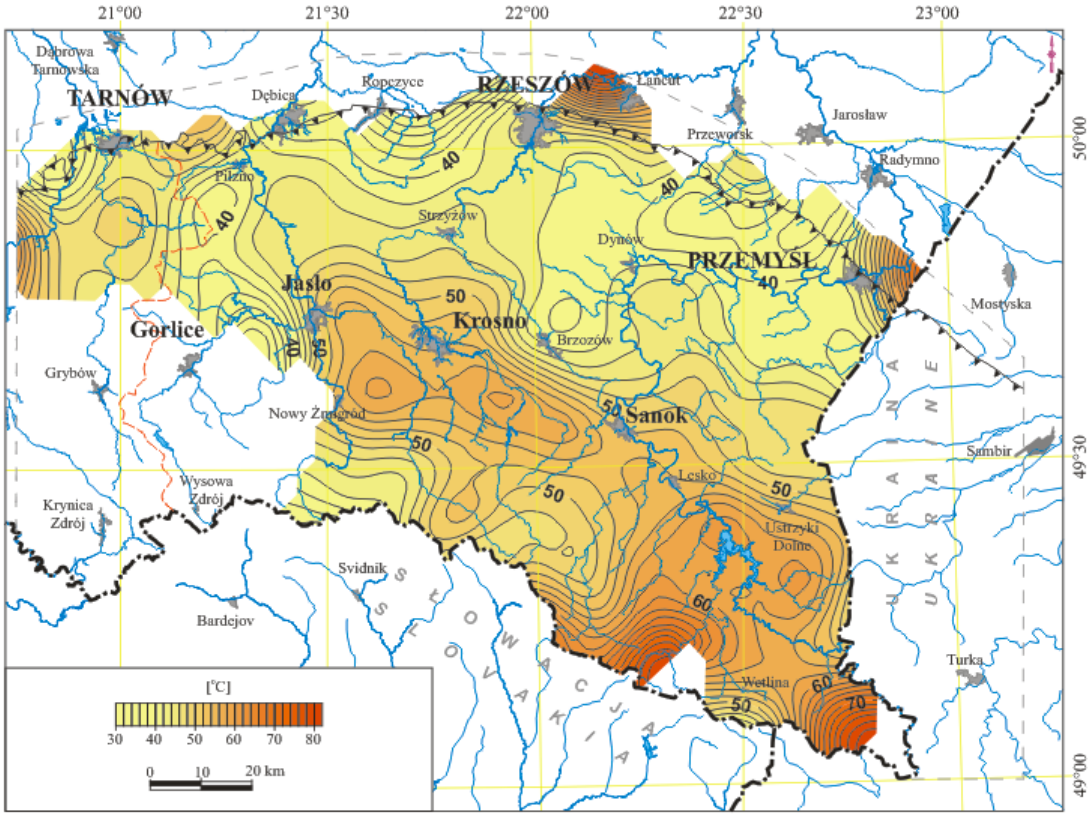


Figure 5: Average temperature map at depth 1250 m bsl on the basis of the linear regression equation between resistivity map on the depth 1000 m bsl (after 1D Occam inversion) and thermal data.

5. CONCLUSIONS

The distribution of thermal parameters within the rock formation depends (among others) on porosity, permeability and petrographic characterization of rock framework. The same set of parameters determines the bulk density as well as significantly influences the velocity of elastic waves, and electric resistivity of rocks. Spatial distribution of bulk density gives rise to the anomalies of gravity field. These regularities provide opportunities to apply the gravity field distribution and variability of both the seismic wave velocity and the electric resistivity within the rock formations to correct and rise the accuracy of the maps of geothermal parameters, i.e., temperature and heat flow.

The recognition of variability of Earth thermal flow density is important for both the geodynamic considerations and for some more practical applications to hydrocarbon generation processes and utilization of geothermal energy. For example, the Earth heat flow field was used for estimation of the thickness of Earth crust.

Unfortunately, the values of geothermal parameters originate from a small number of properly sampled wells irregularly distributed over the study area. The quality of the results of geophysical surveys is much better due to higher density of observations, e.g., density of gravimetric survey reaches several measurement sites per square kilometers. Therefore, the distribution of geophysical anomalies may support the interpolation of the pattern of thermal parameters providing a chance for significant improvement of the quality of thermal maps.

The values of correlation coefficients determined with the interpolation grids were relatively low for gravimetric data (below 0.3). However, we observed the increased values of correlation coefficient for electric resistivity maps drawn for shallower depth intervals. If the population of thermal values was reduced to the results derived from wells, we found the increasing values of correlation coefficients for both the gravimetric and magnetotelluric data. The correlation coefficient plots demonstrate that the increasing values of one parameter correspond to the increasing or the decreasing values of another one. It must be emphasized, however, that such dependence may not be (and, commonly, is not) the causative-consecutive connection.

The determined correlations can be applied to the construction of alternative maps of temperature and heat flow. However, the construction methodology presented in this paper requires further studies focused particularly on the increase of the number of data involved in correlation analyses. Also, an interesting problem will be the development and implementation of corrections resulting e.g., from the local peculiarities in distribution of density or thermal parameters. Apparently, our approach to the construction of thermal maps need further studies.

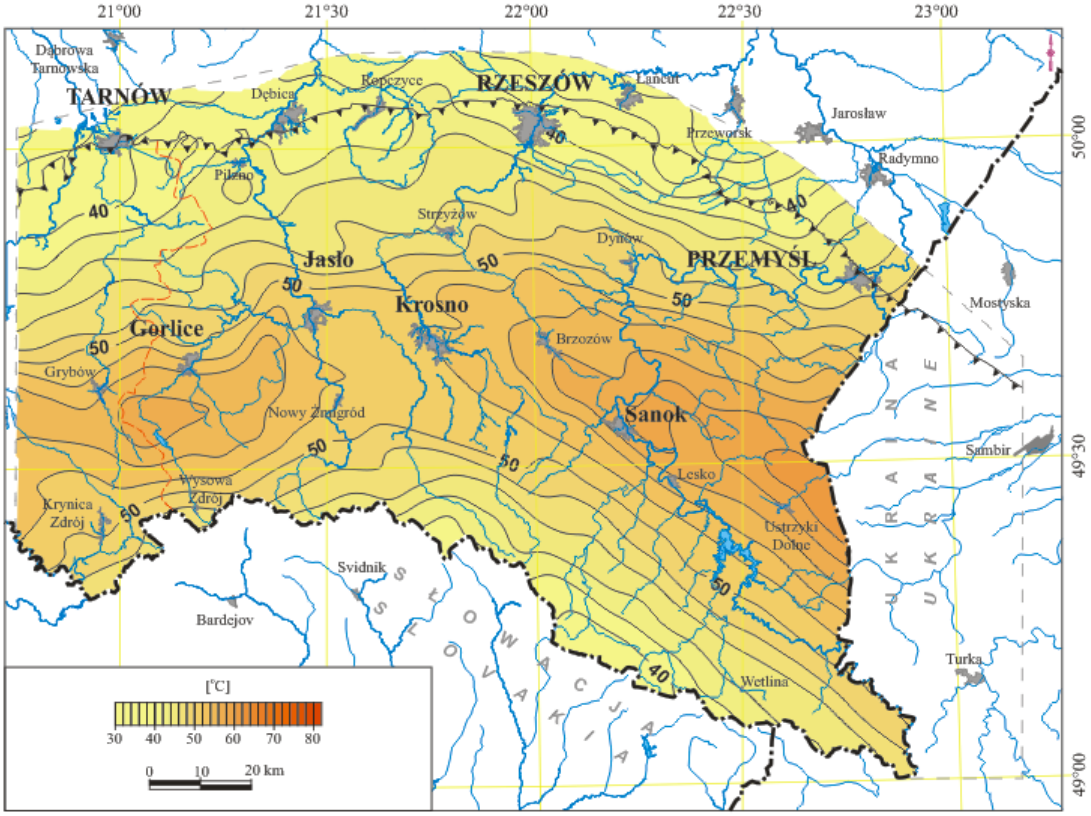


Figure 6: Average temperature map at depth 1250 m bsl on the basis of the linear regression equation between gravity regional anomaly (on the depth 1000 m bsl) and thermal data.

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REFERENCES

Bieda F. Geroch S., Koszarski L., Książkiewicz M., Żytko K.: Stratigraphie des Karpates externes Polonaise. Biuletyn Instytutu Geologicznego, (1963), 181: 5-174.

Bostick, Jr. F.X.,: A Simple almost exact method of magnetotelluric analysis. Proc. Workshop on electrical methods in geothermal exploitation. U.S. Geolocigal Curvey, (1977), 174-183.

Gluško V. V.: Tektonika i neftegazonosnost' Karpat i prilegajm]cih progibov. Nedra, Moskva, (1968), 1-263.

Górecki W., Kuśmierek J., et al.: Dokumentacja merytoryczna projektu PBS/PUPW/6/2005 pt. "Badania transgraniczne wgłębnych struktur geologicznych brzeżnej strefy Karpat w aspekcie odkryć i udostępnienia nowych złóż ropy naftowej i gazu ziemnego". Archiwum KSE AGH, Kraków, (2005-2009).

Jankowski L., Kopciowski R., Ryłko W.: Geological Map of the Outer Carpathians: Borderlands of Poland, Ukraine and Slovakia 1:200 000. Wydawnictwo PIG, Warszawa, (2004).

Jucha S. and Kotlarczyk J.: Próba nowego podziału stratygraficznego serii menilitowej i warstw krośnieńskich, (1958).

Książkiewicz M.: Budowa geologiczna Polski. IV ¨C Tektonika, 3-Karpaty. Wyd. Geol. Warszawa, (1972), 228: 1-228.

Kuśmierek J. et al.: Zastosowanie zintegrowanych modeli geodynamicznych i petrofizycznych do prognozowania potencjału naftowego. Proj. cel. nr 9 9319 93C/1599, KBN-PGNiG, Warszawa, (1991-1995).

Kuśmierek J., Baran U. and Golonka J.: Charakterystyka tektoniczna i geologiczna wschodniej części Karpat polskich oraz strefy transgranicznej z Ukrainą. [In:] Górecki (red.) - Atlas geotermalny Karpat wschodnich. Wyd. AGH KSE, Kraków, (2013).

Kuśmierek J.: Uzasadnienie perspektyw ropo- i gazonośności formacji fliszowej we wschodniej części polskich Karpat i propozycje udokumentowania zasobów. [In:] Ocena prognoz i efektywności poszukiwań ropy i gazu ziemnego w Polsce. Materiały Konferencji Komitetu Gospodarki Surowcami Mineralnymi, PAN. Wydawnictwa AGH, Kraków, (1984), 27-49.

Kuśmierek J.: Zarys geodynamiki centralnokarpackiego basenu naftowego. Prace Geol. Kom. Nauk Geol. PAN. Oddz. w Krakowie, (1990), 1-135.

Świderski B.: Z zagadnień tektoniki Karpat północnych. Prace Instytutu Geologicznego, Warszawa, (1952), 8.

Żytko K., Gucik S., Oszczypko. N., Zając R., Garlicka I., Nemčok J., Eliaš M., Menčik E., Dvorak J., Stranik Z., Rakuš M., Matejovska O.: Geological Map of the Western Outer Carpathians and their foreland without Quaternary formations, [In:] Poprawa D., Nemčok J., (eds.) Geological Atlas of the Western Carpathians and their Foreland. Państwowy Instytut Geologiczny, Warszawa, Poland, (1989).