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Terrestrial heat flow density in Poland — a new approach

Jan SZEWCZYK and Danuta GIENTKA

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The Earth's thermal field, particularly the heat flow density (HFD), is a valuable source of information on geodynamic processes within the Earth's crust, conditions for hydrocarbon generation and on areas and formations promising for geothermal energy. Lithospheric thermal and rheological modelling is critically dependent on high-quality surface heat flow values. The available maps of heat flow density, not only for the area of Poland, are not reliable from the point of view of the current state of knowledge. The main critical factor in determining heat flow density is the knowledge of depth distribution of thermal conductivity. We used a new method of estimating the thermal conductivity from well logging data interpretation with control calibration based on laboratory determined thermal parameters. We consider that the observed vertical variations of HFD in the shallow part of profiles (<2000 m) are mainly due to a Holocene warming. We have proposed a new original method of determination of HFD based on modelling of palaeoclimatic effect. Using this method, we have calculated new HFD values for 308 deep boreholes and completed a new map of this parameter for Poland, which is the first of this type. We propose to undertake a critical analysis of all the existing heat flow data not only for Europe that may change the present understanding of global heat flow.

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INTRODUCTION

Thermal field in the upper portions of the Earth's crust, in particular the near-surface heat flow density (HFD), can be a source of important information on the subsurface geological structure, conditions for hydrocarbon generation as well as on areas and formations promising for geothermal energy. HFD data are extremely useful for consideration lithosphere mechanics and evolution of crustal structure. It was recently found out (e.g., Šafanda and Rajver, 2001; Szewczyk, 2002*a*, *b*; Szewczyk and Gientka, 2003; Kukkonen and Joeleht, 2003) that changes in the heat flow density with depth can also be a significant source of information on palaeoclimate in the past.

Heat flow density determines the amount of thermal energy passing through an area unit per time unit from a hot to a colder rock body. Of the three major physical processes responsible for thermal energy transfer i.e. conductivity, convection and radiation, conductivity is commonly believed to play the dominant role in energy transport within the Earth's crust (Stenz and Mackiewicz., 1964; Haenel *et al*., 1988).

The basis for heat flow density determination is depth-related temperature variation observed in boreholes. Such analyses are commonly made along with investigations of thermal conductivity of rocks. Both Earth's mantle heat (so-called remnant heat) and radiogenic heat, being permanently produced as a result of natural decay of long-lived radioactive isotopes of U-235, U-238, Th-232 and K-40, are the sources of thermal energy in the Earth's crust (Adams and Gasparini, 1973). The average continental heat flow value is estimated at 67 mWm^{-2} (Pollack *et al*., 1993). Heat flow density measurements were made at over 22000 sites across the globe (Gosnold *et al*., 2005). Many of them are situated in offshore areas.

Heat flow values from geothermal data of Poland have been measured over many years by a number of authors using various, sometimes their own developed, methods (e.g., Plewa, 1994; Plewa *et al*., 1995). Recently, the values became the basis for the construction of three heat flow density maps covering the whole area of Poland (Plewa, 1994; Gordienko and Zavgorodnyaya, 1996; Karwasiecka and Bruszewska, 1997), which were later critically analysed by Majorowicz *et al*. (2002). The maps exhibit considerable (in some areas very distinct) differences suggesting significant discrepancies in determined heat flow values. Such differences cannot be explained solely by poor quality of source data because the maps' authors utilized similar geothermal data sets. Therefore, it is obvious that the basic reason for the differences could be different methods used for calculating the heat flow values.

In 2001, this situation prompted us to an attempt, promoted and supported by Jacek Majorowicz from the University of North Dakota, USA, to both make a revision of the method used in determining heat flow values and develop a new heat flow density map, initially for the Polish Lowlands and currently for the whole territory of Poland. It should be stressed that some doubts as to the correctness of the existing maps have recently arisen not only in Poland. Similar critical opinions, both questioning the correctness of the heat flow measurement methods being currently in use and pointing to low reliability of the maps previously constructed for areas covering other regions of Europe, were set forth in a number of publications (Balling, 2002, 2004; Kukkonen and Joeleht, 2002; Lotz and Forster, 2002; Majorowicz , 2004).

The construction of geophysical and geological databases for most of exploratory boreholes in Poland in the last years, and the development of data interpretation methods (including development of the GEOFLOG system at the Polish Geological Institute; Szewczyk, 1994, 1998) have created a good opportunity to introduce a modified methodology of heat flow density measurement. It is based primarily on geophysical data derived from boreholes (Szewczyk, 2001).

GEOTHERMAL DATA FROM POLAND

In Poland, temperature measurements were made in a few hundreds of wells under conditions formally considered an equilibrium state (Karwasiecka, 2001). Many of the measurements were made in relatively shallow boreholes (<2000 m deep) of coal basin areas. Due to both the large costs of geothermal researches and decreasing number of drilling experiments, no increase in the volume of measurement data on the spatial distribution of subsurface temperatures in Poland can be currently expected. The existing data are and will be in the future the basic source of information on the geothermal field. In this situation, analysis of the existing data seems to be the only way for gaining new information, despite some objections as to the data quality.

Therefore, a verification of all geothermal data, supported by a thorough analysis of the whole of geophysical investigations and hydrogeological tests in wells, can be the chance for correct reinterpretation of the data.

PREVIOUS METHODS OF HEAT FLOW DETERMINATION

The classical method of heat flow density (Q) determination, commonly in use for over a few decades both in Poland and elsewhere, is based on both temperature measurements in wells in an equilibrium state (Tu) and laboratory analyses of thermal conductivity (K) of drill cores. It is usually assumed that the vertical component of the heat flow is constant (Q = const), and the conductive strata show a horizontal and parallel pattern with the conductive component of the heat flow being the only one present. The Q/K relationship for any depth along the "z" axis of the well follows the Fourier's law (Haenel *et al*., 1988):

$$Q = -K \times dT / dz \qquad [1]$$

where: dT/dz — temperature gradient.

Significant errors that may arise while estimating the two values in the formula [1] result in difficulties in determination of heat flow density values (Plewa *et al*., 1995; Karwasiecka and Bruszewska, 1997; Szewczyk, 2001; Lotz *et al*., 2002; Majorowicz *et al*., 2002; Szewczyk and Gientka, 2004).

The crucial element in the method of estimating heat flow density values (Q) is the conductivity (K) of rocks composing the borehole section. Values of the conductivity parameter used to be determined from laboratory analyses of drill cores. The most important problem in this research method is insufficient representativeness of the research results. Due to the commonly small number of drilling runs in deep boreholes, determinations of the K parameter for low-volume (several cubic centimetres) samples collected from drill cores are weakly characteristic of longer intervals of the borehole sections for which the temperature gradient was estimated (Griffiths *et al*., 1992). In Poland, most of previous measurements of the K parameter were made in boreholes from mining areas, not exceeding 2000 metres in depth (Karwasiecka and Bruszewska, 1997; Karwasiecka, 2001; Szewczyk and Gientka, 2004). There are very few data derived from greater depths.

There are also some doubts about reliability of many of laboratory analyses of the K parameter. The analytical results suggest that the measurements may have been made under inappropriate physical conditions i.e. at incomplete sample saturation. It may significantly raise the error of conductivity determinations especially in samples taken from highly porous sedimentary rocks (>10%) commonly observed in depositional sequences down to a depth of 3000 metres (Fig. 1). In consequence, the method is highly limited in terms of its practical use for heat flow measurements. Figure 2 shows the results of modelling of the effect of porosity changes on thermal conductivity for various types of pore space fill (water, air). The modelling were carried out on sandstones and claystones using a geometric model of the relationship between rock components and effective thermal conductivity (Brigaud and Chapman, 1990). Due to large, almost 20-fold differences in the thermal conductivity of water relative to the air (0.59 and 0.03 W/m°K, respectively), incomplete saturation of rock samples results in a considerable underestimation of the measured values of thermal conductivity in relation to the real value.

The results of the modelling indicate a very strong effect of the pore space on thermal conductivity values (especially when filled with the air). It has a very serious consequence for the results of laboratory analyses of the parameter. The results of laboratory analyses performed on dry or partly saturated porous samples should be treated with much caution. It must be stressed that this shortcoming in the research is observed not only in Poland (Lotz and Foester, 2002).

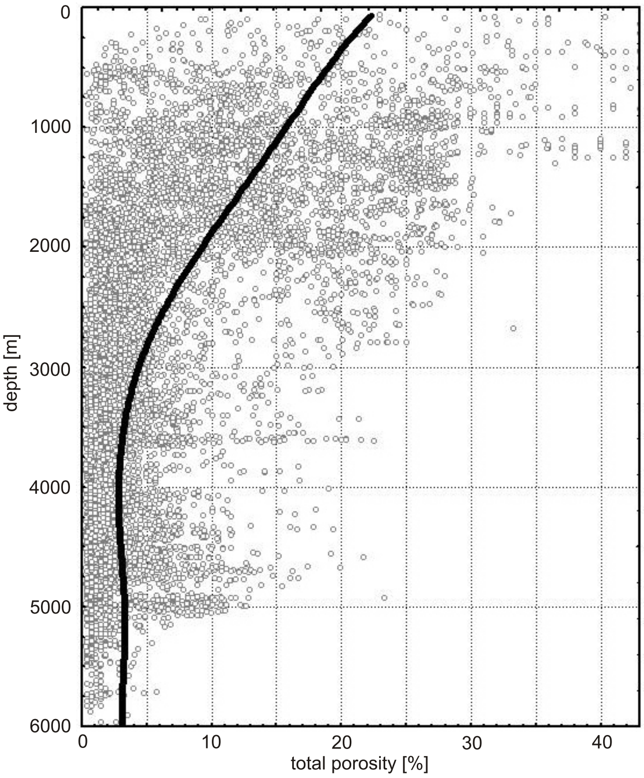

Fig. 1. The relationship between laboratory determined total porosity and depth for sedimentary rocks from the Polish Lowlands (after Szewczyk, 2000); it was shown averaged value of porosity calculated after square method

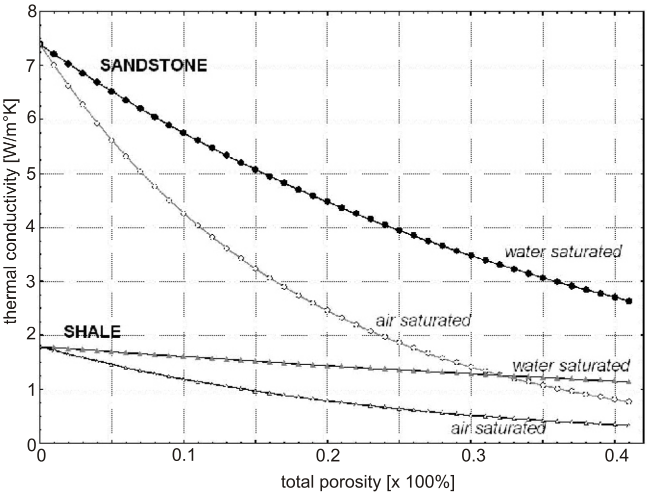

Fig. 2. Results of thermal conductivity modelling *versus* porosity for dry and water saturated sandstone and shale; for determining of thermal conductivity it was used geometric mean model

THE STATE OF GEOTHERMAL EQUILIBRIUM

In previous analyses of sources of errors in determining heat flow density values, low accuracy of temperature measurements due to a disturbed state of geothermal equilibrium was considered the main reason for such errors (Plewa, 1994).

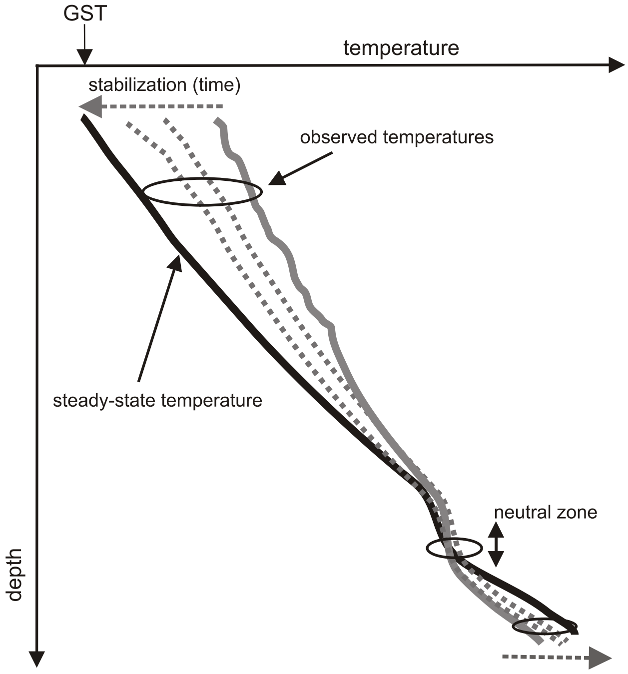

Fig. 3. Schematic a time changing of temperature observed in boreholes due to perturbed of the underground thermal regime after mud circulation processes

GST — ground surface temperature

A difficulty in experimental studies results from the fact that the well-drilling process alone (and even an individual measurement) disturbs the geothermal environment.

A prolonged drill mud circulation (months or years in duration) during drilling operations causes a disturbance to the thermal equilibrium. The upper part of the borehole section gets warmer, while its lower part becomes cooler. This process is schematically shown in Figure 3. The lack of thermal equilibrium is best manifested by a deviation of the current ground surface temperature from the long-term annual mean temperature (so-called ground surface temperature — GST). The return to thermal equilibrium is a relatively slow process, or even the disturbance can be a permanent state (due to convectional movement of the drill mud within the drill string), as currently claimed. The relatively least disturbed temperature is observed at the borehole bottom (BHT — bottom hole temperature; see Fig. 4B).

Figure 4A presents the results of temperature measurements made in Poland (after a 10–14-day drilling break) at near-equilibrium conditions. For comparison, GST variability is also shown. Most of the temperature measurements in Poland (and not only) exhibit a clear deviation from the thermal equilibrium state.

In contrast to data on the environment temperature, which is “passive” information, thermal conductivity (*K*) is the main element necessary for interpretations. It can be approximated by an iteration approach as a result of a number of analyses. The results of heat flow measurements presented in this paper are based on both a geophysical method of thermal conductivity determinations and a newly developed method of heat flow value calculation.

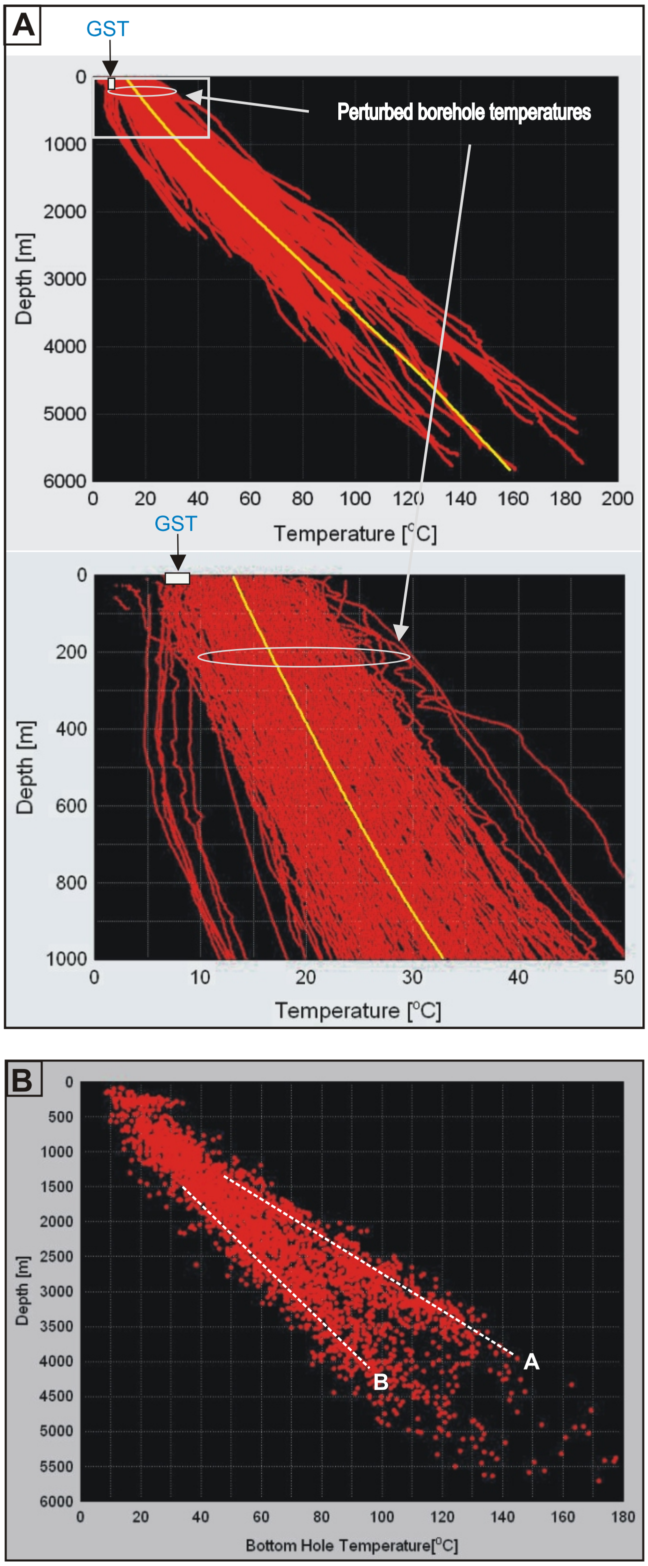

Fig. 4A — steady-state temperature logs in Poland; it was shown the subsurface temperature (GST) range for Poland (after Szewczyk, 2005); B — bottom hole temperature (BHT) for Polish Lowlands after GEOFLOG data base: A — Fore-Sudectic Monocline and south part of Szczecin Trough, B — Precambrian East European Platform

The starting point for the use of the method was the construction of lithological-porosity models for many deep boreholes drilled by the Polish Geological Institute (Szewczyk, 1998, 2000), based on many years' methodical work. It has appeared that the data can also be useful in both thermal conductivity and terrestrial heat flow density determinations (Szewczyk, 2001, 2002*a*).

THERMAL CONDUCTIVITY DETERMINATION

The thermal conductivity coefficient is a function of mineral composition of rocks, their internal structure, texture, temperature and pressure (Brigaud and Chapman, 1990; Vasseur *et al.*, 1995; Waples and Tirsgaard, 2002; Popov *et al.*, 2003). The main factor affecting the amount of thermal conductivity is the total porosity *F*. The high porosity of sedimentary rocks occurring down to a depth of 3000 m is the major factor differentiating the value of the thermal conductivity coefficient of sedimentary rocks across the Polish Lowlands (Szewczyk, 2000, 2001). Empirical and theoretical researches of the relationship between the mineral composition of rocks, their structure, size and spatial distribution of individual constituents enabled the development of a number of mathematical models. They allowed determination of thermal conductivity of rocks based on their lithological-volumetric model (Brigaud and Chapman, 1990; Griffiths and Brereton, 1992; Joeleht *et al.*, 2002; Popov *et al.*, 2002). It has been assumed that the so-called geometric model is a sufficiently accurate approximation of the thermal conductivity parameter (*K*) of sedimentary rocks:

$$K = \prod_{i=1}^{n} k_i^{V_i} \qquad [2]$$

where: n — number of rock components; k_i — thermal conductivity of component "i"; V_i — volume of component "i".

Thermal parameters of minerals, referred to in the formula [2], are commonly defined with a sufficient accuracy. Moreover, thermal conductivity of the main macro components of sedimentary rocks (rock framework, clay content, pore space) is generally very varied (Szewczyk, 2001).

Thermal conductivity values, calculated from the formula [2] over the entire borehole section, represent a rock volume that is several times greater than the volume of rock samples analyzed in the laboratory. Information about the parameter *K*, obtained from geophysical data, corresponds in terms of its representativeness (similar observation scales) with temperature values recorded in the borehole.

A generalized image of lithology, reflecting only the main rock-forming minerals and total porosity values, has appeared to be sufficient for acquiring information on thermal conductivity of rocks encountered in the section. Figures 5A and 5B illustrate a comparison of thermal conductivity coefficient values determined by the discussed geophysical method with the results of laboratory analyses of drill cores. The paper presents the results of data from two deep boreholes (the only ones drilled in the Polish Lowlands with well-defined thermal con-

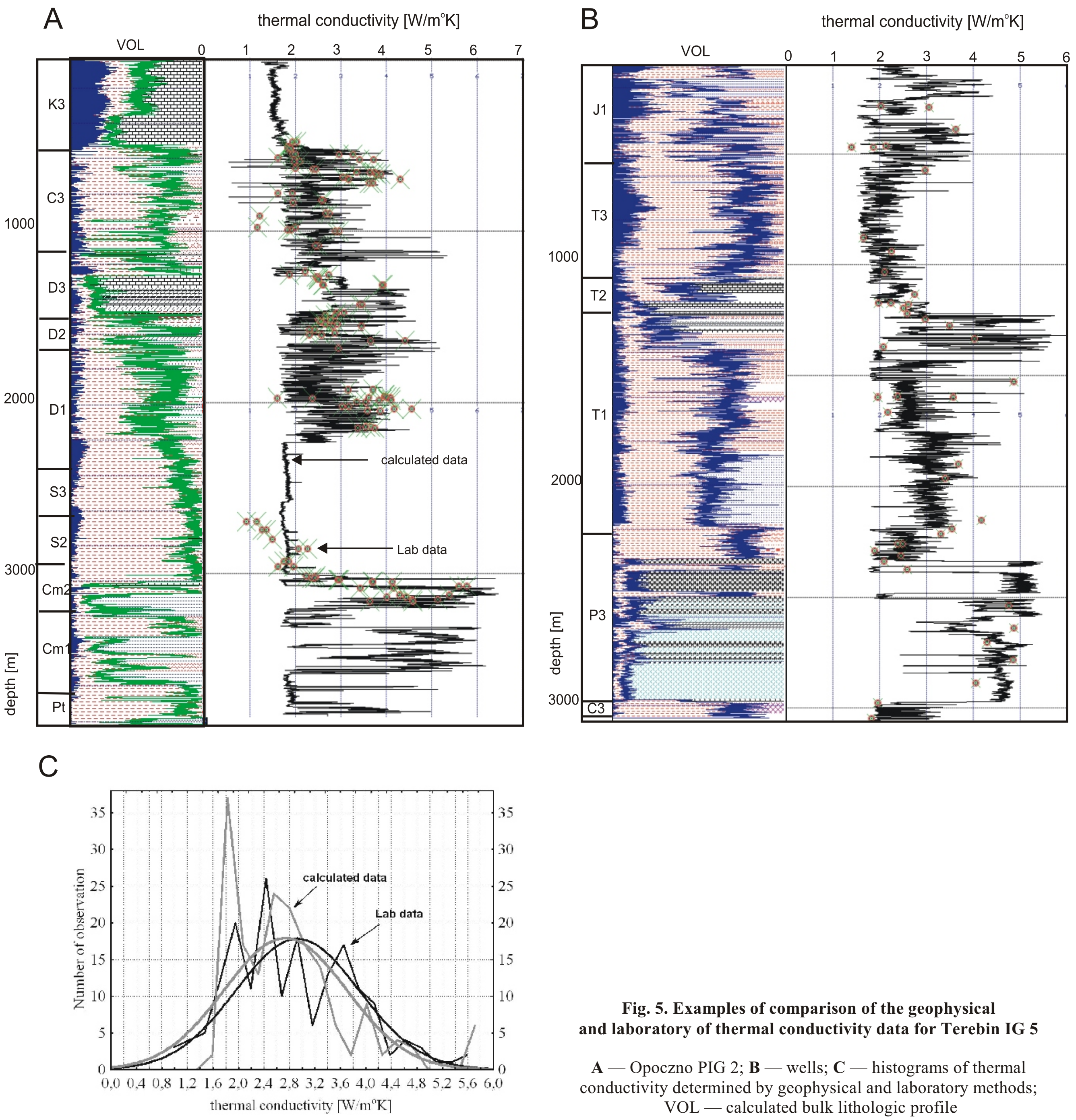

Fig. 5. Examples of comparison of the geophysical and laboratory of thermal conductivity data for Terebin IG 5

A — Opoczno PIG 2; **B** — wells; **C** — histograms of thermal conductivity determined by geophysical and laboratory methods; VOL — calculated bulk lithologic profile

ductivity profiles). Figure 5C shows histograms for the boreholes and corresponding normal distributions.

Taking into account both the complex nature of the comparing procedure, resulting from different observation scales (the compared data refer to inhomogeneous objects differing in their volumes by 3–4 orders of magnitude!), and the considerable differences between logger's and driller's depths, the presence of correlative relation has been unambiguously proved (Griffihs and Brereton, 1992).

A direct application of the method of thermal conductivity determination of rocks in the lithological-volumetric profiles of sedimentary rocks from the Polish Lowlands has appeared to be an effective way for determining this parameter (Szewczyk, 2001, 2002*a*; Szewczyk and Gientka, 2004). The results of continuous interpretation research conducted at the Polish Geological Institute, which aimed at determination of physical properties of rocks composing the borehole sections from the Polish Lowlands, are very useful for a direct effective application of the above-described research method. The compiled (and being continuously developed) set of geophysical-geological data can be a starting point for both the ongoing and planned research projects concerned with the prediction of petrophysical properties of rocks occurring in these borehole sections (Szewczyk and Gientka, 2004).

HEAT FLOW DETERMINATION METHOD

The temperature distribution *vs*. depth is, as seen from the formula [1], a function of the amount of heat flow Q and the value of thermal conductivity coefficient $K(z)$ of rocks. If a homogeneous horizontally layered rock body contains radiogenic heat sources, and there is climatic disturbance at the Earth surface, then the temperature is a function of depth z and time t, and is defined by the following formula (Clauser, 1999):

$$T(z,t)=T(h)+Q\int_{0}^{z}\frac{dz}{K(z)}-M(z)+Tp(z,t) \qquad [3]$$

where: $T(h)$ — initial temperature at depth h; dz — thickness of an elementary bed of constant thermal properties; $K(z)$ — thermal conductivity coefficient value at depth z; $M(z)$ — radiogenic component of heat flow; $Tp(z, t)$ — climatic disturbance; Q — the heat flow at depth h.

It is assumed that the "subsurface" component of heat flow (Q) is the sum of the remnant component (subcrustal heat) and the radiogenic component associated with radioactive elements present mainly in the upper crust.

Determination of the distribution of $K(z)$ values along the entire borehole section allows the calculation of the co-called "synthetic temperature" at any depth, assuming a constant value of the vertical component Q. By assuming, as it is usually the case while using the formula [1] in heat flow determination, the lack of both radiogenic heat sources (or their small contribution possible to be neglected) and thermal disturbance within the borehole section, we have a possibility to calculate the synthetic temperature defined by the first two components of the formula [3]. If there is reliable information about temperature values at least at any two points of the section and about depth-related variability of the coefficient K at these points, then it is possible to determine stationary heat flow values (Q).

THE EFFECT OF PALAEOCLIMATIC FACTOR ON HEAT FLOW DENSITY

Already the first applications of the above-discussed research method of thermal regime determination in deep boreholes (>2.5–3.0 km) revealed the presence of distinct deviations of temperatures calculated using the formula [3] from the real temperatures. The deviations were recorded in the upper parts of the sections down to a depth of <2 km. Malbork IG 1 and Prabuty IG 1 were the first historical boreholes where the phenomenon was observed and considered to have been the effect of a palaeoclimatic factor. Figure 6 illustrates this situation in the Malbork IG 1 borehole, not corrected (upper portion) and corrected (lower portion) for the palaeoclimatic effect. The remarkable difference between the calculated thermal profiling (T_s) and the profiling recorded in the borehole (T), observed in the upper part of the section, can be associated neither with thermal balance disturbance nor with little probable anomalously large increase in thermal conductivity of rocks composing this part of the section.

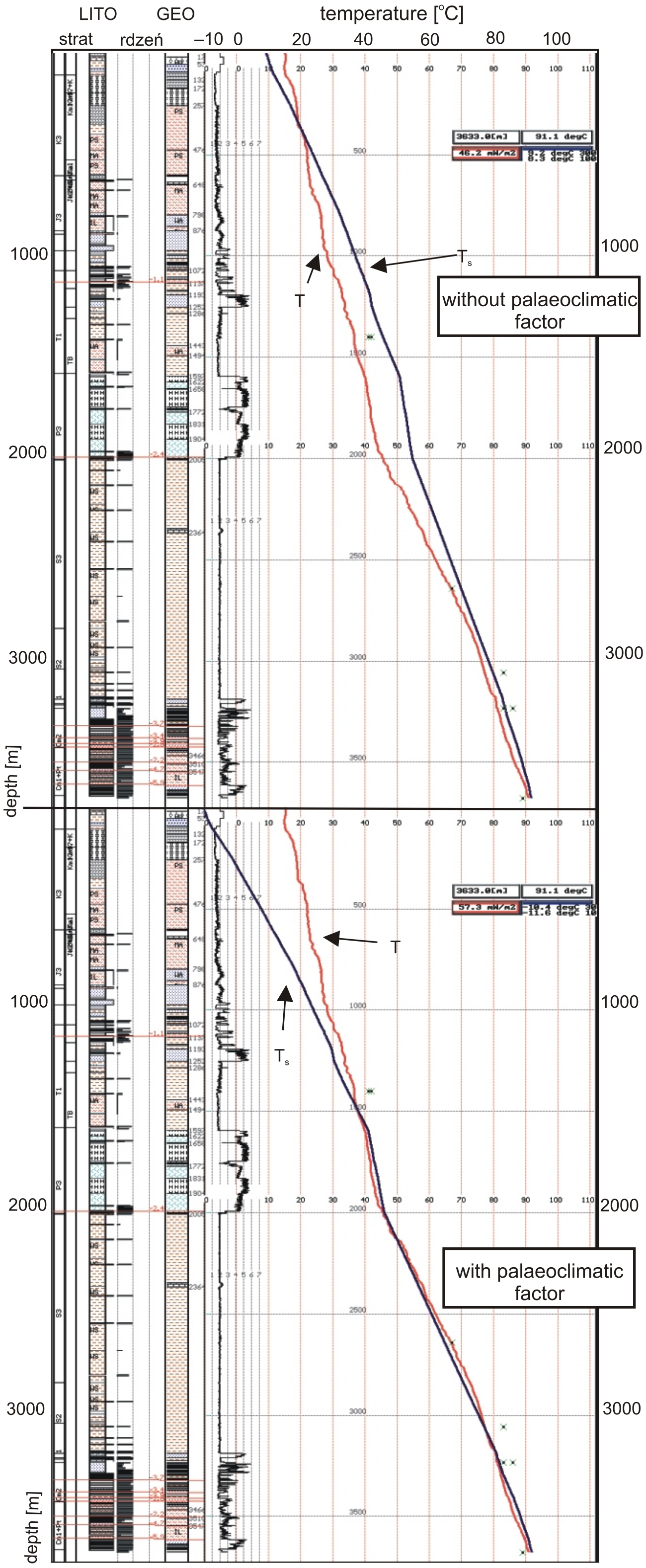

Fig. 6. First signal about palaeoclimate detected in Malbork IG 1 borehole

The top part of temperature profile (<2000 m) is a superposition of palaeoeffect and (party) unsteady-state thermal condition. Climatic effect is visible in the characteristic bending of temperature logs at a depth shallower than 2000 m. There is a good agreement between the calculated (T_s) and observed temperatures (T) for the deeper part of profile

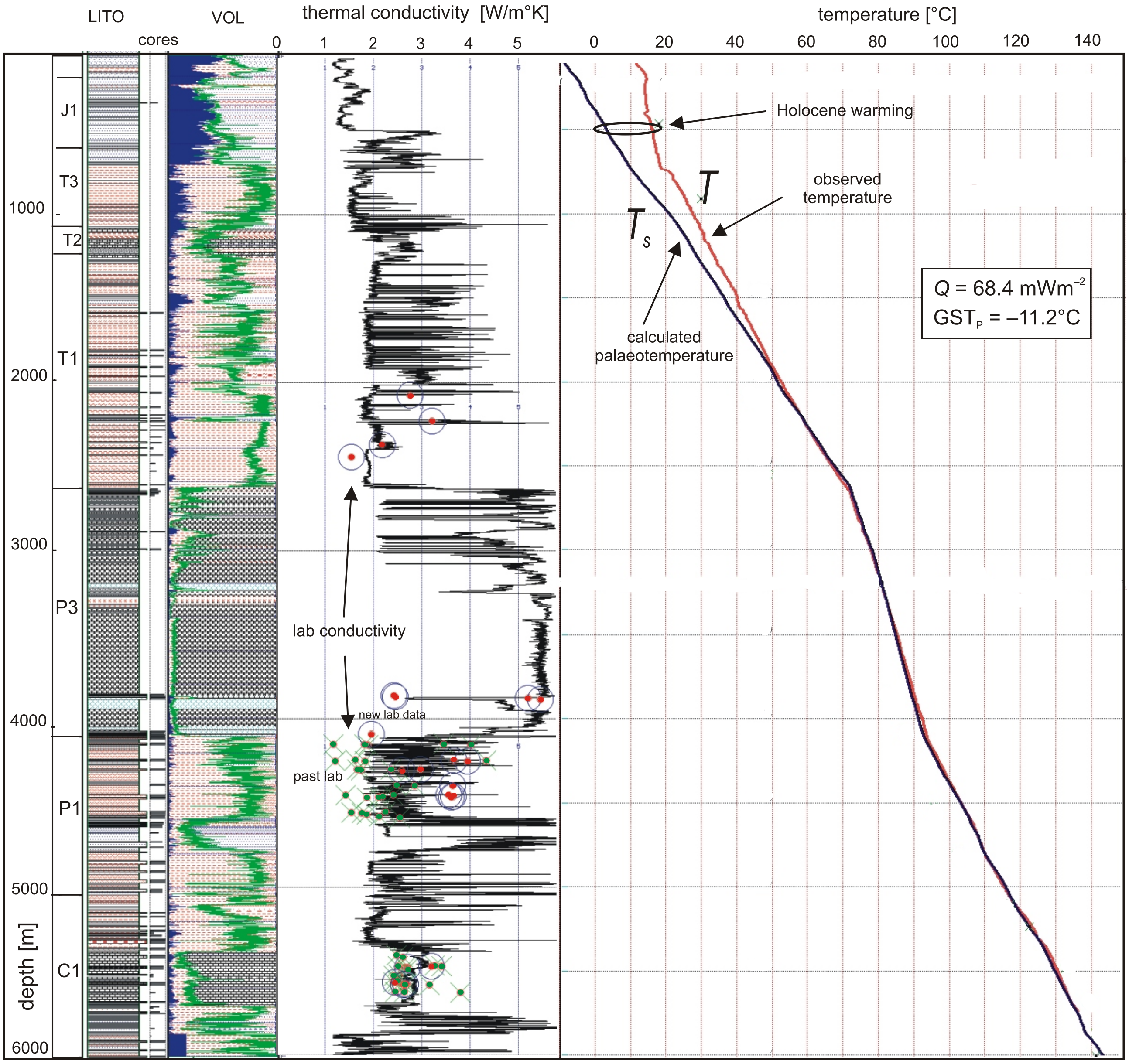

Fig. 7. Comparison of geophysical and laboratory determined thermal conductivity data in Czaplinek IG 1 well based on classical (points) and Popov's thermal scanning (circle) methods

Observed (T) and calculated (T_s) palaeotemperature, the heat flow value and the palaeoground surface temperature (GST$_P$) have been show; other explanations as in Figures 1 and 5

Later research revealed that this phenomenon is commonly observed. Figure 7 shows the results of observations made on the phenomenon in the Czaplinek IG 1 borehole, one of the deepest wells in Poland with thermal measurements recorded under steady-state conditions.

It has long been known that climatic fluctuations in the history of the Earth, controlled by glacial cycles, might have an influence on the present-day subsurface thermal regime (Stenz and Mackiewicz, 1964; Čermak, 1976). However, much time had passed until the phenomenon was unambiguously recognized. Only quite recently, the effect was noticed in thermal profiles of some deep wells. In Central Europe, it was reported from the super-deep borehole KTB drilled in Germany (Clauser, 1999), in boreholes drilled in eastern Karelia (Kukkonen *et al.*, 1998; Kukkonen and Joeleht, 2003), in the Czech Republic and Slovenia (Šafanda and Rajver, 2001), the North Sea (Balling, 2002, 2004).

The research results made by Majorowicz (1976) reconsider the origin of the geothermal anomaly in the Suwałki Anorthosite Massif, discovered already in the 1970's. That author claimed then that the depth-related temperature inversion, observed within the sedimentary cover of the massif and unique on a European scale, was an effect of deep infiltration of cooled postglacial waters. The present modelling of thermal regime has proved that the anomaly is the effect of permafrost that occurred in this area during the last glaciation. The permafrost might have originally reached a depth of over 550 m (Šafanda *et al.*, 2004). It was also estimated that the effective mean annual surface temperatures were of –10°C during that period.

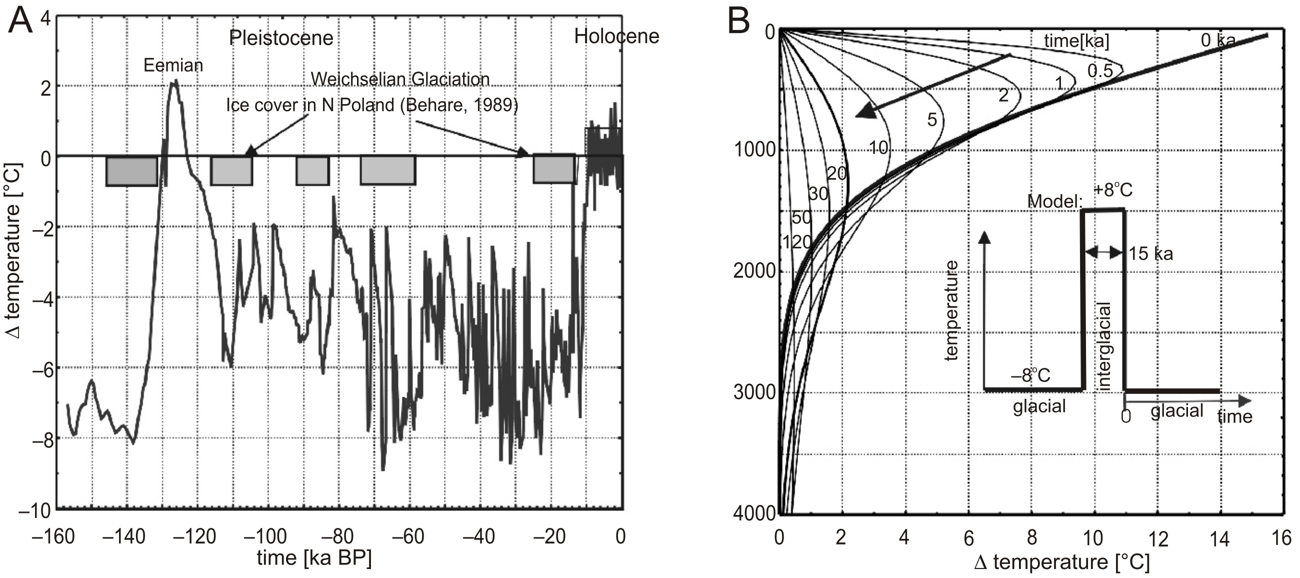

Fig. 8A — palaeoclimate for the last 160 000 years based on Vostok stations data on Antarctica (Petit *et al.*, 1999); B — results of theoretical modelling of subsurface temperature anomaly changing after typical interglacial episode as function of depth and time

Duration of assumed warm interglacial episode Δt = 15 000 years , temperature decrease ΔGST = 16°C has been assumed

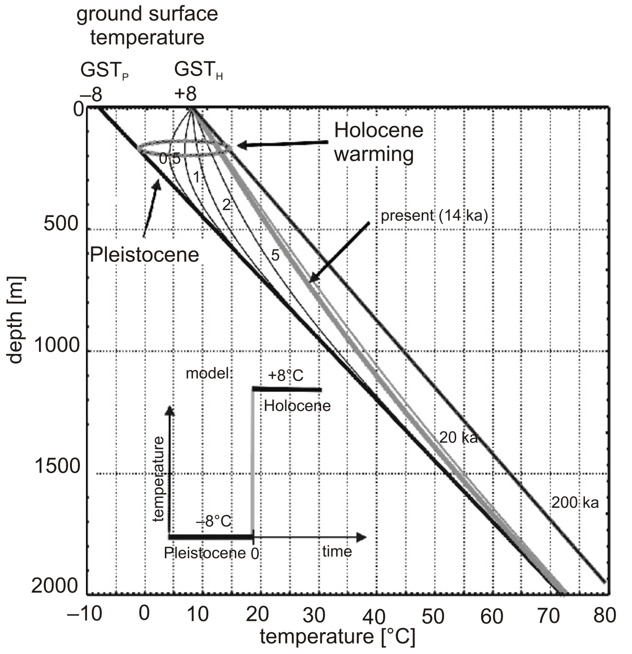

Fig. 9. Result of theoretical modelling of the subsurface temperature changing for homogeneous space for the Pleistocene–Holocene warming of the figure has been shown

Temperature jump for Pleistocene–Holocene (ΔGST = 16°C), coefficient of thermal diffusion $A = 0.01$ cm^2 s^{-1}, and, gradient of 40 mKm^{-1} has been assumed; GST$_P$ — ground surface temperature for Pleistocene; GST$_H$ — ground surface temperature for Holocene

The modelling has shown that thermal regime of the shallow crust has been influenced mainly by the last two climate periods of the Vistulian Glaciation and Holocene (Szewczyk, 2005). Because of the predominance of glacial times over the last 420 000 years, the thermal regime was controlled by cool climate periods down to a depth of several kilometres. Warmer interglacial periods disturbed that stable regime only for short times. The situation is illustrated in Figure 8.

The modelling have also shown (Fig. 9) that the effect of the warm Holocene climate (about 14 300 years long) has reached a depth of 1500–2000 metres till now. Beneath that depth, the geothermal conditions are still dominated by low temperatures of the last glaciation.

A periglacial climate dominated in Poland during the Vistulian Glaciation. The only areas periodically occupied by a thin ice-sheet cover (100–300 metres thick) were the very northern ends (Marks, 2007, pers. comm.).

The results of both interpretations and the modelling enabled introducing a new method of heat flow calibration by comparing it to the values corresponding with the conditions typical of late Pleistocene glacial periods and best coinciding with natural conditions of thermal stability (Szewczyk and Gientka, 2004). It is easy to find out that the previously applied method of heat flow calibration by comparing it to interglacial periods is much less accurate. A disturbance of thermal conditions and the resulting necessity for introducing climatic corrections to the calculated heat flow values occurs here practically at all depths. The situation is schematically illustrated in Figure 10.

The previously used method of heat flow calibration, developed in a paper by Čermăk (1976), was a result of then accepted erroneous assumption that interglacial periods dominated in the Pleistocene climate history. The results of recent investigations on ancient climate, based largely on ice core studies from the Earth's polar areas, unambiguously indicate the definite dominance of glacial periods (Petit *et al.*, 1999). The need of obtaining information about the heat flow value controlled primarily by geological factors resulted in a proposal of using a different method of heat flow calibration. Because the zone extending down to a depth of 1500–2000 m remains under an unstable thermal regime, heat flow calibration to the glacial period climate is the best way to meet the condition. In general, the heat flow value in this case is a superposition of two independent

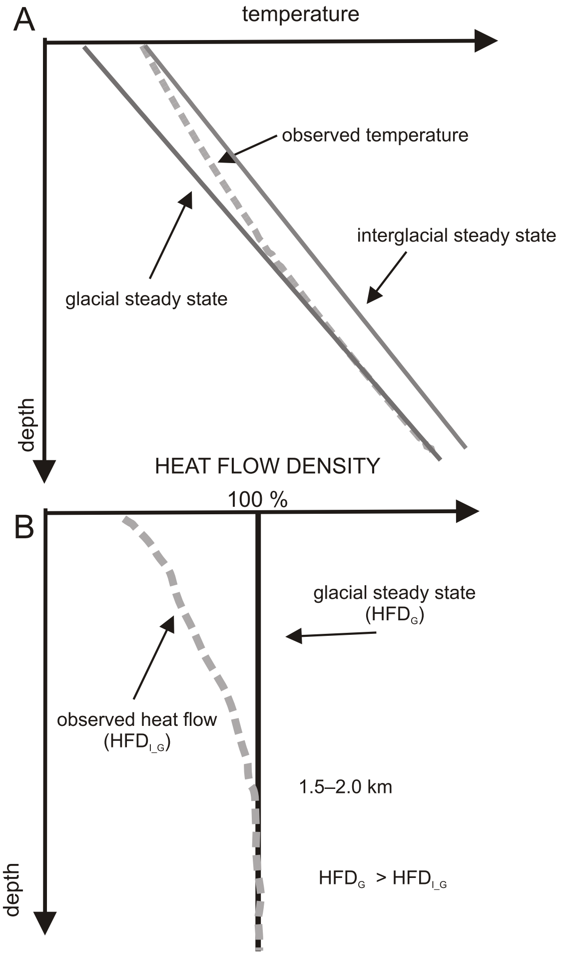

Fig. 10A — glacial *versus* interglacial steady-state and their influence on heat flow density determination (B)

phenomena: subsurface stationary heat flow running from the Earth interior towards the surface, and changes in climatic temperature during glacial periods (including primarily the Vistulian Glaciation). Temperature of the Earth's surface was controlled in the past by climatic changes of much longer duration than those from the last four glacial cycles i.e. about 100 ka years (Petit *et al*., 1999). For earlier time the period cycles was 41 ka. Thermal regime at greater depths would have had a slow-changing quasi-stationary character.

By calibrating heat flow values with reference to a glacial period we eliminate the effect of climatic disturbances to extract information related mainly to geological factors controlling the heat flow value (see formula 3).

The idea of this method and the results of modelling of temperature changes for a homogeneous medium (stepwise temperature change is assumed between glacial and interglacial periods) are illustrated in Figure 11.

If we take any one of the points from the drill log (whose temperature is relatively weakly disturbed i.e. situated at section BC) as the first point, and a point representing the palaeotemperature ($\mathrm{GST_P}$) at the Earth's surface (point A corresponding to climatic conditions from the Late Pleistocene) as the second point, then we can calculate a heat flow value and create a palaeotemperature profile for the glacial period. This temperature is a special case of the synthetic temperature T_s calibrated in the upper, near-surface part of the section with reference to the climatic palaeotemperature of this period ($\mathrm{GST_P}$).

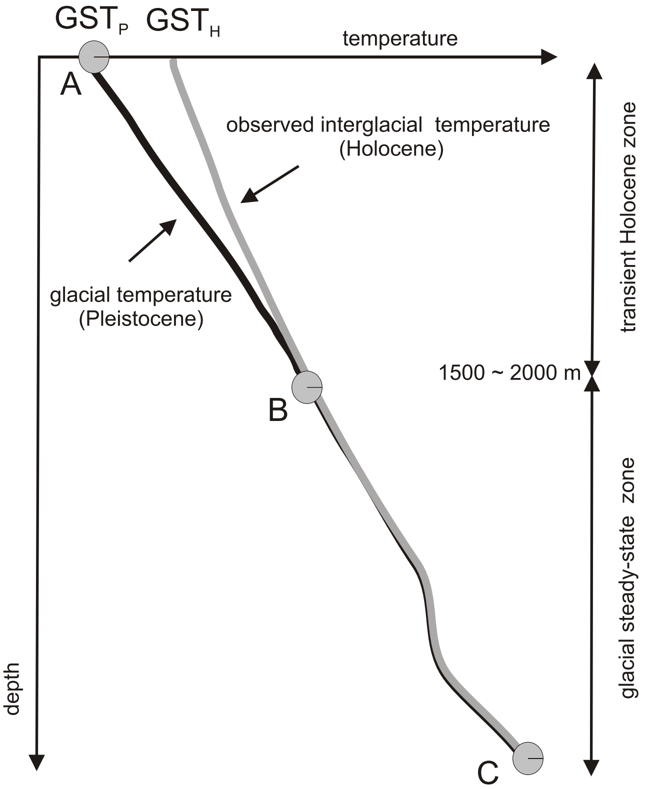

Fig. 11. Proposed new method of the determination of the heat flow density

Explanations as in Figure 9

It is worth noting that this method can substantially extend the range of geothermal data possible to be used in determination of heat flow density. Boreholes with even single temperature measurements (bottom hole temperature) can be used for this purpose.

Two methods can be used in estimating the heat flow value: (1) a "global" iteration method of fitting the calculated temperatures to real temperatures for individual sections of the temperature profile in areas that remain beyond the influence of the Holocene warming (section BC >1500–2000 m), and (2) the afore-mentioned two-point method (section AB). The results of both these methods for steady-state temperature profiling within the depth zone situated beyond the range of the Holocene warming are equivalent.

By making such a calibration along the section BC we can calculate the mean palaeotemperature value in the near-surface zone ($\mathrm{GST_P}$) for the Vistulian Glaciation. Such calculations have been made for 66 deep boreholes with sufficiently long thermal measurement intervals remaining beyond the range of climatic fluctuations. Figure 12 presents a histogram of $\mathrm{GST_P}$ values — the average value is –7.0°C at standard deviation SD = ±4.0°C. The relatively high standard deviation value is due to errors in both temperature measurements and thermal conductivity determinations. It can also result from a spatial variability in the mean climatic temperature for the Vistulian Glaciation in Poland, impossible to be determined at the present stage of research.

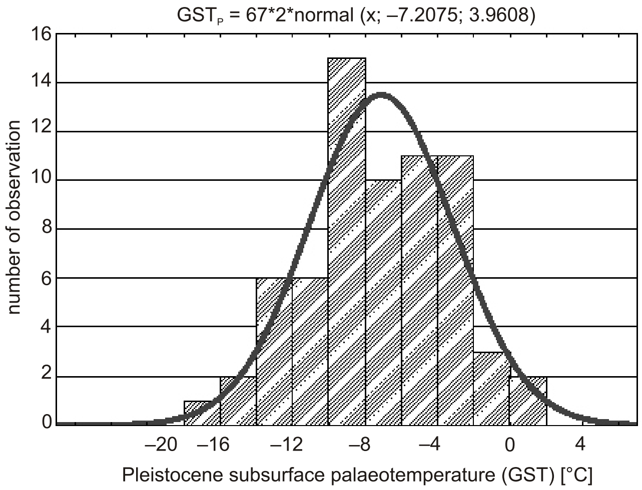

Fig. 12. Histogram palaeotemperature GST for Weichselian Glaciation for Poland based on geophysical method

HEAT FLOW DENSITY MAP

Interpretation work has resulted in calculation of heat flow density values for 308 deep boreholes drilled in Poland and southern Baltic Sea. The calculation of heat flow value for all 308 boreholes was based on a two-point method with the mean surface palaeotemperature at 7°C (point A, Fig. 11). Figure 13 presents a resultant map showing also location of measurement points.

The spatial image of heat flow density confirms the presence of high heat flow values across the Palaeozoic platform, especially in areas of Variscan externides. Low values are observed in the Precambrian platform; they are extremely low in areas where rock massifs have low radiogenic heat productivity (Szewczyk, 2005). A distinct change is observed in the range of heat flow density variability that falls within the interval from approximately 38 $\mathrm{mWm^{-2}}$ in the Suwałki Massif to almost 107 $\mathrm{mWm^{-2}}$ in the Fore-Sudetic Monocline. This is a consequent image, although influenced by insufficient number of

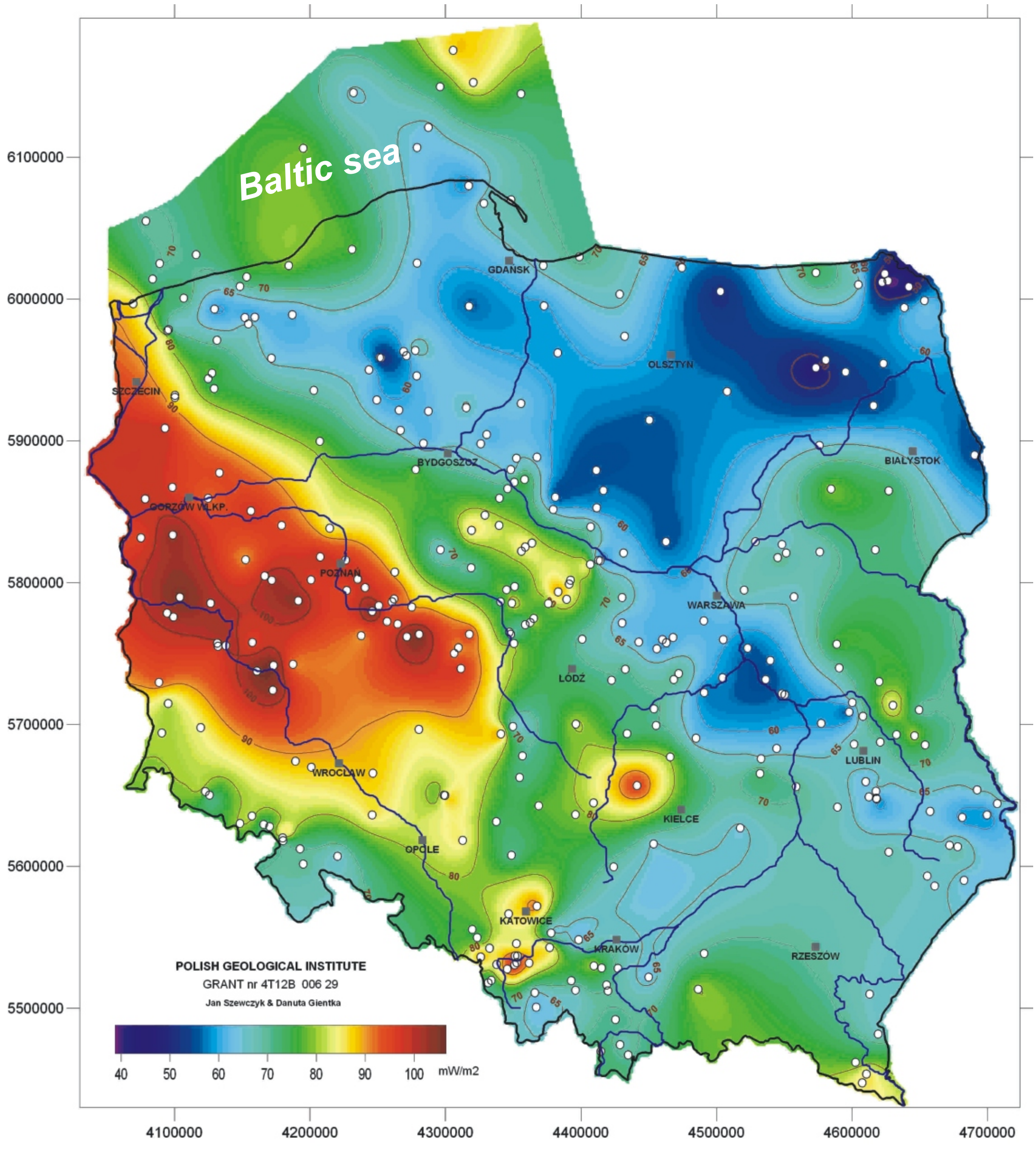

Fig. 13. New map of the heat flow density for Poland

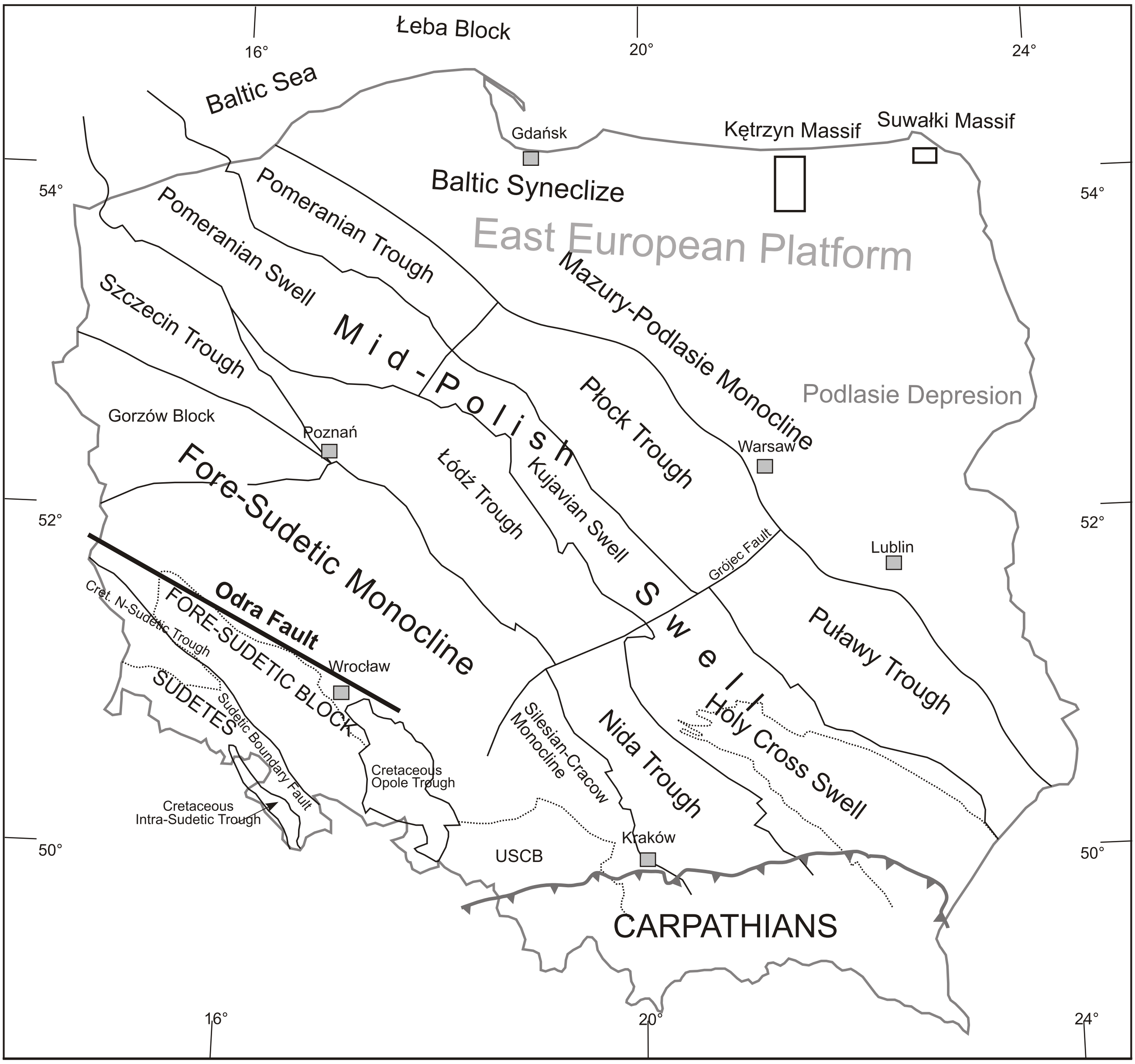

Fig. 14. Geological regional subdivision of Fore-Carpathian Poland at sub-Cenozoic palaeosurface (after Narkiewicz and Dadlez, 2008, modified) with some elements of main tectonic units and a localization information

measurement points in some areas. The obtained heat flow values are generally higher relative to the values from adjacent countries where no palaeoclimatic factors have been taken into consideration for the heat flow map construction.

In general, the pattern follows the previously recognized image of heat flow distribution: low values in the East European Platform and high values in the Palaeozoic platform. Due to the multiple increase in the number of wells drilled (especially in the Polish Lowlands), the image of individual anomalous zones is more detailed.

The overall pattern of heat flow distribution reflects the subsurface geological structure (Fig. 14). The area of old Precambrian platforms is characterized by low heat flow values. The lowest figures (<40 mWm^{-2}) are recorded in the north-east part of Poland (Suwałki and Kętrzyn anortosite massifs) with rocks containing a very low amount of radioactive elements resulting in a low radiogenic heat production. In adjoining areas where granitoids are dominant in the basement, the mean heat flow density is 55–65 mWm^{-2}.

The spatial image of heat flow pattern in the Precambrian platform is undoubtedly highly determined by the distribution of boreholes, including those providing thermal data. Most of the boreholes were drilled in gravity-magnetic anomaly areas because they were aimed mainly at exploration of ores. The basement lithology of these zones is probably untypical of the areas surrounding the anomaly zones.

In the western end of the Pomeranian Trough (Łeba Elevation) there is a zone of elevated heat flow values ranging from over 70 mWm^{-2} in the Słupsk region to 80 mWm^{-2} near Jamno. It continues into the Baltic Sea area. Low heat flow zones ob-

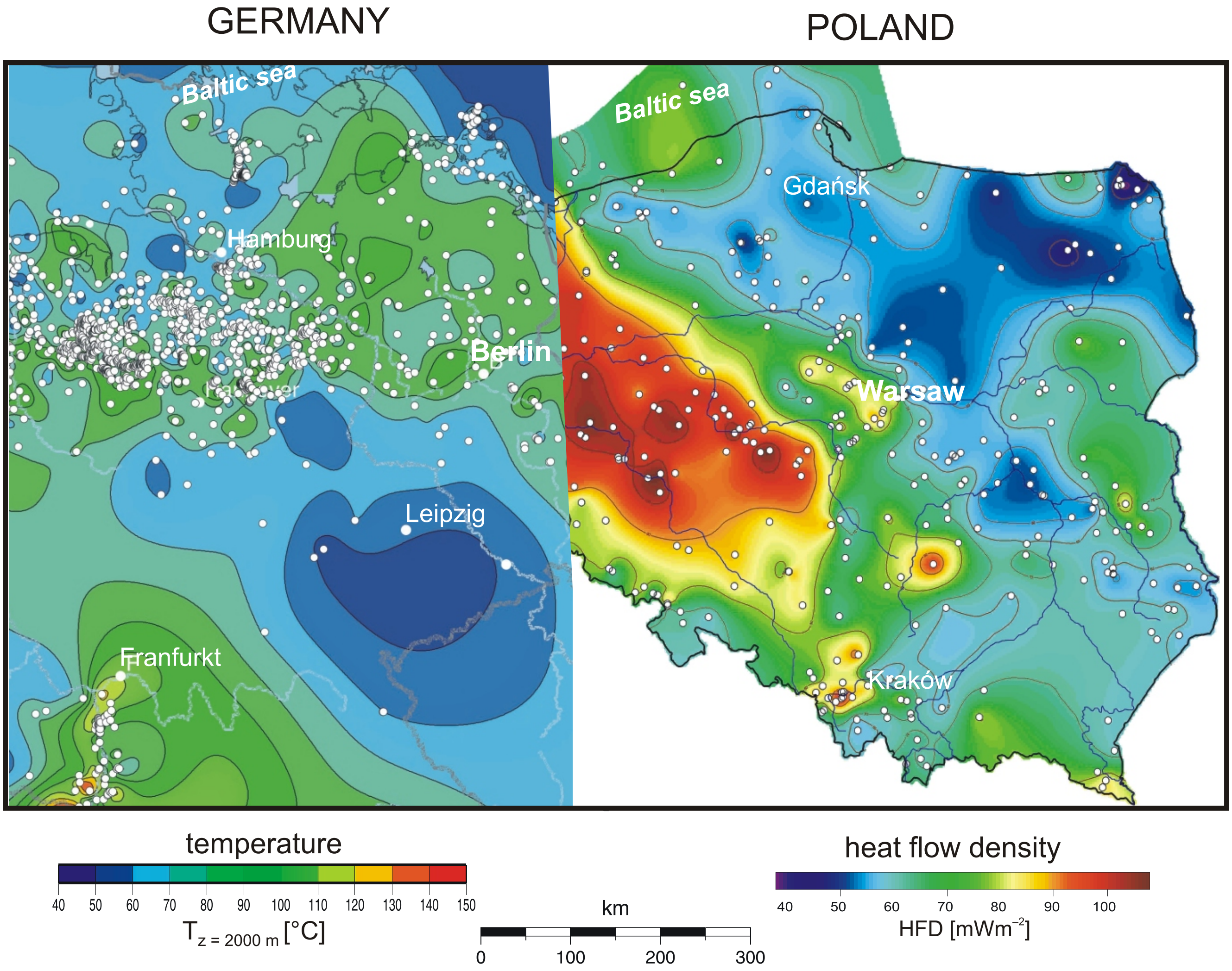

Fig. 15. Comparison of new heat flow map (Poland) with temperature map for 2000 metres depth for NW Germany (temperature map after Schellsmidt, 2006, modified)

served near Kamień Pomorski also continue into the Baltic area. A quite new feature is a prominent zone of elevated heat flow extending to the north of Rozewie within the so-called Łeba Block. This anomaly zone may represent an extention of a zone of elevated heat flow values observed in eastern Sweden and adjacent Baltic areas.

The Kujawy–Pomeranian Swell, with its numerous salt structures, is manifested as a zone of elevated heat flow values (65–89 mWm^{-2}) as compared with the East European Craton. However, the craton boundaries do not coincide with the extent of the high heat flow zone.

The Małopolska Massif splits into two zones: the western zone of the Miechów Trough showing elevated heat flow values of 65–95 mWm^{-2}, and the eastern zone manifested by low heat flow values in the northern end of the Carpathian Foredeep.

The Carpathians, in particular their western regions, are characterized by a low heat flow density gradually increasing eastwards. The central part of the Carpathians shows a distinct increase in heat flow density recorded in the only borehole drilled in this area (Siekierczyna IG 1). A well-pronounced increase in heat flow values is also observed in the eastern part of the Carpathians. It may be associated with an extensive zone of high heat flow reported from Slovakia and Hungary (Hurter and Haenel, 2002).

Generally moderate heat flow values are observed in the Sudetes, very poorly explored in terms of thermal conditions, especially in the western regions.

Upper Silesia is conspicuous by a zone of high heat flow values that finds its continuation into the area of Czech Republic. A mosaic of heat flow values, suggested in earlier reports, has not been corroborated.

Heat flow values rapidly increase in foldbelt areas of Variscan externides and in the northern zone of Lower Silesian internides, reaching the maximum level in Poland of over 107 mWm^{-2}. The northeastern boundary of the Variscan front, probably identical with the well-pronounced limit of the high heat flow zone is relatively clearly expressed here. The southwestern part of the anomaly zone corresponds likely to the Odra Fault.

Unclear is the relationship between the southeastern end of the anomaly zone and the tectonic structure of the area (Dadlez *et al.*, 1994). The anomaly zone has its continuation into the North German Basin. Figure 15 illustrates a set of thermal data from Poland (heat flow map) and Germany (2000 m depth temperature map). The existing heat flow map for Germany is considered to be poorly reliable (Lotz and Forster, 2002) — the temperature map for a depth of 2000 m (beyond the range of climatic influence) is thus a more reliable approximation of the thermal field.

As suggested by Śliwiński *et al*. (2006), a deep depression filled probably with an Upper Carboniferous molasse occurs in a zone adjoining the Variscan front under Permian deposits. It may reflect a contact of folded Lower Carboniferous rocks with the Upper Carboniferous sequence. It is worth noting that the Upper Carboniferous succession is characterized in Poland by the highest gamma ray values up to 145 API (Szewczyk, 2000). It corresponds to radiogenic heat equal to approximately 2.3 μWm^{-3} (Norden and Foester, 2006). Assuming that radiogenic heat of sedimentary rocks outside the anomaly zone is of about 0.8 μWm^{-3}, the observed difference in heat flow values between the anomaly zone and the Precambrian platform (craton) is about 35–40 mWm^{-2}. Such high variations in heat flow values are accompanied by a considerable difference in present-day temperatures in both these areas, reaching over 40–45°C at a depth of 3000 m (Fig. 4B).

Even if the Upper Carboniferous succession is a few kilometres thick (producing radiogenic heat), it does not explain the observed anomaly magnitude. Thus, the source of the thermal anomaly should due to huge differences in lithosphere thickness in both areas. (Jarosiński and Dąbrowski, 2006; Wilde-Piórko *et al*., 2006). This problem could be solved by further investigations. The key element, necessary to analyse properly the relationships, should be recognition of the depth distribution of radiogenic heat within the shallow crust (including sedimentary formations). Both the significant progress in interpretation of archival geophysical data, including those concerning calibration of gamma ray logs (Szewczyk, 2000), and the increasing number of drillholes with spectrometric gamma ray logging currently enable undertaking a study on the estimates of radiogenic heat contribution to the heat flow density values.

The relationships between the thermal field and tectonic structure were subject of numerous analyses and discussions in the past. The regional distribution of heat flow might have been affected by various factors, such as subcrustal remnant heat related to tectonophysic processes and the distribution of radiogenic heat sources in the sedimentary formations and crystalline basement.

The issues of interpretation of geothermal research in terms of relating geothermal parameters to tectonic units should be treated with much caution (Majorowicz, 1982). Further studies of the relationship between the thermal field image and the subsurface geological structure in Poland will undoubtedly provide more detailed information.

CONCLUSIONS

Geothermal data are an important source of information for palaeoclimatic studies in the area of Poland due to its specific position throughout the Late Pleistocene glaciations. During the Vistulian Glaciation, the area was under mainly a periglacial climate as a result of the thick ice sheet in Scandinavia. In Northern Poland, periods of ice sheets (up to approximately 300 m in thickness) were relatively short climatic episodes that weakly influenced the subsurface thermal regime of the areas.

A spectacular achievement, very important in terms of both geothermal and palaeoclimatic problems, was a discovery of a deeply seated relict permafrost (of original thickness reaching almost 600 m) near the Suwałki anorthosite massif (Szewczyk and Gientka, 2003; Šafanda *et al*., 2004). The modelling of this phenomenon resulted in, among others, estimation of effective palaeotemperature during the Vistulian Glaciation, whose value for Northern Poland was determined at –10.3°C (Šafanda *et al*., 2004). Although the phenomenon of deep permafrost formation was related to local geological conditions (Szewczyk, 2007), its presence is an evidence for a specific climate in Central Europe.

The data obtained have significantly modified the knowledge on climatic conditions during Late Pleistocene times in Central Europe. They also pointed to a need of a thorough revision of the existing heat flow determinations in other regions (Balling, 2002; Szewczyk, 2002; Szewczyk and Gientaka, 2004; Gosnold *et al*., 2005).

It should be stressed that in classical method of HFD determination which is based on the relation [1] and laboratory-determined thermal conductivity (*K*), in complete saturation of rock samples in laboratory conditions (especially shale; see Fig. 2), unstable-thermal regime in borehole conditions (Fig. 3), and palaeoclimatic influence (Fig. 4A), will be lower than the actual value in all cases of HFD.

Besides taking no account of the palaeoclimatic factor, the second main shortcoming in the construction of previous heat flow maps, not only for Poland but also for other countries, was inhomogeneous nature of the methods for calculating heat flow values. Those were most often compilation maps constructed based on heat flow determinations made at various times and by different authors usually using different methods and not always comparable laboratory data employed in heat flow measurements.

The very optimistic result of the research was a demonstration that most of the data are sufficiently reliable for heat flow determinations, despite many opinions about their low reliability.

The most important element of the studies was the application of a uniform interpretation method for the whole territory of Poland at all research stages, including a procedure of eliminating palaeoclimatic effects. It highly enhanced the reliability of the results, exposing predominantly geological factors in the observed heat flow variability.

An unsolved dilemma is the problem how to calibrate the heat flow values. For the present authors, the solution is obvious: calibration should be performed with reference to cool periods. Long duration of glacial periods in the Late Pleistocene history indicates that, for depth exceeding 1500–2000 m, the "cool" glacial regime of the Earth (Szewczyk and Gientka, 2003) is a state of thermal equilibrium from the point of view of practical geological knowledge.

The method of heat flow determination, applied in the construction of the present map, will allow easy incorporation of new measurement points. The current state of thermal field exploration in Poland provides the possibility of making the image of spatial variability of the terrestrial heat flow density more detailed, mainly by introducing bottom hole temperature (BHT) data. The created database can be used in any geothermal modelling, including construction of other map versions based on alternative interpretation models.

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