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A 3D model of the thermal field within the Polish Carpathians and the Carpathian Foredeep (S Poland)

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Numerical 3D parametric models of temperature and thermal gradient distribution within the Polish Carpathians and the Carpathian Foredeep are constructed for the interval between ground level and the 160°C isotherm. The model construction was preceded by detailed analysis of over 500 thermal logs from the area investigated and its closest vicinity. This analysis showed that the vertical changes in temperature and thermal gradient have a non-linear character with no regular pattern in the distribution of the parameters modelled, so a 3D modelling approach was chosen as the most appropriate method for their quantitative description. Furthermore, standardization of the thermal logs was recognized as mandatory so the influence of drilling process would be eliminated. Among a broad array of methods and their preconditions discussed, the Kukkonen-Szewczyk method was selected for the data collected in the study area. Modelling results show a close relationship between thermal gradient, lithology and petrophysical rock properties as well as a correlation between the distribution of positive thermal anomalies and yield of hydrocarbon accumulations within the Carpathian Foredeep. The accuracy of the model has been assessed as ~10%. The model was then used for discussion of hydrocarbon generation and prediction of formation temperature.

Key words: Carpathians, Carpathian Foredeep, temperature, thermal gradient, 3D modelling.

INTRODUCTION

This paper describes results of 3D modelling of temperature distribution within the Polish Carpathians and the Carpathian Foredeep, being the first attempt in Poland at a quantitative 3D description of thermal parameters. Detailed recognition of thermal parameters and their spatial variability is of crucial importance for the energy industry: oil and gas as well as geothermal (Dotsey, 2012). The area of interest was limited by the Polish border in the south and east and by the northern and western limits of the Miocene Carpathian Foredeep (Fig. 1).

The model construction consisted of two main steps (1) collection, critical assessment and standardization of available well thermal logs, and (2) construction of a regional 3D model showing the temperature distribution versus depth and its first derivative i.e. the thermal gradient. Analysis of the model constructed allows conclusions regarding lateral and vertical variations of the thermal field within the Carpathians, Carpathian Foredeep and their Mesozoic–Paleozoic substrate.

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EARTH'S THERMAL FIELD AND ITS ANALYSIS – A BRIEF INTRODUCTION

The recognition and understanding of the Earth's thermal field, especially within the shallow (up to 10 km) parts of the Earth's crust, can provide important information to help proper understanding of the generation of hydrocarbons, of the geothermal potential of deep formation waters, and generally of tectonic processes and the evolution of climate.

The basic sources of thermal energy of the Earth lithosphere are: Earth's mantle heat, called remnant heat, and radiogenic heat, being continually produced as an effect of natural decay of the radioactive isotopes of uranium (^{235}U, ^{238}U), thorium (^{232}Th) and potassium (^{40}K) (Adams and Gasparini, 1973; Pasquale et al., 2017). It is generally accepted that 60% of the recent geothermal flow is generated by radioactive elements (26.4% by uranium, 24.6% by thorium, 9% by potassium) and 40% by cooling of the Earth (Pasquale et al., 2017).

The thermal properties of rocks and formation fluids and their relationship, especially the thermal conductivity of dry, water-, brine-, gas- or water-and-gas-saturated rocks, have been widely discussed by e.g., Stenz and Mackiewicz (1964), Plewa (1966), Haenel et al. (1988), Midttømme et al. (1997), Norden and Förster (2006), Szewczyk and Gientka (2009), Fuchs and Förster (2010), Pasquale et al. (2017) and Tatar et al. (2020).

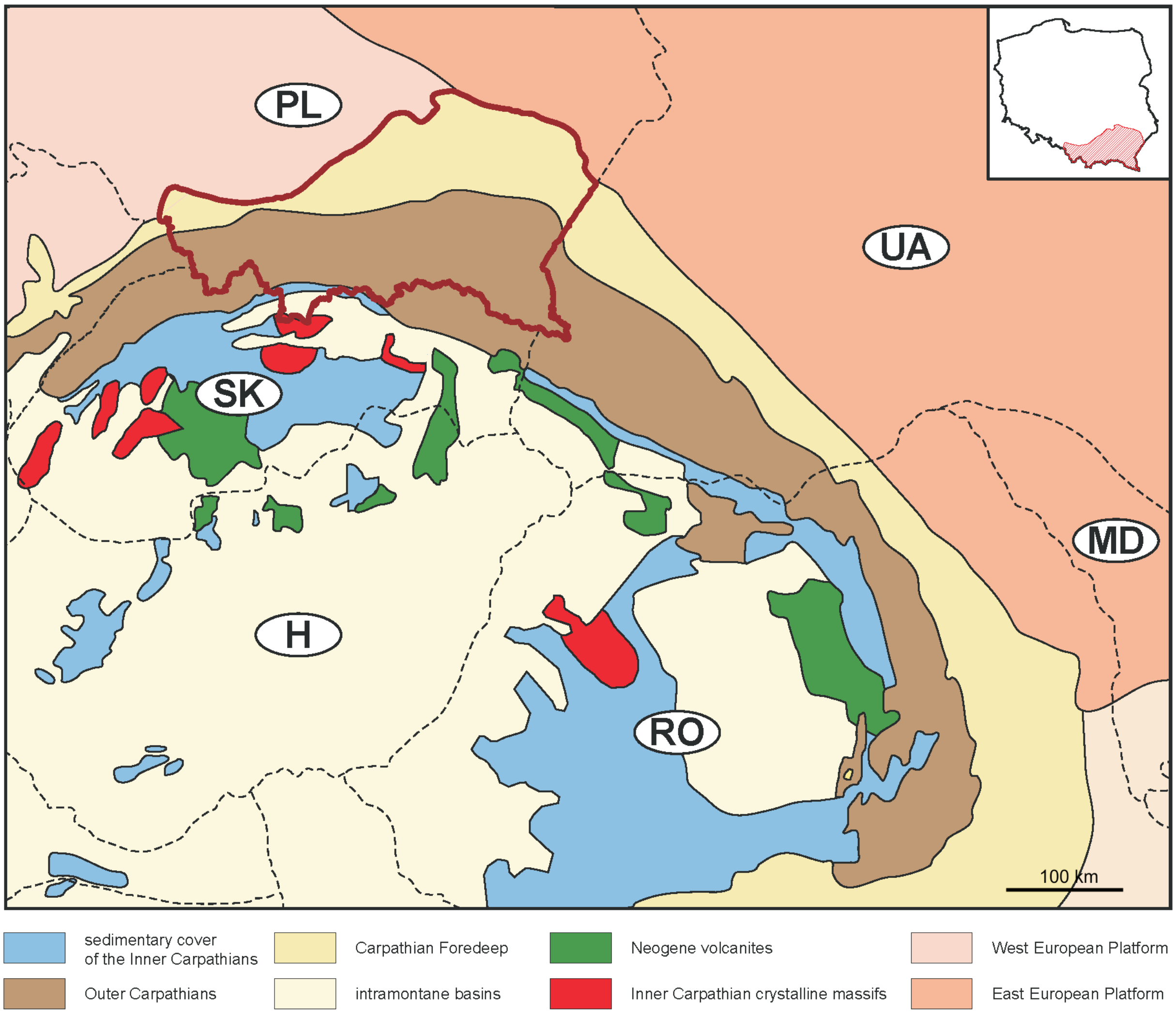


Fig. 1. Location of the study area, delineated by a thick dark brown line, on a simplified map of the Carpathian system (modified after Oszczypko et al., 2006)

THERMAL EQUILIBRIUM OF THE BOREHOLE

Despite the heat transfer from the depth to surface, the rock units remain in a state of thermal equilibrium (e.g., Kaltschmitt et al., 1999; Szewczyk, 2010; Pasquale et al., 2017; Bundschuh and Tomaszewska, 2018). Drilling operations, which take from several months up to several years, generate disturbances in this natural equilibrium. The temperature measured in the well differs significantly from the undisturbed temperature of rocks. These disturbances may vary from 5°C up to 30°C (Szewczyk, 2001, 2010; Szewczyk and Hajto, 2006; Dotsey, 2012).

The disturbance of thermal equilibrium in a borehole is expressed by cooling of its bottom part and warming of its upper part (Fig. 2). At depths close to half of the total vertical depth (TD/2), these two trends tend to neutralize each other. This phenomenon is a result of drilling mud circulation and it has been widely described in the literature (e.g., Plewa, 1966; Szewczyk and Hajto, 2006; Szewczyk and Gientka, 2009; Szewczyk, 2010; Kukkonen et al., 2011; Hajto and Szewczyk, 2012; Allis et al., 2018). In particular cases, the well data may not strictly follow this pattern as the warming-cooling effect of drilling mud circulation is influenced by weather conditions at the well site (Dotsey, 2012). Standardization of thermal logs shows that in Poland the smallest disturbances have been observed in boreholes drilled when the air temperature at a well site varied around ground surface temperature (~8°C).

An important question is how to determine if and when a borehole is in a state of thermal equilibrium, and how to assess the difference between the observed and real temperature of the rock units. From a theoretical point of view, a thermometer should be placed at the bottom of the borehole and equilibrium is reached when the temperature stops changing (increasing). Taking into consideration the symmetrical character of the drilling mud influence on thermal conditions of the borehole, the difference between the observed temperature and real temperature of rocks may be determined by a comparison between the temperature observed at the borehole annulus and the ground surface temperature (*GST*); i.e. long-term annual average temperature (Szewczyk, 2010). The *GST* values for particular well sites in Poland may be obtained from the Institute of Meteorology and Water Management (IMGW) in Warszawa or read from the appropriate map (e.g., Lorenc, 2005).

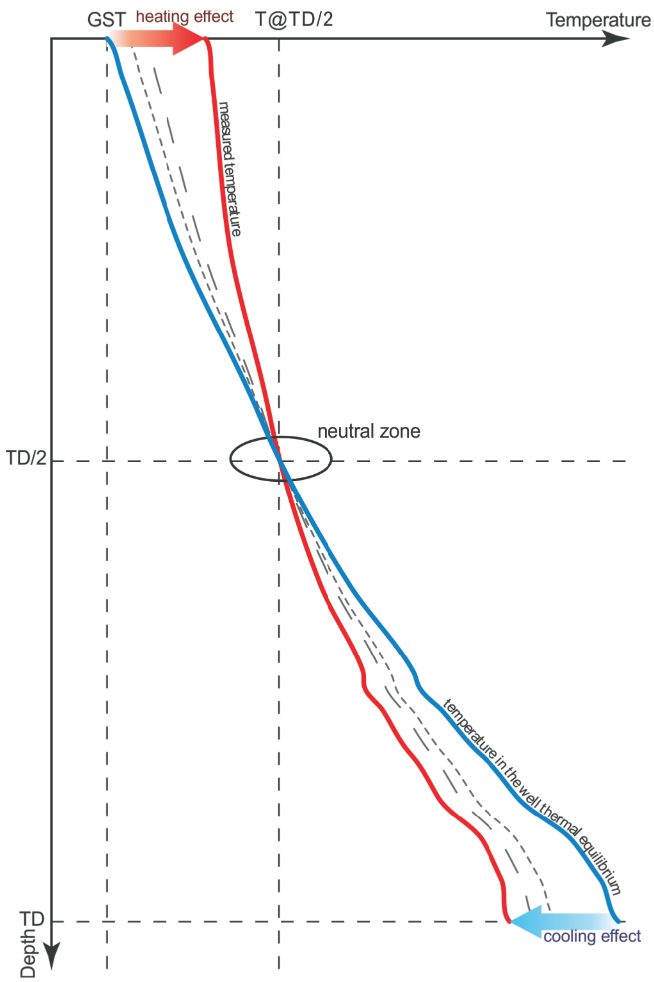


Fig. 2. The thermal equilibrium of a borehole (after Szewczyk and Hajto, 2006, modified)

See text for explanation

The question – how much time is needed to restore the thermal equilibrium of the well – has been widely disputed in the literature. Szewczyk (2010) claimed that independently of the time span from completion of drilling and thermal logging, called time since circulation (*TSC*), the temperature in a borehole will always differ from the surrounding rock temperature. Therefore, he postulated using the term 'thermal quasi-equilibrium". This opinion has a strong theoretical background, but from a practical point of view, after some period of time once mud circulation has stopped, the difference between the borehole temperature and the temperature of the surrounding rocks will be either negligible or below the accuracy of measurement tools. The *TSC* needed to restore the thermal equilibrium varies from 2 days up to 250 days and, in extreme cases, up to several years, and depends on the difference between drilling mud temperature and the temperature of the surrounding rocks, as well as on the diameter and depth of the borehole (Diakonov, 1958; Lubimova et al., 1964; Plewa, 1966, 1994; Förster, 2001). These studies show that there is no universal rule which defines a time span needed to restore the thermal equilibrium of a borehole. As a consequence, it is almost certain that the thermal equilibrium of a well is in fact quasi-equilibrium, as postulated by Szewczyk (2010). In this paper the terms thermal equilibrium or equilibrium denotes thermal quasi-equilibrium *sensu* Szewczyk (2010).

THE MEASUREMENTS USED TO RECOGNIZE THE EARTH'S THERMAL FIELD

Several types of measurement are commonly used to recognize the Earth's thermal field in boreholes or core samples. These include discrete measurements of borehole temperature, called bottom-hole temperature (*BHT*) measurements, thermal logging and measurements of formation fluid temperature made during drill-stem tests (DST), and measurements of the reservoir temperature and of the thermal conductivity of the rocks.

Measurements of rock thermal conductivity have been described e.g., by Pasquale et al. (2017). For this study, the borehole measurements of either *BHT* or thermal logging are of the greatest importance. The basic difference between these two types of measurements is that *BHT* is usually measured after a *TSC* period shorter than thermal logging and in perturbed conditions of thermal equilibrium of the borehole. The discrete measurements are made by use of thermometers which measure and store a maximum recorded temperature. It is also possible to measure a bottom-hole temperature many times during drilling of one well, e.g. separately for each depth interval drilled.

BHT measurements are regarded as a less accurate and point-specific source of information about the vertical temperature distribution in a borehole, even in the cases where the measurement is made directly above the borehole bottom. This type of measurement is always made in a zone of significant temperature disturbance (Semenova et al., 2008).

Thermal logging is usually performed after completion of the drilling, after longer *TSC*. There are several opportunities for thermal logging in particular runs during drilling. This method has been applied in many wells drilled in the Carpathians and the Carpathian Foredeep. The best example is the Kuźmina-1 (deepest in Poland) borehole, which was logged three times, twice over its entire depth interval. Very often the thermal logs are acquired after a short *TSC* for particular measurement runs, and then assembled into a composite log. Such an approach, however, might result in several problems in interpretation, which are described below.

The measurements of temperature performed in boreholes – *BHT* and thermal logs – can be affected by many errors and inaccuracies. These may result from the natural character of heat energy transport through rocks, and from measurement conditions – mostly *TSC* or technical parameters of applied measurement tools. An important factor is the accuracy and calibration of thermometers. In the logging reports attached to recent borehole reports (e.g., Wiśniewska, 2013; Sikorska-Piekut, 2015, 2016; Sowa and Sikorska-Piekut, 2015), it is stated that the thermometers used for determination of *BHT* had an accuracy of 1°C. Szewczyk (2001) points out that electric thermometers, commonly used between 1960 and 1985, at temperatures >100°C, operated at temperatures beyond their linear characteristics.

A detailed, wide-ranging analysis of errors and inaccuracies in temperature measurements in boreholes has been given by Plewa (1994). He noted insufficient calibration, unstable parameters of electric power sources, especially amperage changes as well as short-circuits, breakdowns in cables and thermometers, and inappropriate logging speeds.

Another issue relates to formation fluid temperature measurements, since it is commonly thought that their temperature reflects the formation temperature (Plewa, 1966; Szewczyk, 2001). The temperature of formation fluid may be measured using various methods: (1) measurements during DST, where the thermometer is an integral part of the testing tool, (2) measurements made by a bottom-hole thermometer during the productivity test, and (3) measurements taken during production. The reservoir temperature measurements fulfil the requirements of thermal equilibrium, especially those which were taken during productivity tests and production, when no mud circulation is taking place in a borehole. Both are long-term operations which result in long *TSC*. Moreover, unidirectional flow of formation fluids results in fluid supply from rocks unaffected by a borehole. However, the main condition in measurements of reservoir temperature is the flow of formation fluids – oil or formation water. In the case of gas flow, especially during DST, adiabatic expansion takes place, which results in cooling. In industrial conditions, a reservoir temperature measurement is usually conducted to determine the value of correction for the temperature difference between the reservoir and ground level conditions used for reserves assessment, and its accuracy is directly determined by this procedure. In the case of thick and very thick intervals tested, a precise assignment of the measured value to the particular depth may be problematic.

In considering these problems, obtaining reliable information about the real, undisturbed temperature of rock formations is difficult, because of the natural character of the Earth's thermal field as well as technical issues.

Some authors, such as Szewczyk (2010), considered that temperature logging in petroleum exploratory wells has limited scientific value. The most important weakness of such measurements is their uniqueness. The measurements cannot be repeated because the logged borehole was either abandoned and plugged or rearranged into a producing borehole.

Logging performed in thermal equilibrium is very expensive and, therefore, was discontinued in Poland in the late 1980s. Consequently, for the description of rock thermal properties, the measurements acquired by industry (mostly the petroleum industry), taken in industrial conditions, have been used. Significant increase in information about formation temperatures in Poland is rather unlikely.

BOTTOM-HOLE TEMPERATURE (*BHT*) CORRECTIONS

As stated above, *BHT* is unreliable and needs to be recalculated into the temperature at equilibrium conditions. Since this is an imprecise approach it can be described as a prediction or approximation of the formation temperature on the basis of the *BHT* measurements. In the literature several recalculation methods are described, based on experimental data and ensuing mathematical models. Below, three groups of methods are described in order to characterize their limitations and accuracies. They are: (1) simple corrections; (2) corrections based on experimental data; (3) Horner's correction and its modifications.

Simple corrections. Simple corrections were introduced to predict formation temperature in cases where only the *BHT* is known with no information about the *TSC*. There are many formulae in such corrections.

The first of these is called a Last Resort Correction, expressed as:

$$T_E = BHT + 33°F$$

or

$$T_E = BHT + 18.333°C$$

for measurements in °F and °C, respectively;

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature.

These formulae are based on the results of experiments by Corrigan (2003) that were completed for 983 pairs of corresponding DST and *BHT* measurements. Corrigan (2003) assessed the uncertainty of his method to be around 9°C.

The same author also suggested a formula termed the 10% correction:

$$T_E = f(BHT)$$

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature, *f* – correction factor.

The correction factor *f* varies from 1.1 to 1.15 depending on the author.

A less popular, but more logical, method is an application of correction only for the difference between *GST* and the temperature measured in a borehole:

$$T_E = GST + f(BHT - GST)$$

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature, *GST* – ground surface temperature, *f* – correction factor.

Oxburgh and Andrews-Speed (1981) suggested, for this type of correction, that the *f* factor is 1.15.

Taking into consideration the complex character of temperature distribution within rock formations, these corrections seem to be oversimplifications, but they may help to estimate the formation temperature when only *BHT* is available. Because of the high uncertainty level, this method may be used as a first estimation only.

Corrections based on experimental data. Corrections based on experimental data are a group of methods which may be used when both *BHT* and *TSC* are known, but these data do not meet the requirements of Horner's Correction (see next chapter) or in cases when Horner's correction gives unsatisfactory results (Corrigan, 1997).

One of these correction methods, based only on the *TSC* parameter, is expressed by the following formula:

$$T_E \quad BHT \quad a\exp \frac{TSC}{b}$$

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature, *TSC* – time since circulation in hours, *a* – an experimentally defined constant equal to 48°F, *b* – an experimentally defined constant equal to 29.6 hours.

The uncertainty of this correction depends on the *TSC* parameter and varies from 5.5–11.11°C at a *TSC* of ~10 hours to 2.7–5.5°C at a *TSC* of ~30 hours (Corrigan, 2003).

Based on downhole and DST temperatures from the Malay Basin (Malaysia), Waples and Ramly (2001) developed a method of correcting bottom-hole and log-derived temperature measurements. They introduced a correction factor which is applied to the difference between the measured temperature and the *GST*. This factor is a function of *TSC* and measurement depth. It is expressed as:

$$f \quad \frac{0.1462\ln(TSC) \quad 1.699}{0.572d^{0.075}}$$

where: *f* – the correction factor, *TSC* – *TSC* in hours, *d* – measurement depth.

They assessed the uncertainty of this equation as = 0.1421exp(–0.0317*TSC*).

Based on another dataset, from the Gulf of Mexico, Waples et al. (2004) developed a similar method of correcting *BHT* measurements. They derived an experimental equation based on three parameters: *GST*, *TSC*, and depth:

$$T_E = GST + 1.3433\exp(-0.059TSC)\,(BHT - GST) - 0.00139(d - 4498)$$

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature in °C, *TSC* – time since circulation in hours, *GST* – ground surface or sea floor temperature in °C, *d* – depth in m.

The correction strongly depends on the *TSC* and to a much lesser degree on the depth. The depth must be the total vertical depth of the borehole not a measured (driller's) depth.

Horner's correction and its modifications. Horner's correction, also called the **Horner Plot**, is the oldest *BHT* correction method, based upon mathematical models of the temperature build-up in a borehole derived by Bullard (1947) and Lachenbruch and Brewer (1959). The correction owes its name to the fact that it is identical to a formula introduced by Horner (1951) to predict reservoir pressure recovery.

In order to apply the Horner's correction, it is necessary to have a time-dependent set of at least two *BHT* measurements provided from the same borehole, at the same depth, but at a different *TSC* (Deming, 1989).

There are two forms of Horner's correction. The classic one is expressed by a logarithmic formula:

$$T_E \quad BHT \quad \frac{Q}{4 \quad k \ln\frac{TSC}{t \quad TSC}}$$

The second one is expressed by an exponential formula:

$$T_E \quad BHT \quad \frac{Q}{4 \quad k \; Ei\frac{r^2}{4sTSC} \quad Ei\frac{r^2}{4s \; TSC \quad t}}$$

where: T_E – the temperature at thermal equilibrium of the borehole, *BHT* – bottom-hole temperature, *TSC* – time since circulation in hours, *t* – drilling mud circulation time, *Q* – modified linear source strength, *r* – drilling bit radius (a half of the borehole diameter), *k* – combined drilling mud and formation thermal conductivity, *s* – average diffusivity (usually assumed as: 5 10^{-7} m^2s^{-1}).

This exponential formula, resulting from Dowdle and Cobb (1975) and Funnell et al. (1996), indicates the influence of the borehole diameter on the corrected temperature.

Both formulae include a parameter *t* (a drilling mud circulation time) that should be used in the description of measurement conditions but, unfortunately, in most cases is not available. In such a situation, it is assumed that it varies from 2 hours for shallower (<3500 m) boreholes (Waples and Ramly, 2001) to 5 hours for deeper (>4500) ones (Förster, 2001).

Horner's correction has a good reputation and is the most popular method of formation temperature prediction, although it is also criticized for some of its imperfections. The main strong point is its independence from local conditions while the most important weak point is the fact that it underestimates the formation temperature (e.g., Waples and Ramly, 2001; Förster, 2001). This underestimation varies from a few degrees up to an extreme value of 24°C (Waples and Ramly, 2001). Hermanrund (1988 in Waples and Ramly, 2001) reported an underestimation at the level of 7°C for the Norwegian Shelf, and Förster (2001) between 8 and 9°C for the Northeastern German Basin.

Basic preconditions of Horner's method application are a short, undisturbed circulation time and long *TSC*. When these preconditions are not met, both formulae, the logarithmic and the exponential, fail. Shen and Beck (1986) stated that this method is inaccurate for *TSC* shorter or equal to time of circulation. The formation temperature underestimation is reciprocally proportional to *TSC* (Beck and Balling, 1988; Förster, 2001). Waples and Ramly (2001) indicated that the required minimum *TSC* depends on the diameter of the borehole and varies from 7 to 1.6 hours for 17½" and 8½" boreholes, respectively. Corrigan (1997), based on the correlation between temperatures from DSTs and *BHT*s corrected by Horner plots, assessed the uncertainty of Horner's method at a level of 8°C.

Horner's method also fails when the difference between the *TSC* for the points used for correction is too small. In such cases, the reservoir temperature is also underestimated.

DISCUSSION OF THE APPLICATION OF CORRECTION METHODS

Several authors (e.g., Förster, 2001; Waples and Ramly, 2001; Waples et al., 2004) have suggested cross-checking Horner's correction results with other methods, and in the cases where the preconditions described in the previous chapter are not met, to replace this method with alternative ones. They suggested the use of corrections based on experimental data and formulae derived from statistical analysis. However, experimental formulae might be influenced by local conditions. In cases where an experimental formula derived from a remote basin is applied, it is strongly recommended to cross-check the computed results by several methods and to compare with local reliable information. It is also possible to define an experimental correction for an area of investigation. A precondition for this is a sufficiently large – appropriate for the statistical analysis – collection of corresponding DST and *BHT* measurement pairs, supplemented with metadata containing at least circulation time, *TSC* and measurement depth. Another precondition is a good quality of DST results as well as oil or formation water flow. DST results with gas flow must be rejected.

GEOLOGICAL SETTING

The Carpathians are part of the Alpine-Carpathian-Dinaric mountain system surrounding the Pannonian Basin. They comprise a ~270° orocline, stretching for ~1300 km from Austria through the Czech Republic, Slovakia, Poland, Ukraine, to Romania (Fig. 1). They adjoin the Eastern Alps in the west and the Balkan chains across the Danube valley (Iron Gate) in the southeast (see e.g., Golonka et al., 2006; Ślączka et al., 2006; Schmid et al., 2008; Gągała et al., 2012 for comprehensive overviews and numerous further references). The Carpathian basins opened diachronously between the Triassic and Late Jurassic as a result of break-up and rifting of the European segment of Pangaea and separation of the European and African Plates (e.g., Csontos and Vörös, 2004; Golonka et al., 2006; Schmid et al., 2008). Final emplacement of the Carpathian fold-and-thrust belt took place in the early Miocene to Pliocene (e.g., Nemčok et al., 2006a, b). The Carpathians are traditionally subdivided into the Inner and the Outer Carpathians (Fig. 1). The former was shaped during early stages of collision and comprise accreted pre-Mesozoic basement blocks and deformed and locally metamorphosed upper Permian through Cretaceous sedimentary cover; the latter are an Eocene through Pliocene fold-and-thrust belt, formed during subduction of remnant oceanic domains and final advance of the Inner Carpathians against the margin of the European Plate. During the final convergence, the Carpathians were thrust onto the European margin, causing flexure of the overridden plate and formation of a foredeep (Oszczypko, 1998; Krzywiec, 2001; Oszczypko et al., 2006). The present-day structure of the Outer Carpathians is controlled both by the initial architecture of the sedimentary basins and by the dynamics of the accretionary wedge. Within the general structure of an imbricate fan, several nappes i.e. groups of thrust sheets, were distinguished upon the basis of their stratigraphic content (see e.g., Roure et al., 1993; Roca et al., 1995; Nemčok et al., 1999, 2000, 2001, 2006a, b, c, d; Karnkowski, 1999; Behrmann et al., 2000; Oszczypko, 2004; Ślączka et al., 2005; Kuśmierek and Baran, 2016 for further details and numerous additional references).

From the north and east the Carpathians are bordered by the Carpathian Foredeep (Fig. 1) which was a large, 1300 km long and as much as 100 km wide, sedimentary basin that stretched in front of the Carpathians from Austria through Poland and Ukraine to Romania. To the west, the Carpathian Foredeep is linked with the Alpine Molasse Basin, and to the east, it passes into the Balkan foreland basin. Like other foreland basins, the Carpathian Foredeep is asymmetrical and filled with predominantly clastic deposits of Miocene age as much as 3 km thick at the Carpathian front. The molasse deposits of the Carpathian Foredeep are underlain by the basement of the European Platform, covered mainly by Permian-Mesozoic terrestrial and shelf deposits and locally by Paleogene strata. According to geophysical and borehole data, the platform basement with its Miocene molasse cover dips southwards underneath the Outer Carpathian nappes to a distance of at least 50 km. The early to middle Miocene Carpathian Foredeep developed as a peripheral foreland basin in front of the advancing Carpathian fold-and-thrust belt (see Oszczypko et al., 2006 for further details and numerous additional references).

DATA

DATA AVAILABILITY

Until the end of the 1980s when, due to high costs, exploration companies and research institutions stopped temperature logging at the state of equilibrium, ~500 logs were acquired in Poland (Szewczyk, 2010). The perturbed measurements outnumber this figure several times. In the case of the Carpathians and Carpathian Foredeep, the data set includes 22 boreholes with measurements at equilibrium and 368 boreholes with perturbed measurements.

Thermal logging has been available since the 1950s. Most of the temperature logs acquired at equilibrium were originally acquired in analog form. Newer logs have been registered digitally and are stored in LAS and/or plain ASCII numeric formats.

Analog logs, in the form of paper copies, are stored in the National Geological Archive at the Polish Geological Institute (NGA) as well as in the Central Geological Archive of the Polish Oil and Gas Company (POGC). A number of reports containing analog thermal logs have been rather poorly preserved. The digitalization process significantly improved the quality of this material, and vectorization makes the data fully operable and available for further analysis in the interpretation software. Despite the existence of some dispersed data collections, there is no central well log repository or database devoted to geothermal purposes.

DATA ACQUISITION

The data used for in this study were collected in two campaigns: (1) in the late 1990s by the Geological Bureau “Geonafta” (a subsidiary of POGC), and (2) in 2016 within the BlueGas 2 research program. During the campaign carried out in the 1990s a collection of 152 thermal logs was made. These logs were digitized, stored in the Central Geological Archive of POGC in *MS Excel* and discussed in the short accompanying text. During the 2016 campaign thermal logs from 407 boreholes located within the Carpathians and Carpathian Foredeep were collected.

DATA QUALITY

Three types of temperature measurements were considered as a source of data for the temperature distribution modeling. These were *BHT* measurements (point measurements), reservoir temperature measurements and thermal logs.

Despite the limitations described above, some *BHT* measurements were used in further data preparation process as an auxiliary data source. They proved to be useful when the thermal logs did not reach the bottom hole, or in the case of gaps in the logs. In such cases, these measurements allowed or supported data interpolation.

The reservoir temperature measurements theoretically fulfil all requirements for a high-quality source of information on formation temperature. In the early stages of the data collection process, it seemed that these would be excellent control points for the modeling.

In the area of the Carpathians and Carpathian Foredeep 185 oil and gas fields have been discovered. A significant number of these are stacked pool fields. For reserves assessment by the volumetric method there is a need to determine a correction for the difference between the reservoir and ground level temperatures. Because of this, every field report contains a reservoir temperature, and some of them contain reservoir temperatures for each pool. However, this information is not precisely depth-annotated. In cases where a reservoir is thinner than the interval in which the temperature change is measurable and unaffected by tectonics, the temperature might be assigned to the centre of the saturated interval. In other cases, especially where the reservoir rocks form steep anticlines, as is common in the Carpathians, such an assignment is impossible. Having reservoir temperatures from the field reports and thermal logs from the boreholes drilled within respective fields, an attempt has been undertaken to correlate the reservoir temperatures with the logs to obtain a depth assignment. It seems that reservoir temperature measurements are more related to the reservoir top, but this conjecture was not proven correct in enough cases

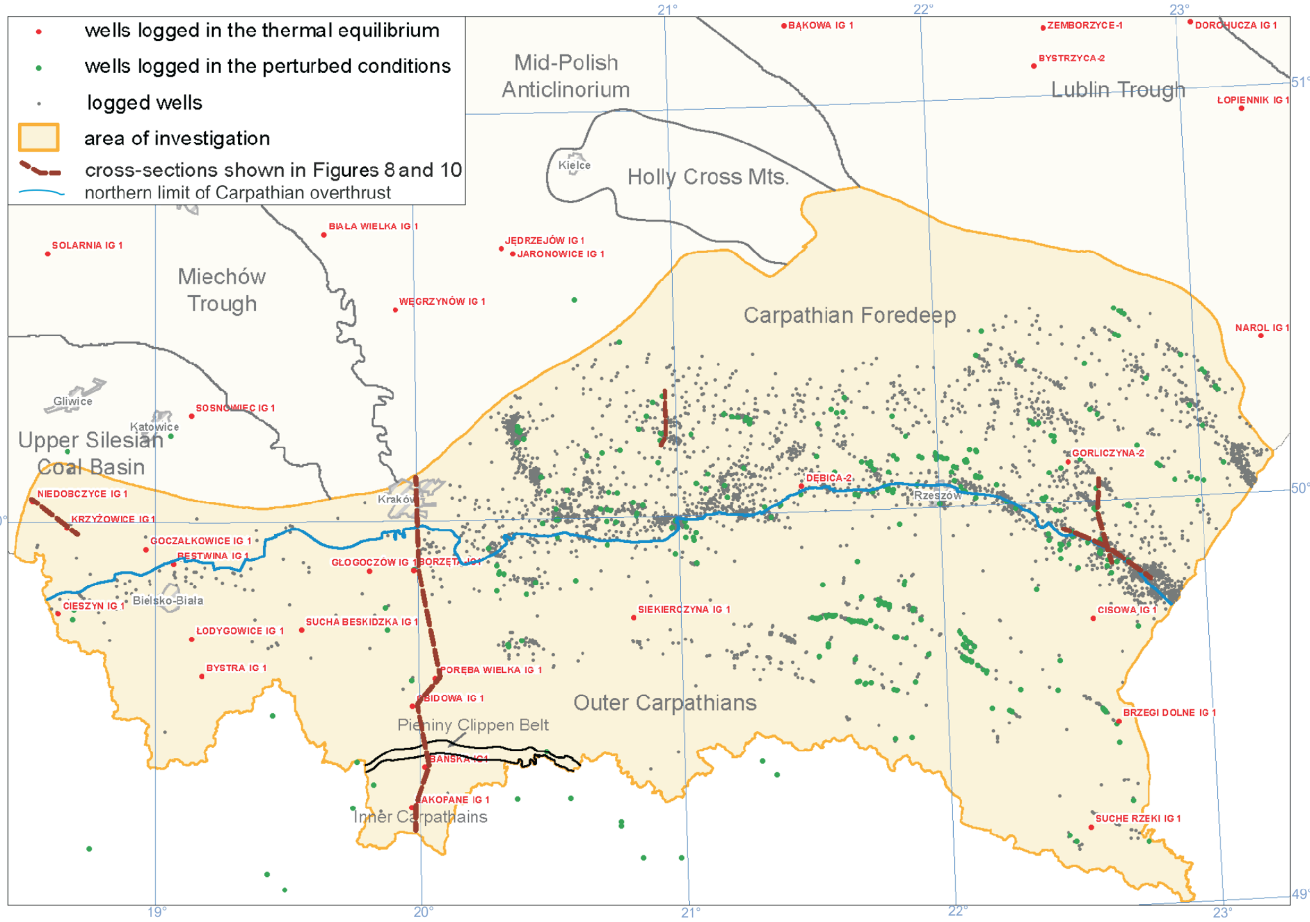


Fig. 3. Location of boreholes used in this study

to be treated as a rule. In cases where the reservoir temperature measurements might be positioned thermal logs, it is more convenient to use the logs for modelling purposes. In other cases, the reservoir temperature measurements cannot be used as control points for the temperature distribution modeling.

In this study, temperature logs from 598 boreholes were collected. Measurements from 39 boreholes had to be rejected because of technical failures. Rejected measurements were either incomplete or had too many gaps which could not be filled by interpolation. There is a number of boreholes with very short logs which did not reach a half of the total depth of the borehole. Such measurements cannot be standardized according to the method described below. The final category of rejected logs was those which included a comment that the logging was provided in order to control casing cementation.

Consequently, measurements from 538 boreholes were selected for this study, of which 388 are located in the Carpathians and Carpathian Foredeep (Fig. 3). The remaining 150 boreholes are located in close proximity to the study area within the Upper Silesian Coal Basin, the Miechów Trough, the Holy Cross Mountains and the Lublin Trough, and control data distribution from the north.

In this study, the thermal logs were divided into two groups depending on the presence or absence of information about the measurement conditions. Only those logs which have appropriate information, either in the LAS header or in the form of descriptions attached to the dataset, can be treated as acquired at well thermal equilibrium. The other measurements must be treated as perturbed.

QUALITY OF DIGITAL DATA

The logs used in this study are of very different quality. Almost all measurements acquired in the state of equilibrium were originally recorded in analog mode and then digitized. All digitized logs are stored as composites which means that all runs are combined together and properly correlated within the overlaps, in LAS version 1.2. They have a precise location and a vertical resolution of 25 m. The LAS headers unfortunately contain almost no metadata, making interpretation and quality control complicated, but the collection has a short textual comment, which contains information on the borehole equilibrium conditions for all measurements.

The measurements classified as made in perturbed conditions were originally stored in analog as well as in digital forms. The older, analog digitized by POGC are stored as LAS version 1.2 files with a vertical resolution of 30 cm. Similarly, they have a small amount of information in file headers. The newer data, acquired and stored originally in digital form, have been recorded as LAS versions 1.2 and 2.0 with vertical resolution varying from 10 to 30 cm. In this group, the file headers contain some metadata, but are in many cases incomplete. In the case of temperature measurements, the most important failure is a lack of information about the *TSC* and/or no indication on equilibrium conditions. Scarcely any of the logs contain information about the drilling mud circulation time.

The overall quality of digital data should be assessed as moderate, due to a lack or incompleteness of metadata, and gaps between runs or selected logging. The strong point of the data used in this study is the existence of boreholes where thermal logging was performed at borehole equilibrium.

METHODS

INITIAL DATA ANALYSIS

Initial data analysis was performed by simple visual assessment of the data set acquired as a result of many decades of exploration activity, in order to find any patterns, or correlations between temperature changes and stratigraphy.

The next step involved several attempts to derive non-linear functions which satisfactorily approximate thermal logs: (1) for the entire collection, (2) for each log and (3) for arbitrarily defined group of boreholes, e.g. characterized by close proximity.

DATA PREPROCESSING

The dataset was a mixture of continuous logs and discrete point measurements (*BHT*) stored as particular runs and composites in numerous files in different numeric formats. Most of the data were acquired in perturbed conditions.

Therefore, the data preprocessing was executed in two main stages: (1) technical editing, and (2) standardization to a state of quasi-equilibrium.

TECHNICAL EDITING

Almost all thermal logs belonging to the group acquired in perturbed conditions needed some technical editing. Technical assumptions for the parametric modelling process required one log per one modelled parameter for each borehole. A consequence of this assumption was the preparation of composite logs for each borehole. Some boreholes were logged several times. Usually the longest uninterrupted and latest log was selected for further processing. Taking into consideration the physical character of vertical temperature changes and possible limitations of the modelling software, the thermal logs with a vertical resolution smaller than 5 m were resampled. Such data resampling does not eliminate local changes of the parameter analysed but reduces the size of the input dataset (in this case by 95%) and increases the modelling speed.

STANDARDIZATION TO A STATE OF QUASI-EQUILIBRIUM

The dataset used for modelling consisted of logs and point measurements acquired under different technical and weather conditions, in thermal equilibrium as well as in perturbed conditions. To make the data comparable, a standardization process was needed. Taking into consideration the discussion on the *BHT* correction methods, their limitations and uncertainties as well as the character and quality of the dataset collected, especially a lack of metadata describing measurement conditions, it was decided to use a standardization or a formation temperature prediction method based on the phenomenon of borehole thermal equilibrium.

The method described below is based on Kukkonen's (2011) experiment, repeated by Allis et al. (2018). The maximum difference between the temperature in a state of thermal equilibrium and the temperature during logging operations is expressed as the difference between the temperatures observed at the wellhead and *GST*. It is also assumed that the influence of drilling mud circulation is entirely reduced at a half of the total vertical depth of a borehole.

Based on these assumptions, a linear correction which allows the recalculation of the observed temperature to the temperature in a state of thermal quasi-equilibrium (formation temperature) might be introduced.

Let the temperature observed in a borehole be described by the function:

$$T = f(d)$$

where: T – temperature observed in the borehole, d – depth.

The temperature in a state of equilibrium is described by the function:

$$T_E \quad g(d) \quad f(d) \quad (T_0 \quad GST)\frac{d \quad D_0}{D_0}$$

where: T_E – temperature at equilibrium, d – depth, T_0 – temperature measured at the borehole annulus, GST – ground surface temperature at the well site, D_0 – reference point or equilibrium point

by the assumption that:

$$g(0) = GST$$

the correction is a linear function of the depth.

The correction transforms the measured thermal log when it is possible to determine a temperature at the depth of equilibrium (Fig. 4A). When it is not possible to define a temperature at the depth of equilibrium but it is possible to define the *BHT* with the application of Horner's or another method, the reference point (D_0) may be located at the bottom of the borehole, as shown in Figure 4B.

This method of standardization, or correction of temperature logs to the quasi-equilibrium conditions will be termed hereafter the Kukkonen-Szewczyk method or equilibrium method.

It was impossible to apply Horner's method as well as to define an experimental correction for borehole data available from the study area. Moreover, for the data from the Carpathian Foredeep most of the drill-stem tests had to be rejected due to gas flow.

The standardization of well logs was achieved by means of the Kukkonen-Szewczyk method. The ground surface temperatures at a particular well site were determined based on the digital version of the *GST* map of Poland (Lorenc, 2005). In most cases, the standardization was a routine operation except for some logs, which contained evident technical errors (e.g., anomalously high values) that were corrected manually. The logs that did not reach a half of the total depth of a borehole were rejected. However, some of the boreholes with incomplete thermal logs were of crucial importance for the modeling, e.g. because of a lack of other reliable data sources.

The Kukkonen-Szewczyk method, as with other formation temperature prediction methods, has its limitations and weak points. The assumption that the influence of drilling mud circulation is eliminated at a half of the total depth of a borehole is a theoretical assumption only and might be treated as a simplification. In real conditions, this equilibrium point (a pivot point), might be located at a depth different than a half of the total depth (Förster, 2001). Several authors have suggested that this

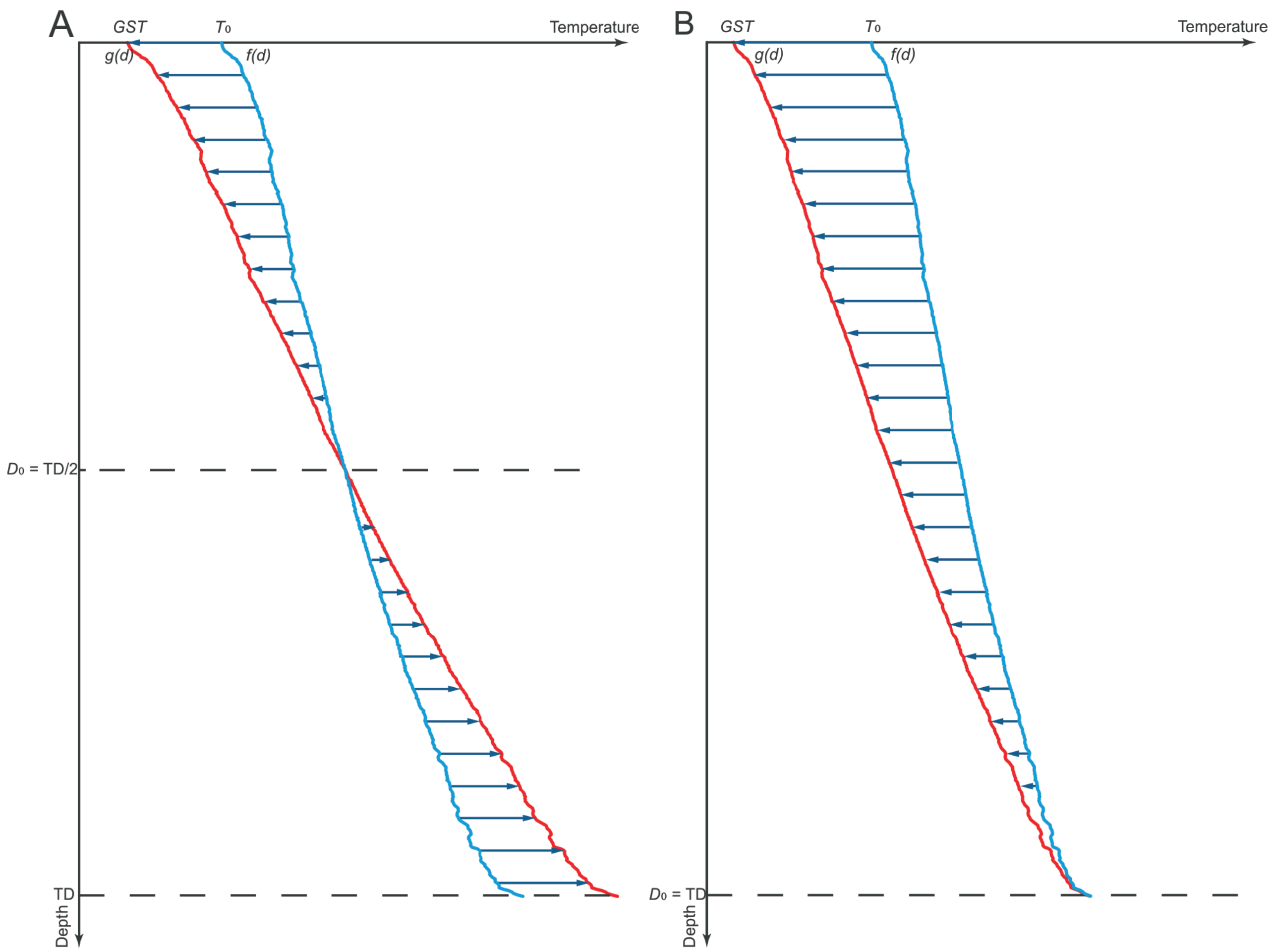


Fig. 4. The Kukkonen-Szewczyk or equilibrium method of thermal well log correction

See text for explanation

point might be located slightly above the theoretical assumption (e.g., Kukkonen et al., 1998, 2011; Förster, 2001; Szewczyk, 2010; Allis et al., 2018). The strength of the Kukkonen-Szewczyk method is related to the fact that it is independent of local conditions and it may be applied when information about *TSC*, circulation time or borehole diameter is unavailable.

THERMAL GRADIENT LOG COMPUTATION

Thermal gradient logs were computed after the completion of the temperature log standardization process. In each borehole, for each pair of neighboring points representing the temperature at a certain depth, an interval thickness (*d*) and a temperature difference (T_2-T_1) were calculated. The thermal gradient (*T*) is a quotient of temperature difference and interval thickness. The thermal gradient expressed in K/100 m was assigned to a point representing the middle of the interval. The curve (polyline) connecting each point representing the value of thermal gradient in the middle of the corresponding interval creates a thermal gradient log.

MODELING

Modelling was completed using one of the most popular interpretation and modelling software packages in the petroleum industry for the construction of parametric models of hydrocarbon accumulations. The parametric model should be understood here as a 3D static model of spatial distribution of attribute(s). The application mentioned above follows the principles of the finite element method (FEM) and shows the results as a 3D grid consisting of cuboids or cubes (voxels) (Zakrevsky, 2011; Wygrala, 2014; Ringrose and Bentley, 2015; Papiernik and Michna, 2019 and references therein). In the case described here, the 3D grid has been populated with the application of a deterministic method – a kriging algorithm, preceded by a semivariogram analysis. All computed values >160°C have been automatically rejected, because modelling below this surface would be extrapolation only. The modelling process was divided into several stages, which are characterized below.

The initial data loading consecutively comprised borehole headers, borehole trajectories and "thermostratigraphy" – a set of control points representing the position of each modelled isotherm surface in each borehole. Finally, thermal logs were loaded providing standardized temperature measurements and thermal gradients. The latter were used for construction of the model's structural framework.

Parametric modelling of temperature changes as well as of thermal gradient should be carried out within a structural framework i.e. a set of surfaces, which defines the constraints preventing uncontrolled interpolation. In the case of rock thermal parameters, a natural constraint is the ground level. The bottom of the structural framework was defined arbitrarily. Other surfaces have been defined by the interpreter as a series of

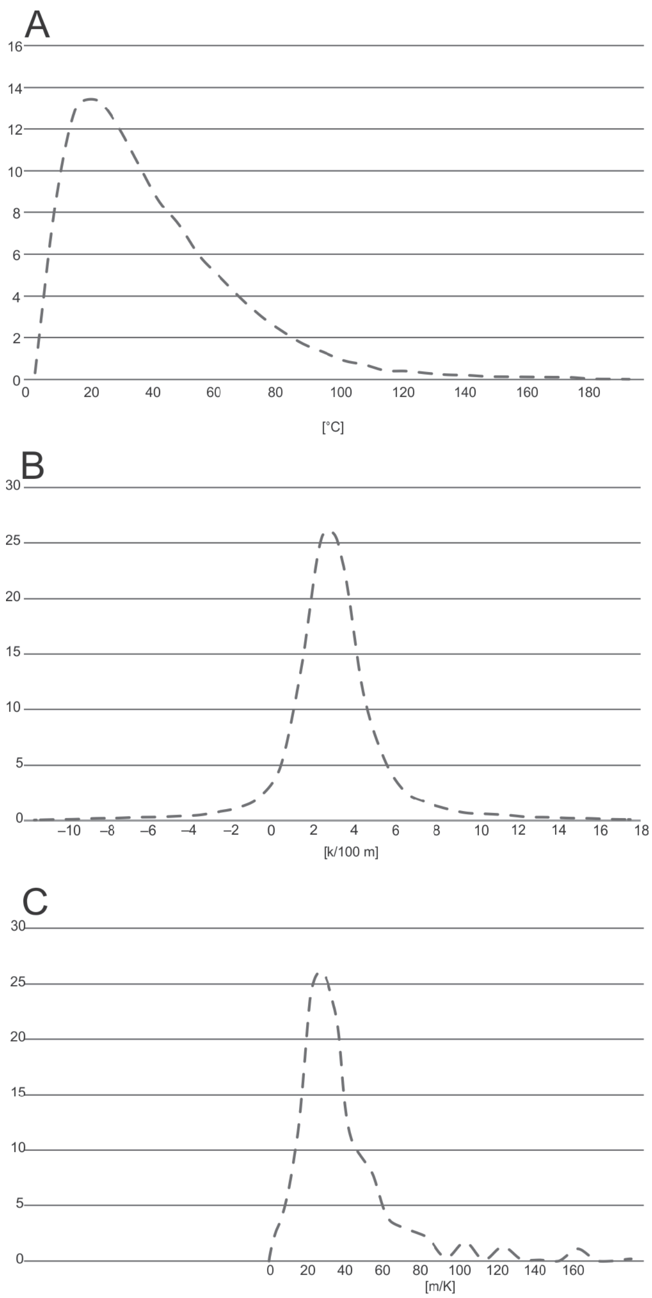


Fig. 5. The statistical distribution of: A – temperature, B – thermal gradient in K/100 m, C – thermal gradient in m/K

isobath maps representing isotherms starting from 10°C up to 160°C with increments of 10°C. These maps were compiled from maps of temperature distribution published by Górecki et al. (2006a, b, 2011, 2012, 2013) and control points derived from thermal logs.

In order to compute a detailed parametric model and to reflect the vertical distribution of modelled parameters, the structural framework is usually divided into smaller parts. In this case, each zone between the 10 and 160°C isotherms was proportionally layered into 10 parts. The part of the model between the 10°C isotherm and ground level was not subdivided.

The next step was a 1D modelling process, called upscaling, completed along each borehole. This process averages the log-derived values within the previously defined layers. This average value is assigned to the whole layer. The upscaled log, in contrast to the measured one that is characterized by a continuous or quasi-continuous distribution, has a discrete distribution. Based on the theory by Goncharov (1954) and because of a normal distribution (Fig. 5) of temperature and thermal gradient, an arithmetic averaging method was selected. The upscaled logs were compared to original measurements on the plots, histograms and cross-checked by analysis of statistical distribution parameters. Extreme high and low values have been rejected, because they did not match the physical qualitative characteristics of the modelled parameters. The temperature has to be within the interval between 5 and 160°C. The first limit is defined by the distribution of *GST* observed in Poland (Lorenc, 2005), whereas the second was defined arbitrarily by the initial assumptions. Thermal gradient does not reveal such noticeable cut-offs. The identification of anomalously high or low values was arbitrarily made after analysis of the distribution histograms. The latter was based on the fact that thermal gradient has a narrow normal distribution. Two solutions were analysed: the average plus/minus one standard deviation, and the average plus/minus a half of the standard deviation. An advantage of the second option was the shape of the distribution curve, while the first option was favored by the narrow limits that may eliminate local anomalies. After consideration, the first option was eventually selected.

The construction of parametric models comes down to filling the structural framework with the parameters derived from the well logs.

RESULTS

RESULTS OF INITIAL ANALYSIS

An initial visual assessment of the thermal curves did not show any clear patterns and in general a very poor correlation of temperature curves with stratigraphy. The first attempt, examining if there is a regression equation common for the whole data set, failed because the correlation coefficient was significantly below 1/ 2(0.707), which is the limit used in natural sciences (Żuk, 1989). The second effort was to compute a regression equation with the highest possible correlation coefficient (>0.95) for each log and compare the formulae among groups of boreholes related to particular areas. This operation resulted in sets of equations of different types: linear, exponential, logarithmic as well as polynomial of different orders. It was impossible to find any similarities. Even very closely located boreholes yielded completely different equations.

A similar experiment has been described by Plewa (1966), who computed regression curves for several boreholes. He also developed different regression equations – linear and power formulae. The results of both experiments, by Plewa (1966) and those described in this paper, show that the temperature changes vertically in a very irregular mode. It is impossible to define intervals having a stable thermal gradient related, for instance, to stratigraphy. It seems that vertical temperature changes are determined by a combination of local conditions and their interferences; mostly by lithology, facies changes, water saturation and circulation conditions, as well as structural style.

A similar conclusion was made by Dotsey (2012), who modelled formation temperatures of the Delaware Basin in Texas and New Mexico. He proposed that every lithostratigraphic formation can be characterized by a parameter called an interval thermal gradient, which depends on depth and lithology. This statement is obviously true, but it assumes a lithological homo-

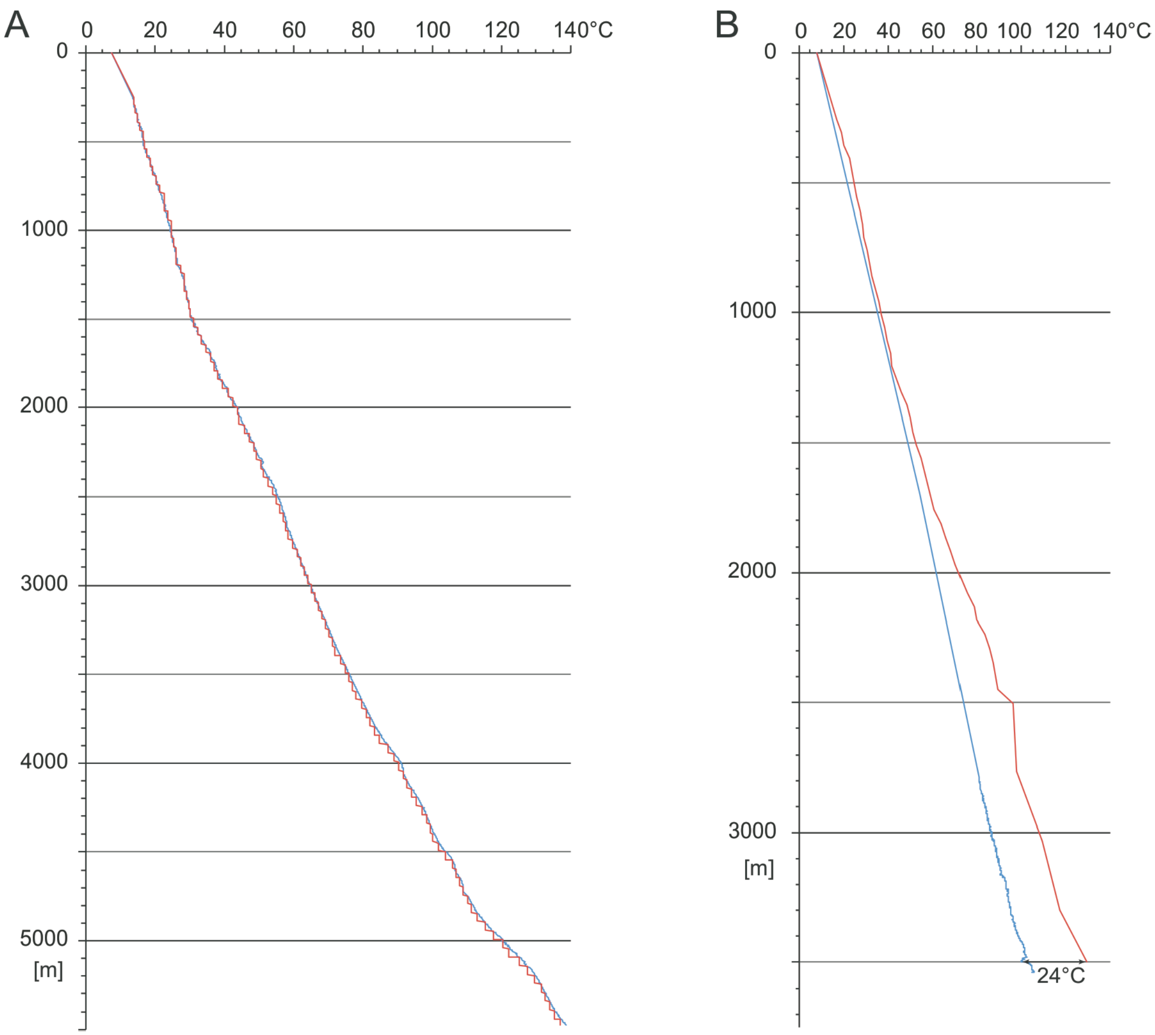


Fig. 6. Modeled temperature (red) *versus* measured temperature (blue)

A – D-1 borehole (Carpathians) upscaled temperature log essentially follows the measured one – the model is properly borehole-tied; **B** – T-2K borehole (Carpathians) drilled after model completion, shows overestimation of predicted temperature; see text for explanation

geneity of particular formations. It seems that such an assumption leads to some simplifications and should not be generally applied in the areas like the Carpathians and Carpathian Foredeep, especially for intercalated formations.

From the above, it seems that the only reliable method of describing formation temperature and thermal gradient changes is the construction of a three-dimensional parametric model based on thermal logs.

QUALITY AND ACCURACY OF THE MODEL

The first-order control was the comparison of synthetic logs made from the model and real thermal logs. This control was possible only along the boreholes studied. The statistical analysis of differences between synthetic and measured logs, completed for the entire population, indicates an average difference at a level of 1°C with a standard deviation of 0.5°C (Fig. 6). In the case of the D-1 borehole (Carpathians), illustrated in Figure 6A, the discrepancy varies from –0.94 to 2.40°C. These values correspond to the accuracy of the industrial thermal logging (see Wiśniewska, 2013; Sikorska-Piekut, 2015, 2016; Sowa and Sikorska-Piekut, 2015). This error or inaccuracy is a result of averaging during the upscaling process. The match described above indicates that the model is borehole-tied to the measured data. Another control was a comparison between synthetic logs derived from the model and thermal logs measured after construction of the model. This was done for two boreholes: K-1 (eastern part of Carpathian Foredeep) and T-2K (Carpathians), drilled by POGC. In the first case, the predicted temperature at the bottom hole was 130°C and the measured one was 118°C, a 10% overestimate. In the second case, the synthetic thermal log derived from the model follows the measured one in the upper half of the borehole (~1250 m), but in the lower one shows an overestimate from several degrees up to an extreme value of 24°C, which amounts to a ~19% overestimate (Fig. 6B). The difference between these two cases is caused by the distance to the nearest measurement points. The first borehole is located close to other ones, but the second one is more distant from the nearest logged borehole, and moreover is a deviated well.

Taking into consideration the regional character of the model as well as a rather sparse and irregular spatial distribution of the input data, this level of inaccuracy is acceptable. It seems that the main reason for overestimation of temperature is the spatial distribution of the data, especially where neighboring boreholes are more distant and logging took place in different intervals.

MODEL DESCRIPTION

The modelling process results in three-dimensional models of temperature (Fig. 7A) and thermal gradient (Fig. 7B, C) expressed in K/100 m and in m/K. The models have the form of 3D grids composed of rectangular voxels with horizontal spacing 500 by 500 metres and vertical spacing of 50 metres, referenced to the mean sea level and official Polish geodetic reference system PL-1992. The first model illustrates the temperature distribution between the ground level and the isotherm of 160°C and it is coloured from blue to red in increments of 10°C (as in Fig. 7A) The thermal structure of the study area seems to be of a generally layer-cake type and monotonous. Particular isotherms are in general parallel to the ground level. This similarity is more significant at the top than towards the bottom. In the bottom part of the model, the isotherms become more similar to the shape of 160°C isotherm. When analyzing the spacing between particular isotherms some positive as well as negative thermal anomalies may be observed that are expressed by a decrease or increase of the vertical spacing between the isotherms, respectively (Fig. 9A – left part between the Zakopane IG 1 and Bańska IG 1 boreholes).

The numeric 3D parametric model can be also visualized on maps of the average value of the modelled parameter computed for the entire volume as well as for some defined intervals. The examples of cartographic visualization of the modelling results are shown in Figure 8, which includes maps of the average thermal gradient in K/100 m (Fig. 8A), the average thermal gradient in m/K (Fig. 8B), the structural depth map of the 100°C isotherm (Fig. 8C) and the temperature distribution at the base of the Carpathians (Fig. 8D).

Another type of three-dimensional model visualization takes the form of cross-sections. The section (Fig. 9) passing from Zakopane to Kraków is an example. The cross-section is divided into two parts: A and B, which depict the distribution of temperature and thermal gradient, respectively. Generally, in the cross-section described here, the temperature distribution (Fig. 9A) does not show extreme anomalies. The part of the section illustrating the thermal gradient distribution (Fig. 9B) is characterized by a generally high level of variability.

NEW THERMAL ANOMALIES

Modelling in 3D space allowed the recognition of several new positive thermal anomalies in the eastern and north-eastern parts of the area investigated (arrowed red in Fig. 8A). These newly mapped anomalies, as well as a number of previously known ones, correlate with gas accumulations (Fig. 10).

DISCUSSION

MODELLING RESULTS IN COMPARISON TO PREVIOUS STUDIES

The comparison of results of this and previous studies is very difficult, or in some cases even impossible. Previous authors (e.g., Plewa, 1966; Majorowicz, 1971; Szewczyk, 2010; Górecki et al., 2011, 2012, 2013; Hajto, 2012) have used two-dimensional or two and half-dimensional modelling techniques only. Some maps were published 45 or 50 years ago and, thus, were based on a relatively limited set of borehole data (Figs. 11 and 12). A considerable amount of measurement data remains the exclusive property of POGC and is unavailable for researchers from outside the Company (cf. Figs. 3, 11A and 12A). The broader data set and the first attempt in Poland to model the thermal parameters of the formation rocks in three-dimensional space have allowed the identification of some, previously unknown, positive anomalies within the Carpathian Foredeep (red arrows in Fig. 8A).

THERMAL PROPERTY CHANGES

The increase in temperature of the shallower part of the interval investigated reflects the morphology of the ground surface. In deeper intervals this correlation fades completely.

The variability of the terrestrial thermal field is much better characterized by changes in thermal gradient. This parameter is sensitive and indicates relatively small changes of temperature, indistinguishable on maps or cross-sections that show temperature distribution. Comparison between maps showing the average thermal gradient for the entire depth interval analysed (Fig. 8A) and four 1000 m thick intervals starting at ground level is particularly interesting (Fig. 13). All five maps show a general similarity in the distribution of the main positive and negative anomalies. However, they differ in detail. The newly mapped positive anomalies are accentuated in the first two intervals (Fig. 13A, B), but fade in the two deeper ones (Fig. 13C, D). Comparing the maps shown in Figure 13, they clear differ significantly in amplitude. The amplitudes increase in the second interval (1000–2000 m, Fig. 13B), and systematically diminish downwards. A noticeable tendency towards the average value (~3.12 K/100 m colored in shades of yellow) is observed in the same direction. Strong positive anomalies within the Upper Silesian Coal Basin (western part of the area analysed, NW of Bielsko-Biała), reaching up to 4.5 K/100 m, (Karwasiecka, 2001, 2008; Górecki et al., 2006a, b; Szewczyk, 2010) or a series of positive anomalies within the Carpathian Foredeep located at the front of the Carpathians, can be easily observed in each interval shown. Analysis of parallel cross-sections led to the inference that the thermal anomalies mapped are caused rather by thick layers that are characterized by an increased thermal gradient. In several places, interference of numerous layers of this type is observed (Fig. 14).

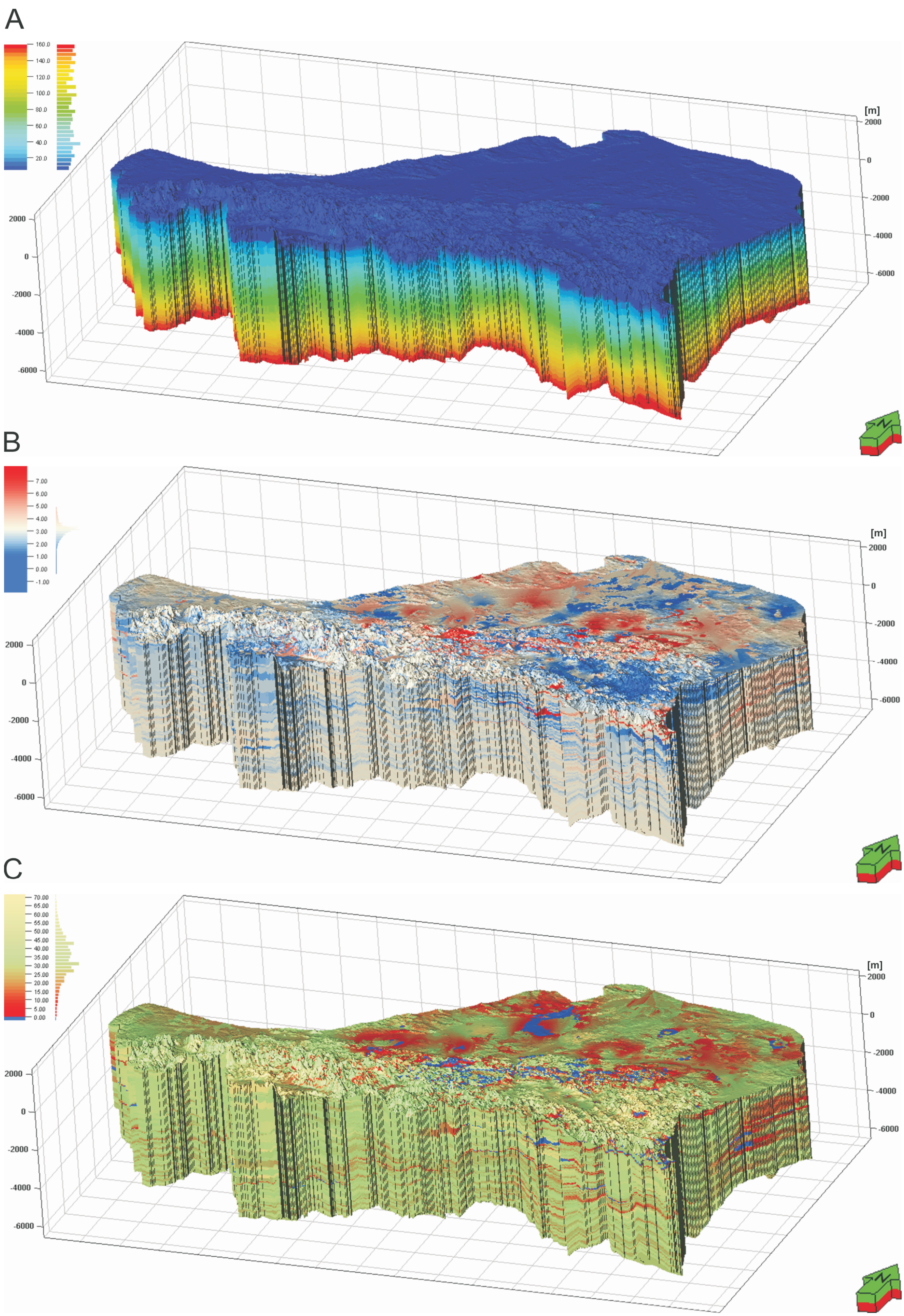
The maps as well as cross-sections do not reflect the structural pattern of the area analysed. Application of a different set of constraints, reflecting the complex internal structure of the Carpathian nappes, will result in a different pattern of thermal parameter changes.

THERMAL PROPERTIES *VERSUS* LITHOLOGY

As discussed in the literature (e.g., Plewa, 1966; Midttømme et al., 1997; Norden and Förster, 2006; Pasquale et al., 2017), the thermal gradient reflects the thermal conductivity of the rock – formation fluids association. A thermal gradient log can precisely indicate the boundaries between highly conduc-

Fig. 7. Three-dimensional parametric model of the distribution

A – temperature, **B** – thermal gradient in K/100 m, **C** – thermal gradient in m/K, within the Polish Carpathians and the Carpathian Foredeep; vertical scale 10 times exaggerated


A
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
[m]
2000
0
-2000
-4000
-6000
B
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
C
70.00
65.00
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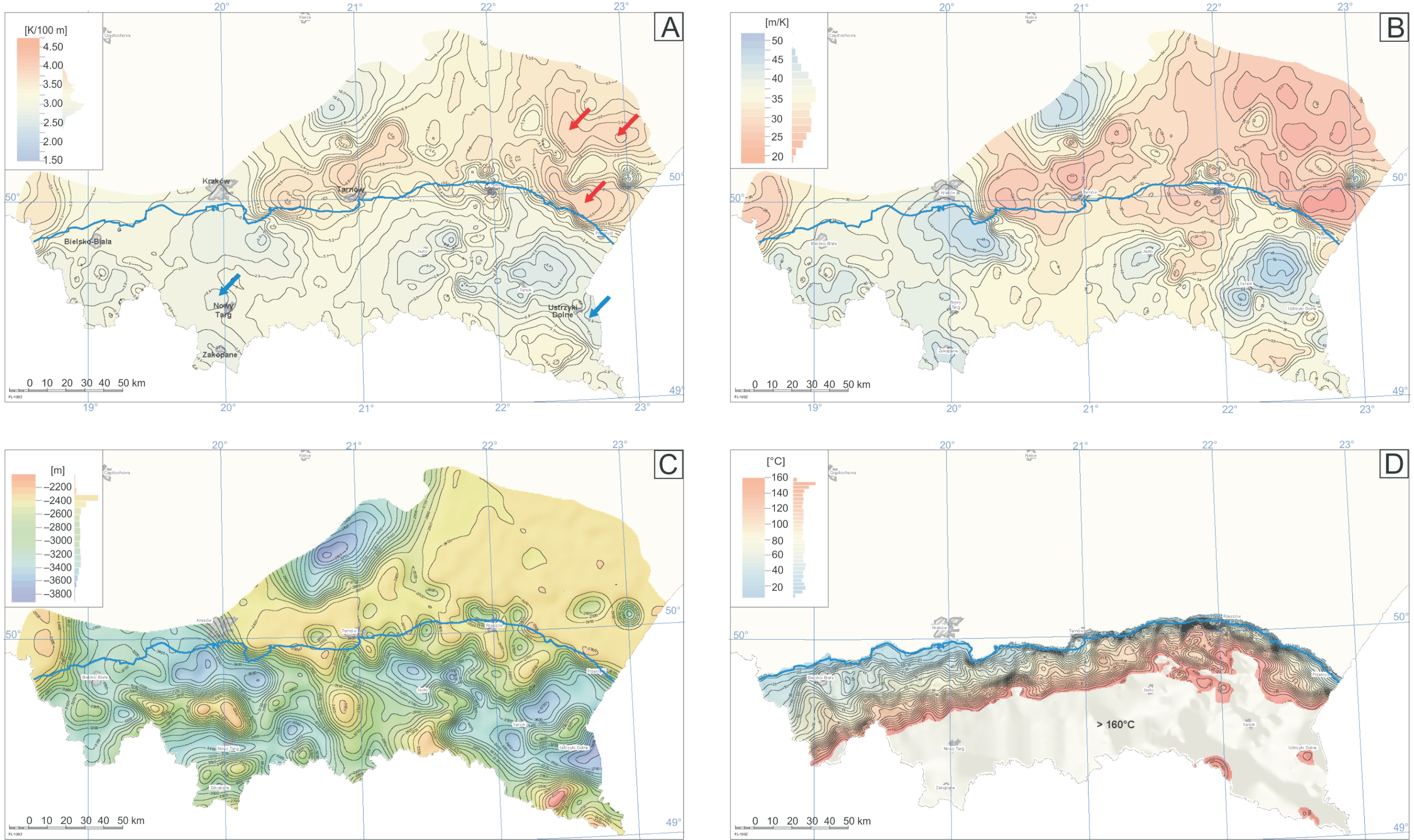

Fig. 8. Maps of the distribution

A – the average thermal gradient in K/100 m; **B** – the average thermal gradient in m/K, **C** – the structural depth map of the 100°C isotherm, **D** – the temperature distribution at the base of the Carpathian overthrust; all maps computed from the three-dimensional model; structural map of the base of the Carpathian overthrust after Papiernik (2012)

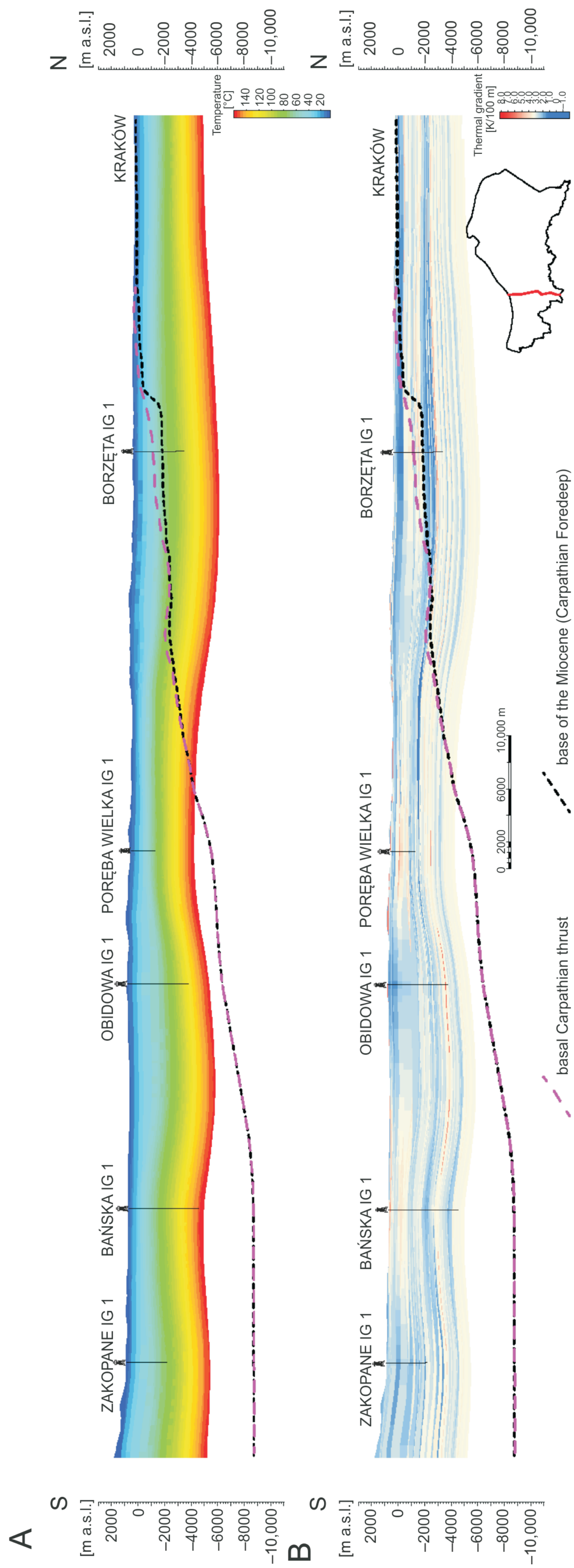

Fig. 9. N–S oriented geothermal cross-section through the Zakopane IG 1, Bańska IG 1, Obidowa IG 1, Poręba Wielka IG 1, Borzęta IG 1 boreholes and towards the city of Kraków: A – temperature distribution, B – thermal gradient distribution

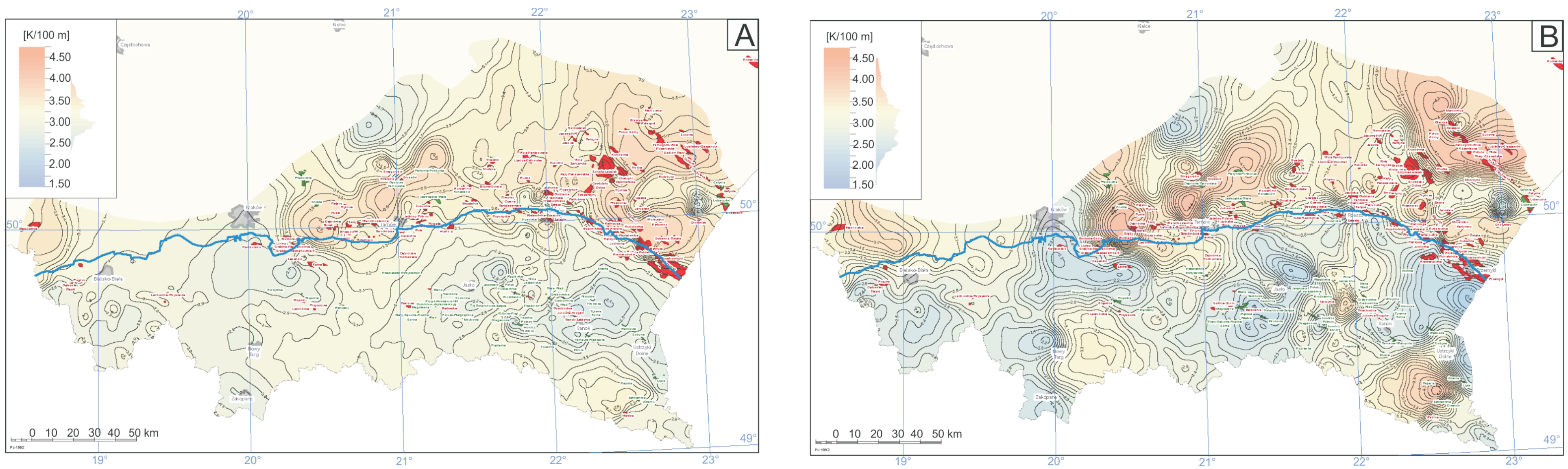

Fig. 10. Map of hydrocarbon accumulations on the base of: A – map of the average thermal gradient, B – map of the interval thermal gradient computed for the first 1000 m b.g.l.

Oil fields – marked green; gas fields – marked red; cf. Figure 10A–C

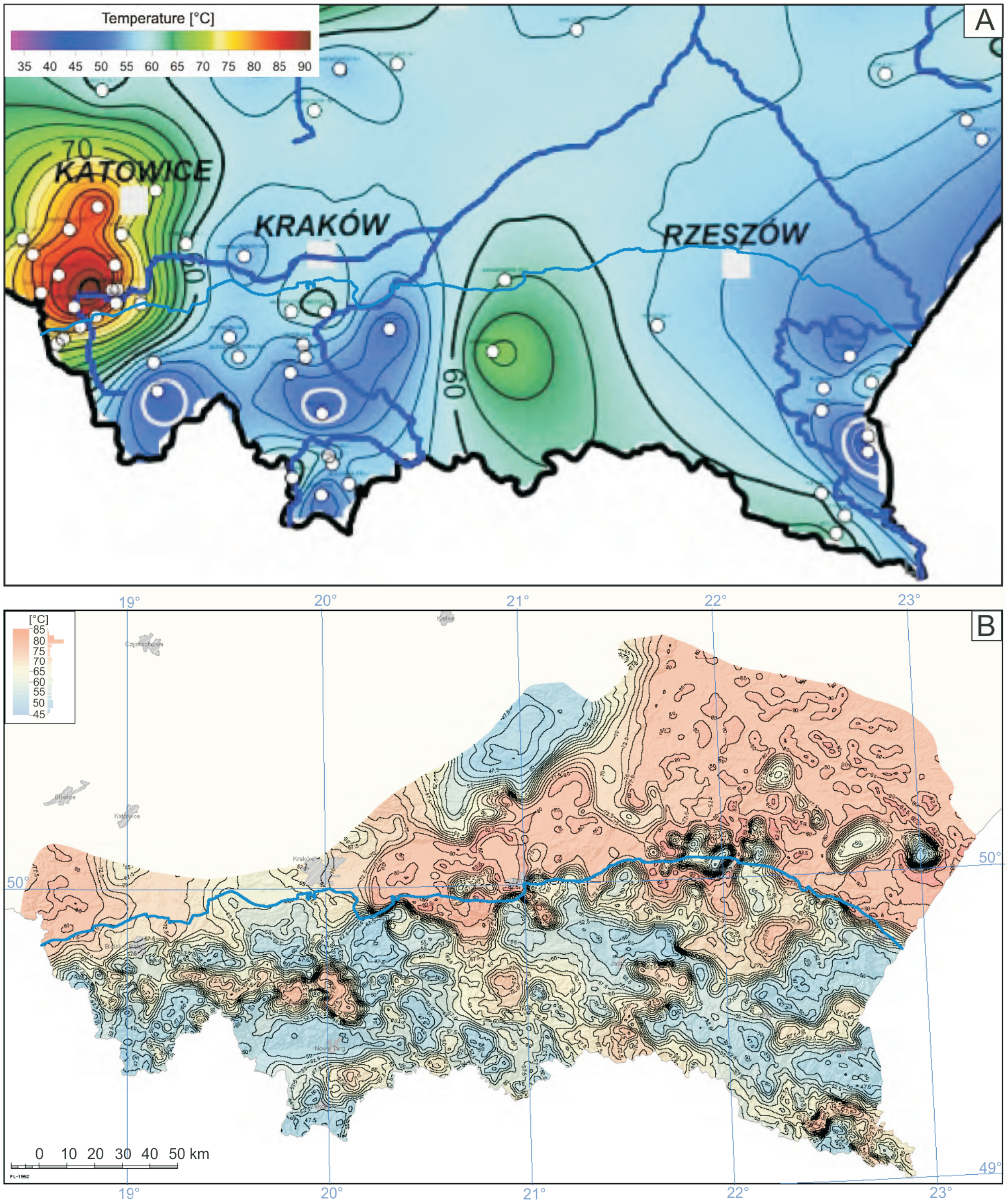

Fig. 11. Maps of the temperature at 2000 m b.g.l. A – after Szewczyk (2009), white dots – boreholes used for map construction (cf. Fig. 3); B – derived from the model described in this paper

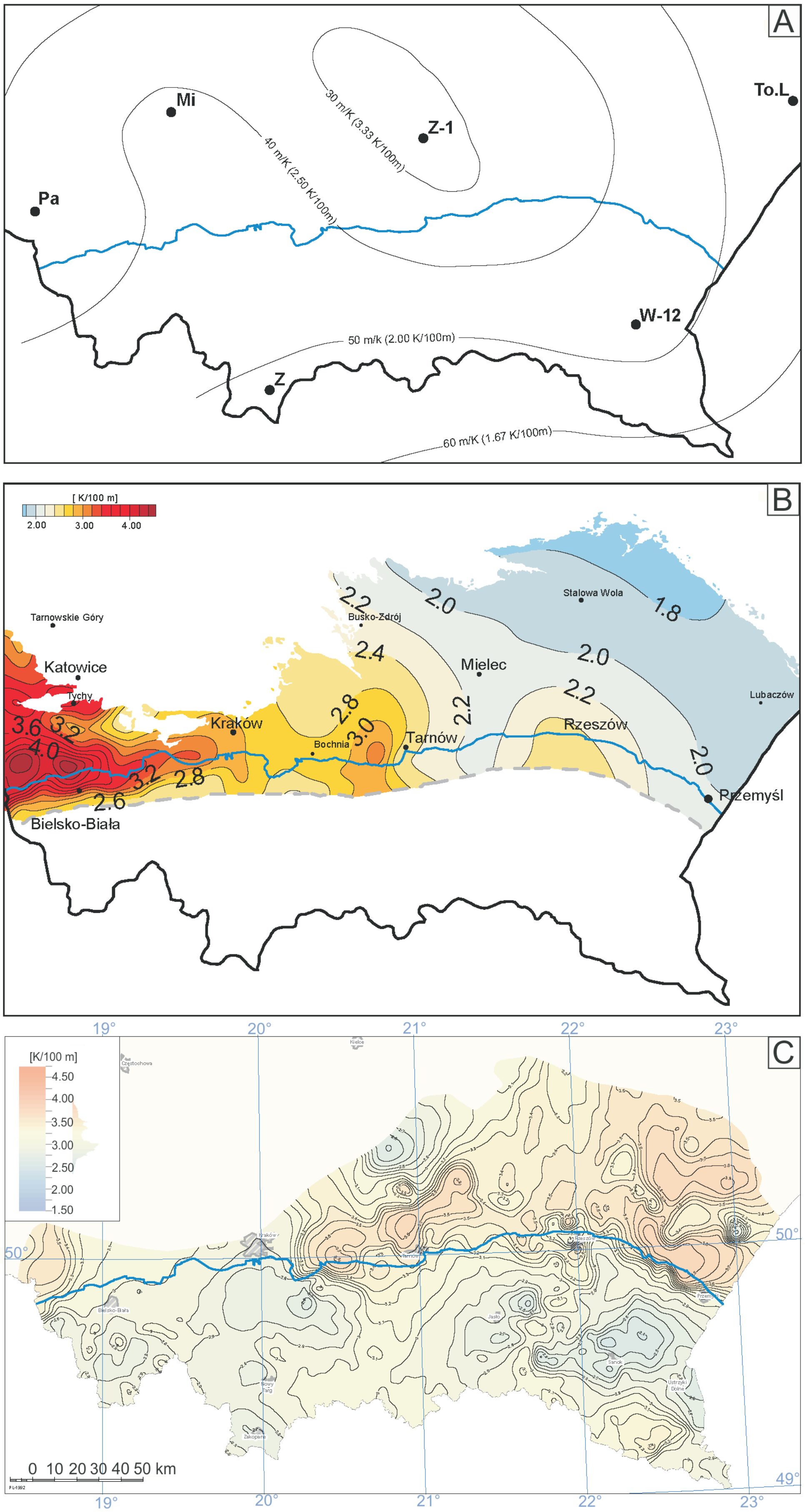

Fig. 12. Maps of average geothermal gradient derived from the model (C) *versus* maps of previous authors: A – redrawn part of Majorowicz's (1971) map of average thermal gradient in Poland originally scaled in m/K, black dots – measurement points used for map construction; B – average geothermal gradient within the Carpathian Foredeep (after Hajto in Górecki et al., 2012, slightly modified)

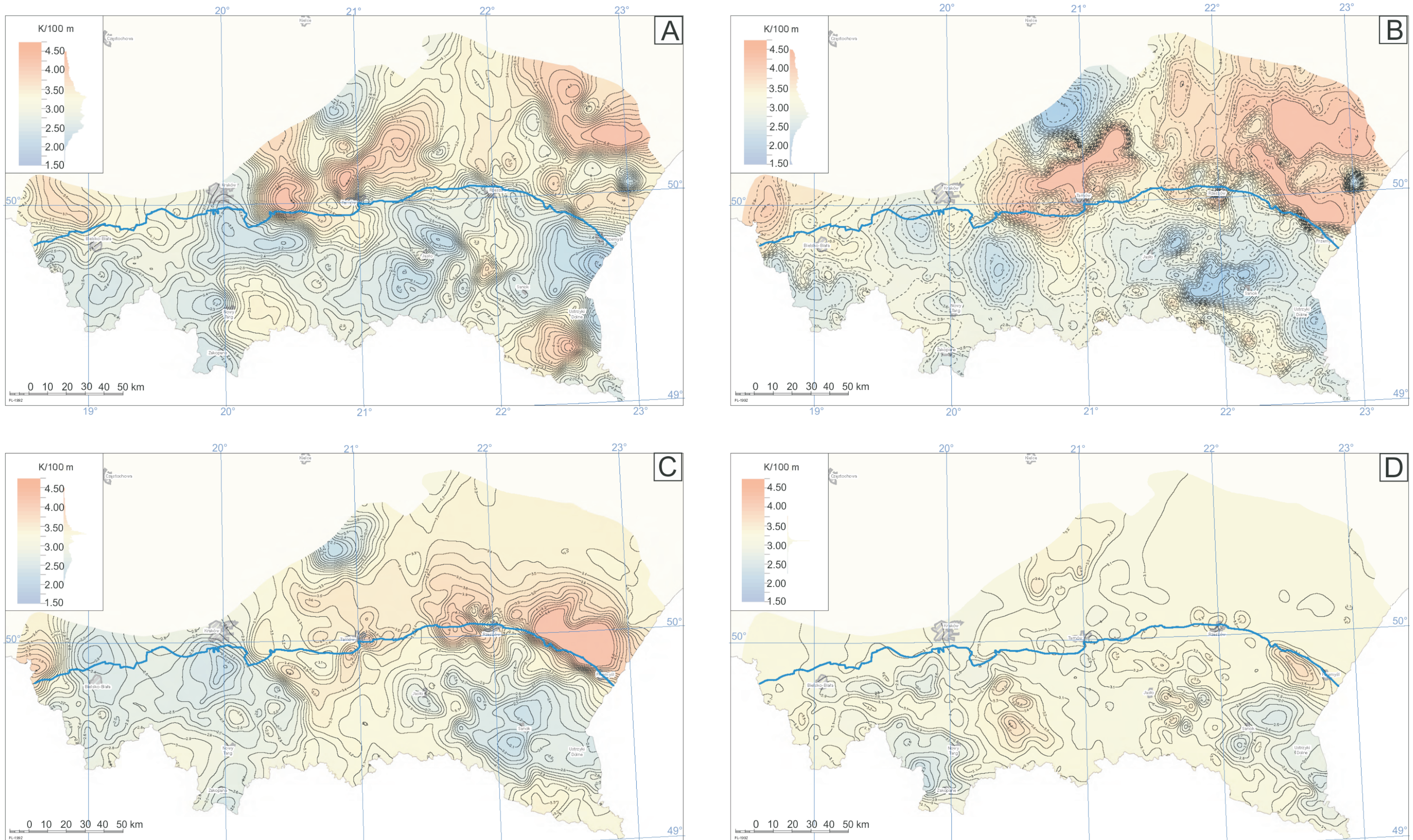

Fig. 13. Maps of the distribution of the average (interval) thermal gradient in the intervals

A – ground level – 1000 m b.g.l., **B** – 1000–2000 m b.g.l., **C** – 2000–3000 m b.g.l., **D** – 3000–4000 m b.g.l., within the Polish Carpathians and the Carpathian Foredeep; explanation in the text

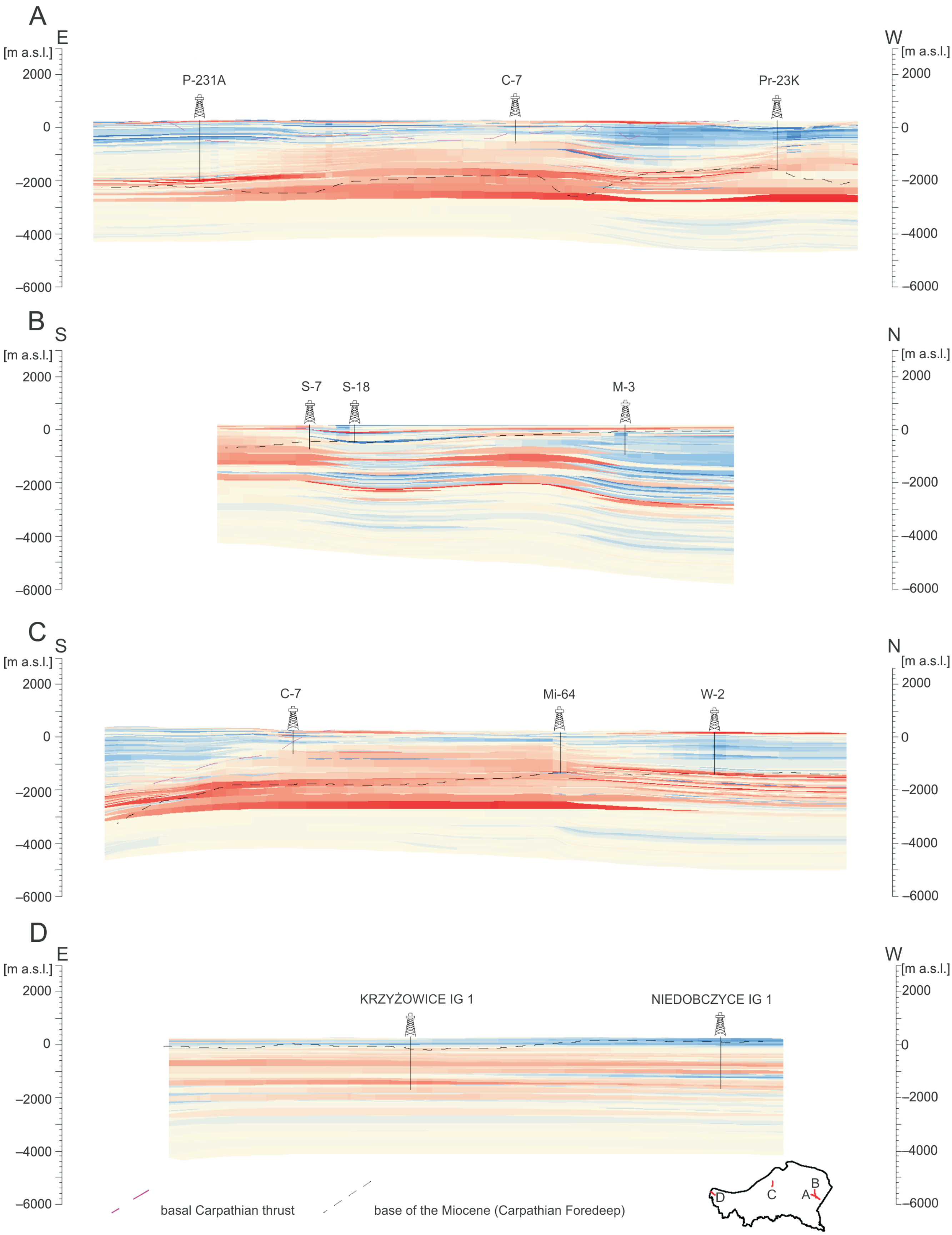

Fig. 14. Examples of interference of high-conductivity (lower thermal gradient – in blue) and low-conductivity (higher thermal gradient – in red) layers

A, C – eastern part of the area investigated, **B** – central part, **C** – eastern part, **D** – western part; note the correlation between high thermal gradient and yield of gas fields within the Carpathian Foredeep (A–C; cf. Fig. 13) tive strata, such as evaporites, and the low-conductivity ones, such as clays or marls. In the area studied, the thermal gradient log can indicate also boundaries between sandstone and claystone/mudstone layers. A correlation between gamma ray and thermal gradient logs is visible (Fig. 15), as is a correlation between higher thermal gradient values and the presence of gas-saturated intervals (Fig. 14A – P-231A borehole, Fig. 14B – S-7 borehole).

In summary, the horizontal as well as vertical variability of the thermal gradient is an effect of the natural thermal conductivity of the rock – formation fluids association. The main factors influencing this parameter are lithology, water-, air- or gas-saturation and porosity.

CORRELATION OF TEMPERATURE AND THERMAL GRADIENT CHANGES WITH OTHER GEOLOGICAL PHENOMENA

Analysis of the temperature and thermal gradient models does not show an explicit correlation of thermal properties with one dominant geological phenomenon. The correlation of the temperature and thermal gradient distribution and structural development of the area investigated seems to be poor, and should be further studied.

Negative anomalies observed on the maps of average and interval thermal gradients in the vicinity of Ustrzyki Dolne, and north-west of Nowy Targ (blue arrows in Fig. 8), may be correlated with negative Bouguer gravity anomalies in these areas (Fig. 16). Very often, positive thermal anomalies correlate with elevated structural elements observed in the basement of the Carpathian Foredeep that are expressed as positive gravity anomalies. Negative thermal anomalies in the same area coincide with gravity lows. In the Carpathians the correlation between Bouguer gravity and thermal anomalies successively diminishes towards the south. This is caused by increasing thickness and the presence of a complicated fold-and-thrust belt. The correlation between the Bouguer anomaly and the average thermal gradient has already been studied for the area of the Carpathian Foredeep (Probulski, 2002); this study showed that, in general, the average thermal gradient may be correlated with the depth of the crystalline basement, that comprises highly conductive rocks (Plewa, 1966), and which might be modified by the thermal conductivity of the Miocene sedimentary infill of the Carpathian Foredeep.

Comparison of the maps that show average thermal gradient or interval thermal gradient calculated for the first 1000 m below ground level and the map of hydrocarbon accumulations (Fig. 10) indicates a clear correlation between gas field occurrences and positive thermal anomalies mapped within the Carpathian Foredeep. This type of correlation has already been described in the literature (e.g., Forster et al., 2017). It may be caused by the significantly lower thermal conductivity of gas-saturated formations in comparison to water-saturated or non-porous and dry ones. The influence of formation fluids on the thermal properties of rocks has been qualitatively and quantitatively described in many studies. A theoretical background was given by Lichtenecker (1924, 1931), laboratory experiments have been described, e.g. by Plewa (1966) and Robertson (1988), and a critical synthesis of quantitative methods was given by Tatar et al. (2020).

The observed spatial distribution of thermal properties within the Carpathians and Carpathian Foredeep seems to be a result of the combined influence of several factors: the structure

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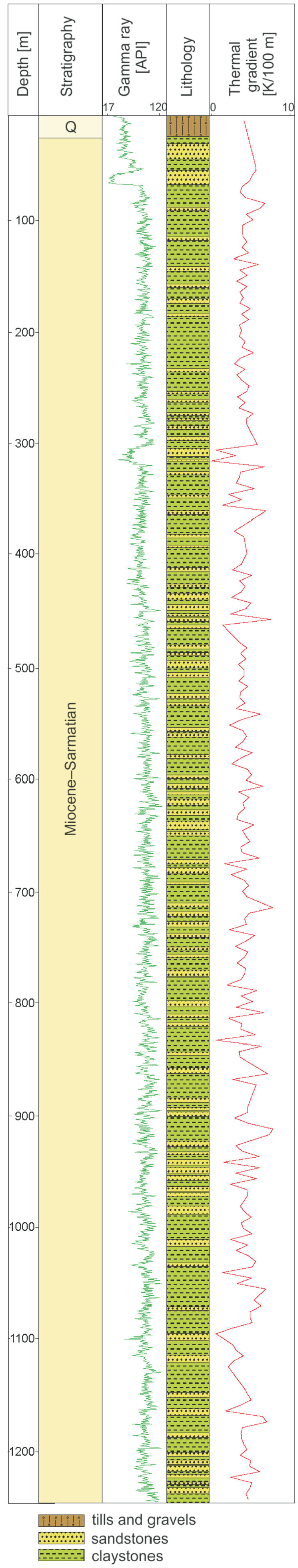

Fig. 15. Correlation between the gamma ray and the thermal gradient logs in the Ch-5 borehole in the Carpathian Foredeep

Note the thermal gradient changes at the boundaries between sandstones and claystones (stratigraphy and lithology after Słyś, 1996)

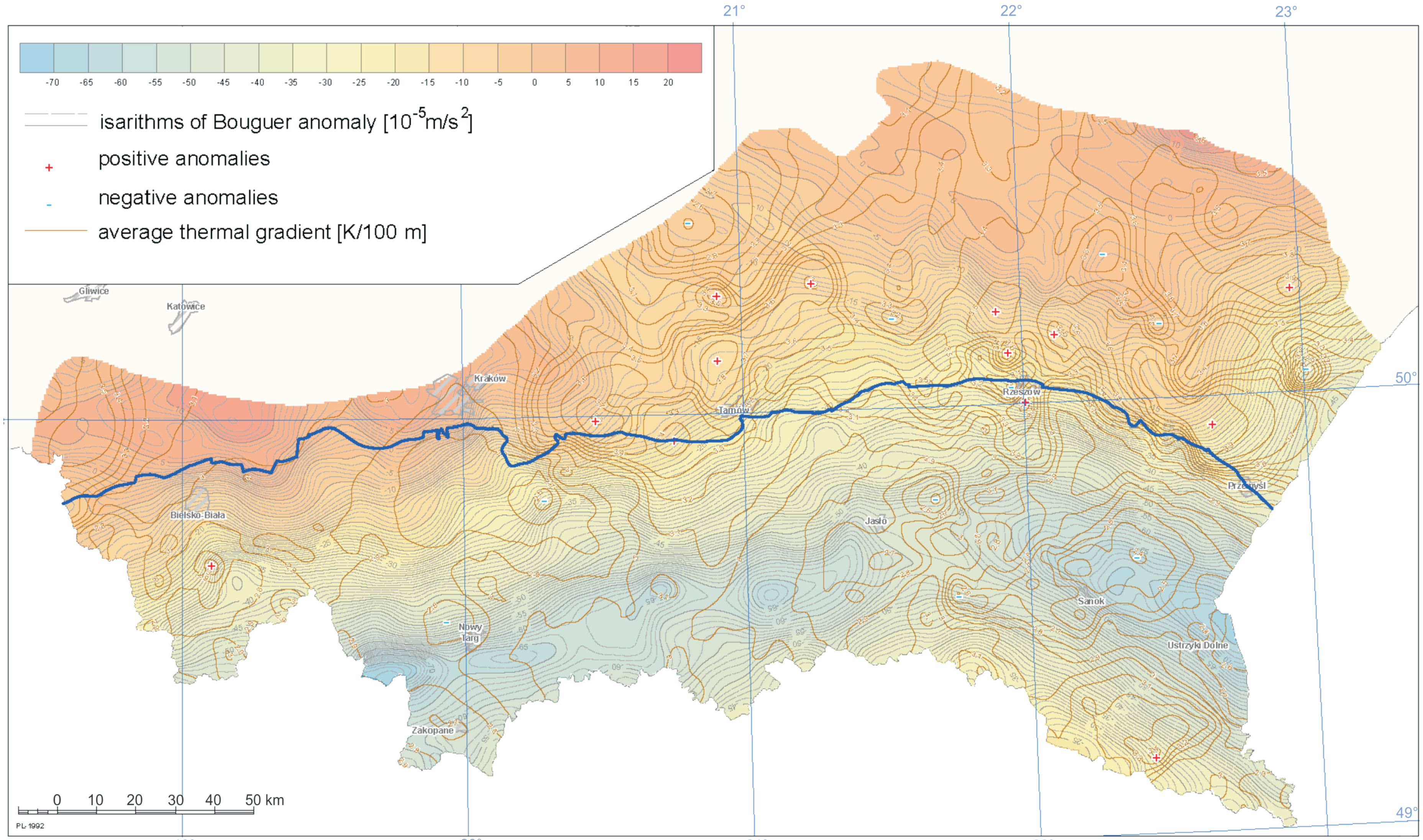

Fig. 16. Map of the average thermal gradient (brown contours), thermal anomalies (red "+" and blue "–" signs) expressed as extreme values of the average thermal gradient on a Bouguer anomaly map (compiled after Królikowski and Petecki, 1995; Pepel and Szczypa, 2000; Jamrozik et al., 2012)

See text for explanation

of the crystalline basement, the presence or lack of an orogen, the lithological variation in the sedimentary cover of the area and the presence of gas accumulations.

VERTICAL VARIABILITY OF THE THERMAL GRADIENT

The thermal gradient is characterized by high lateral and, in particular, vertical variability (Figs. 9, 13 and 14). The interval average thermal gradient computed for a sequence of four, 1000 m thick, intervals significantly changes with depth. Moreover, the gradient curves do not show any regular pattern. The vertical variability of the thermal gradient generally has not been discussed in detail in previous studies (Majorowicz, 1971; Górecki et al., 2006a, 2006b, 2011, 2012, 2013; Wójcicki et al., 2013).

The vertical variability of the interval thermal gradient has also been described from other regions. Plewa (1966) suggested the vertical variability of this parameter within the Fore-Sudetic Monocline. Karwasiecka (1996, 2008) indicated an exact correlation between thermal gradient and lithological and facies variability within the Upper Silesian Coal Basin and Lublin Basin. She assigned high thermal gradient values to coal-bearing and fine-grained clastic rocks. The presence of low-conductivity organic matter, even dispersed, may diminish the thermal conductivity of rocks and as a result increase the thermal gradient.

FURTHER USE OF THE MODEL OF TEMPERATURE DISTRIBUTION

The model described in this paper might be used in further geological, scientific or industrial research. It can be used as a tool in exploration for hydrocarbons as well as for alternative energy sources and, combined with hydrogeological data, also in balneology and/or in the sport and entertainment industry.

Analysis and discussion of the terrestrial thermal field properties help to explain hydrocarbon generation processes, determine the type of hydrocarbons expected and determine whether there was an opportunity to generate oil or gas or if the hydrocarbons were destroyed due to overheating. Detailed analysis of the thermal properties of a petroleum basin may help in the discovery of oil or gas fields. In an interesting example from Denver Basin (Forster et al., 2017), geothermal research of the eastern extension of the Colorado Mineral Belt, and the recognition of some positive thermal anomalies in that area, led to the discovery of significant reserves within the Redtail field.

The 3D temperature model described here, as well as experience in the interpretation of thermal logs, was used for predicting the temperature in newly designed boreholes. This type of prediction is of crucial importance for the security of drilling and exploration work. It allows selection of appropriate drilling and measurement tools and helps avoid overheating and destruction of expensive geophysical and testing equipment. In several cases tested in 2019, the inaccuracy of such a prediction was at a level of 10%. All these predictions were slight overestimates, the result of prudent interpretation of synthetic thermal logs generated from the model.

The 3D model of temperature distribution described here was used for construction of a dynamic model of the petroleum system within part of the Carpathian Foredeep (Sowiżdżał and Słoczyński, 2017; Sowiżdżał et al., 2019, 2020). The latter model reflects the evolution of the sedimentary basin in all aspects including structural development, facies characteristics as well as formation parameter changes through geological time. The recent spatial distribution of temperature was used to calibrate a dynamic model of the thermal evolution of the Carpathian Foredeep. During the calibration process, assumed values and variability in the palaeo-heat flow within the basin were tested and adjusted in order to obtain the recent temperature distribution at the end of the modelling process. The thermal parameters of a petroleum system determine the conditions of the hydrocarbon generation process including its timing and speed. These concern both the thermogenic and microbial processes.

Modelling indicates that the thermal parameters of rocks (especially gradients) are irregularly distributed in three dimensions. Awareness of this reality should encourage change in industrial routine, to carry out thermal logging of newly drilled wells.

CONCLUSIONS

The 3D parametric model of spatial distribution of temperature and thermal gradients described in this paper is the first attempt at modelling of this type in Poland. Initially, a regional character of the model was assumed that determined the modelling techniques used and the accuracy of the final result. Despite its regional character, the model described can be used as a basis for further scientific and industrial research including the processes of hydrocarbon generation and exploration for alternative sources of energy. Most thermal models constructed in the world are based, because of budget shortages, on *BHT* measurements or *DST* results (Dotsey, 2012); therefore, the method presented here can be treated as an original scientific approach.

The data collected in this study may form a basis for construction of a borehole database designed for geothermal studies.

All logs collected were standardized by the same method, called here the Kukkonen-Szewczyk method. Application of this method was necessary because of lack of metadata or inconsistent descriptions of measurement conditions. The method seems to have universal application, in contrast to those based on experimental results.

The modelling described here has resulted in a coherent image of the temperature and thermal gradient within the area of the Polish Carpathians and the Carpathian Foredeep in the interval from the ground level to the depth of the 160°C isotherm. The results provided show that (1) Standardization of thermal logs is an absolute necessity to remove the influence of surface conditions and drilling processes, particularly drilling mud circulation. (2) The number and spatial distribution of thermal well logs acquired in Poland suggest the application of 3D modelling as a tool for investigating temperature and thermal gradient changes. (3) Thermal anomalies, expressed as anomalies of the thermal gradient, result from the basement structure, a system of faults and fault zones at the base of the Carpathians and the Carpathian Foredeep. They are moderated by facies and lithology changes, particularly by alterations of high- and low-conductivity layers in the overlying strata. (4) When discussing the spatial distribution of a thermal gradient, it is necessary to indicate for which depth interval it was computed. Lack of such comment may lead to misunderstanding. (5) The modelling results seem to support the hypothesis that the thermal parameters of rocks (especially gradients) are irregularly distributed in three dimensions to a considerably higher degree than previously thought.

Future work on the properties of the thermal field in Poland should concentrate on the following issues: (1) archival query to collect data for the area of the Polish Lowlands, and subsequently to extend the model across the whole area of Poland; (2) detailed study to quantitatively describe the relationship between thermal gradient, lithology, and other petrophysical properties, measurable by logging; (3) 3D numeric regional models including of structural, lithological and facies patterns as well as petrophysical parameters for the Carpathians and Carpathian Foredeep; (4) detailed analysis of the relationship between the Bouguer anomaly distribution and thermal gradient distribution, to explain the influence of the basement structure and/or lithological characteristics of the Carpathians and Carpathian Foredeep on the present-day thermal field of the Earth within the area investigated; (5) detailed analysis of the correlation between the distribution of positive thermal anomalies and the appearance of gas accumulations within the Carpathian Foredeep, combined with microbiological research to examine this phenomenon.

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