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Burial and thermal history of the Polish part of the Baltic region

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The burial history and thermal evolution of the western part of the Baltic region was reconstructed by means of 1-D modelling for eight boreholes penetrating the lower Paleozoic succession. The Neoproterozoic rifting presumably caused elevation of heat flow, while Cambrian to Mid Ordovician post-rift thermal sag of the Baltica passive margin led to systematic decrease of heat flow with time. Development of the Late Ordovician to Silurian flexural foredeep of the Caledonide collision zone was associated with intensive subsidence, a high rate of sediment deposition and rapid burial of the Upper Cambrian and/or Tremadocian, Upper Ordovician and lower Silurian source rocks, presumably sufficient for the early stage of oil generation. After post-Caledonian Early Devonian uplift, the western Baltic region was subject to Early Devonian to early Carboniferous subsidence and deposition, leading to further burial of the source rocks. Together with elevated heat flow, characteristic of the Variscan broad foreland, this caused further source rocks maturation and hydrocarbon generation. Late- to post-Variscan uplift and erosion (late Carboniferous to late Permian) resulted in complete removal of the Middle Devonian to lower Carboniferous strata and development of the major regional unconformity. During late Permian to Cretaceous time the western part of the Baltic region constituted an eastern flank of the Polish Trough, with the main phases of subsidence and burial during late Permian–Early Triassic time, related to rifting in the Polish Trough, and during Late Cretaceous time, related to the compressional regime. Maturity profiles in boreholes from the vicinity of the studied boreholes indicate the presence of a late Mesozoic (Late Cretaceous?) positive thermal event, causing further maturation of the source rock.

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Key words: Baltic region, Northern Poland, subsidence, burial history, thermal evolution, maturity modelling.

INTRODUCTION

The study area is located in the Northern Poland, on the western slope of the East European Craton, where polygenetic sedimentary basins developed during Neoproterozoic–Phanerozoic times, with two major ones being the lower Paleozoic Baltic region and the upper Permian–Mesozoic Polish region. The major volumetric contribution to the sedimentary basin is, however, made by lower Paleozoic deposits.

In the present research, tectonic subsidence analysis was performed for the area studied to document the subsidence mechanism, and to obtain indirect qualitative constraints on the evolution of the thermal regimes with time. Previous studies of the tectonic subsidence of the Baltic Basin (Poprawa *et al*., 1999; Poprawa, 2006*a*, *b*, 2007*a*) revealed a characteristic pattern that was coherent across the entire basin. Subsidence exponentially decaying with time is indicative of late Neoproterozoic to earliest Cambrian rifting and Cambrian–Mid Ordovician post-rift thermal sag (Fig. 2). A convex-up type of subsidence curve is suggestive of Late Ordovician–Silurian flexural bending of the western slope of Baltica (*op. cit.*).

Sediments deposited in the interval between the Early Devonian to the early Carboniferous, in the Polish part of the Baltic region were nearly completely eroded in late Carboniferous to early Permian time. Their primary presence can be inferred from palaeogeographic and palaeotectonic reconstructions based on extrapolation of profiles of late Paleozoic strata in Western Pomerania, as well as in the Lithuanian–Latvian part of the Baltic Basin (Matyja, 2006).

During late Permian and Mesozoic times the area studied constituted the northeastern part of the Polish region. Subsidence analysis for this area indicate three main tectonic events of regional scale: late Permian–Early Triassic, Late Jurassic, and Late Cretaceous (Dadlez *et al*., 1995; Karnkowski, 1999).

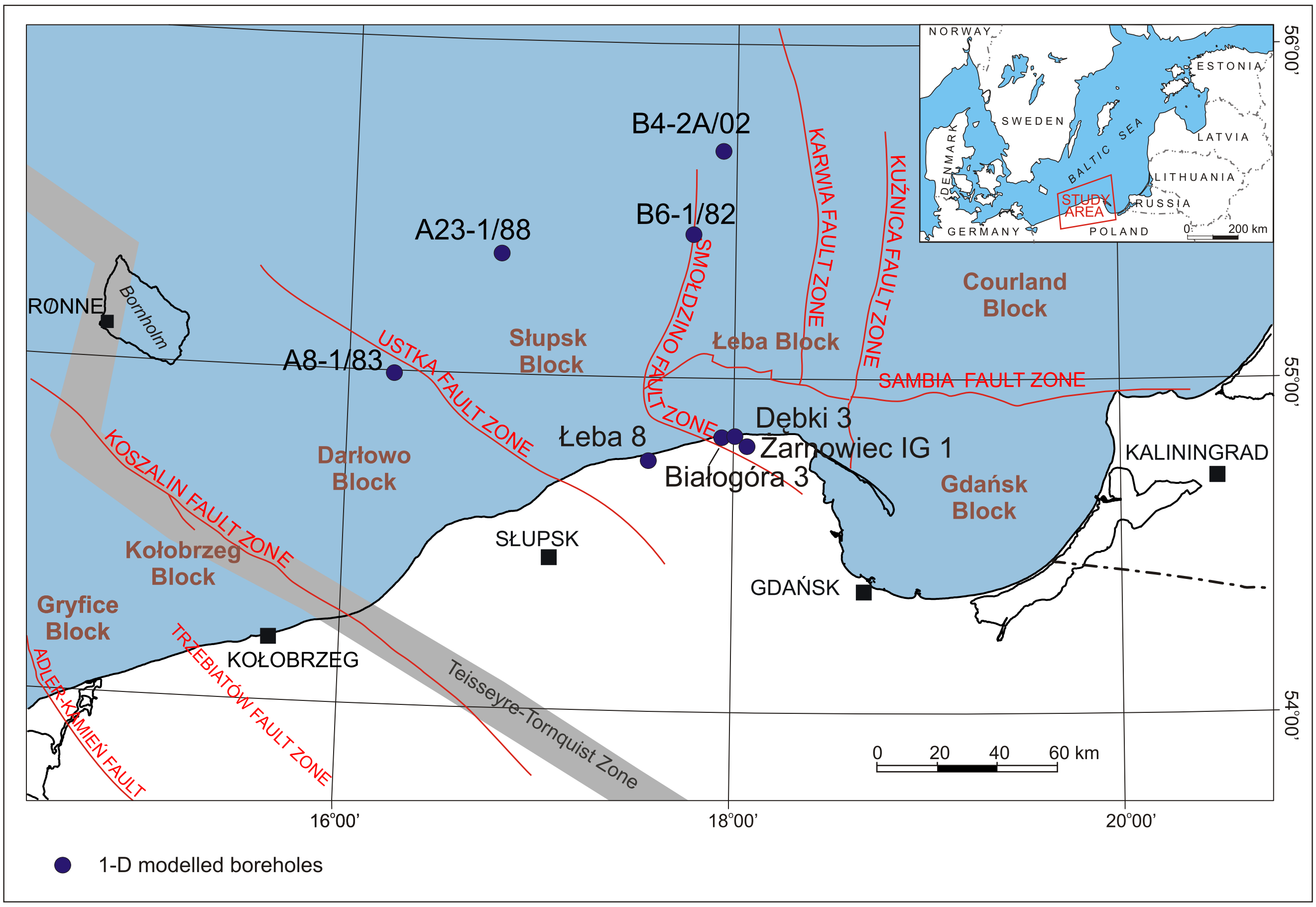


Fig. 1. Sketch tectonic map of the Polish part of the Baltic region and location of 1-D modelled borehole

Fault system after Pokorski (2010)

For the two first an extensional to transtensional regime was suggested, while the last one was related to a compressional tectonic regime (*op. cit.*).

The Permian–Mesozoic succession was are deposited directly on partly eroded lower Paleozoic strata. The thickness of this succession systematically increases to the west, and the presence of evaporites in the Zechstein profile significantly hinders recognition of the Paleozoic strata. The uppermost part of the sedimentary section is composed of poorly consolidated Cenozoic deposits of small thickness.

The presence of a major unconformity, covering a long geological time interval from the late Silurian to the late Permian, has a significant impact on reconstructions of thermal evolution and hydrocarbon generation history in the Baltic region. In the time period represented by the unconformity, two separate tectonic uplift and erosion events occurred, the quantitative proportions of which are difficult to constrain. Total removal of the upper Paleozoic strata significantly hinders reconstruction of the burial history of the lower Paleozoic source rocks, especially reconstruction of the maximum burial conditions.

The main aim of the conducted study was to reconstruct the Phanerozoic thermal history of the area studied. Quantitative reconstruction of heat flow changes through time was of particular importance, due to its direct impact on the hydrocarbon generation history. Previously the thermal history of the Baltic region has been analysed by means of thermal maturity studies, including analysis of the Conodont Alteration Index, reflectance of vitrinite-like macerals and pyrolytic Rock-Eval T_{max} (Nehring-Lefeld *et al.*, 1997; Swadowska and Sikorska, 1998; Kosakowski *et al.*, 1999), as well as maturity numerical modelling (Kosakowski *et al.*, 1999; Karnkowski, 2003; Poprawa and Grotek, 2005).

Some of the analyses have led to the suggestion of Variscan heating as a main thermal event in the evolution of the area (Majorowicz *et al*., 1984; Kosakowski *et al*., 1998; Poprawa *et al*., 2002; Karnkowski, 2003; Poprawa and Grotek, 2005), however, quantitative results of the individual studies are not consistent. Syn-rift heat flow elevation in the Baltic region was proposed by Kosakowski *et al*. (1999) for the Early Cambrian, by a systematic decrease of heat flow, connected with the post-rift stage of basin development. Also, the presence of a late Mesozoic thermal event was suggested based on analysis of maturity profiles, which could be reconstructed by assuming a high heat flow and/or additional heat production during the Cretaceous (Poprawa and Grotek, 2005). According to that model the lower Paleozoic source rocks might have generated hydrocarbons also during late Mesozoic time. Moreover, based on maturity profiles analysis, Poprawa and Grotek (2005) suggested overpressure retardation of maturation within lower Paleozoic fine-grained clastic deposits of the Baltic region. In the current study these hypotheses were tested on the scale of the study area.

METHODS APPLIED

One-dimensional backstripping was conducted to reveal-tectonic subsidence pattern, with the aim of identifying palaeotectonic regimes and subsidence mechanisms. For the analysis the following data were quantitatively balanced: thickness of individual stratigraphic units, numerical ages defining the time interval between the upper and lower limit of each stratigraphic unit, bathymetric changes in time, and petrophysical parameters for the individual units (compaction coefficient, initial porosity, thermal conductivity, heat capacity). The backstripping procedure incorporated isostatic correction, calculated according to the Airy model. A significant difficulty was reconstruction of the thickness of the strata removed by erosion. This was constrained by analysis of regional thickness trends in those areas with a better preserved sedimentary cover, as well as by maturity numerical modelling.

Thermal history was reconstructed with the use of 1-D modelling, calibrated with vitrinite reflectance R_o and Rock-Eval T_{max} temperature (BMRM, 2000). The modelling employed data defining the burial history, comprising the stratigraphy and thickness of the intervals distinguished as well as petrophysical parameters of rocks, the contemporary thermal regime and the present thermal maturity.

The two most important elements in calibration of the modelling of thermal maturity are burial history and changes in heat flow. The burial history is mainly influenced by the thickness and stratigraphy of the intervals distinguished. Sometimes no detailed stratigraphic data were available, therefore lithostratigraphic data were used. The geologic time scale by Gradstein *et al.* (2004) was used.

In the burial model an allowance for decompaction was made with the use of the Baldwin and Butler (1985) algorithm. A comparative analysis was made with an alternative model after Sclater and Christie (1980) as well as Falvey and Middleton (1981), revealing that the influence of the compaction parameter from these models based on the results of modelling is very small. The thickness of the eroded parts of profiles was assessed on the basis of extrapolation of the thermal maturity trend to surface values.

The maturity was modelled using the forward method, i.e. first the initial state of the system and definite geological process were assumed, then its effect on the contemporary distribution of thermal maturity in the profile was calculated. In the case of a discordance between calculated and measured maturity values, the procedure was repeated for other parameters until an optimum calibration was obtained. In the modelling procedure special attention was paid to the unique character of those alternative models with analogous or similar calibrations.

Important parameters in the thermal modelling are the thermal conductivity and thermal capacity of the sediments filling the basin. However, amounts of measured values are low and owing to the quality of the measuring devices applied, the results have a considerable range of error. Therefore, in the current study, for each type of lithology the thermal conductivity and the heat capacity of the mineral matrix were adopted from published values, based on averaged results of laboratory measurements for each lithological equivalent. Petrophysical parameters for each startigraphic unit were calculated taking into consideration the proportions of the basic lithological components. The modelling performed enabled accounting for changes though time of the above parameters as a function of porosity with burial (e.g., Dykstra, 1987).

Determining thermal conductivity and heat capacity is difficult because of the presence of thick successions with contrasting lithologies. The greatest anomalies of thermal conductivity in the profile are related to Zechstein evaporites composed of various types of halite, anhydrite, gypsum, as well as carbonates and clays. Ranges of values of these parameters are also broad for sandstones, claystones and carbonates. The assumed values of thermal conductivity and heat capacity had significant influence on the calculated values of contemporary and palaeo heat flow. In all cases, whenever possible, the contemporary heat flow was calculated on the basis of borehole thermograms.

Thermal maturity was calculated with the use of the Sweeney and Burnham (1990) algorithm. An alternative model of thermal maturity, *i.e.* the Lopatin-Waples algorithm (Waples, 1980, 1985), was also applied for the same sections. For very low thermal maturity, little significant difference from the results of modelling with the Sweeney and Burnham algorithm were observed. Beginning with the early “oil window” phase, the Lopatin-Waples algorithm for the same burial and thermal conditions assumes higher maturity values as compared to the Sweeney and Burnham algorithm. For maturity of the “gas window” phase or higher, the differences between models become more distinct.

As the modelling performed was calibrated with R_o and T_{max}, their quantity, quality and distribution in the profile determined the reliability of the results. In the lower Paleozoic succession the reflectance (R_o) values were measured from vitrinite-like macerals, increasing the range of possible error of analyses.

The performed modelling of thermal history also incorporated changes of average surface the temperature, i.e. temperature to which the entire sedimentary basin cooled down to (*cf.* Szewczyk, 2002). In the case of continental deposits this was established on the basis of reconstructed history of climate, whereas for marine deposits that was the temperature at the bottom of the reservoir. The long-period, mean surface temperatures were reconstructed by comparison of geographic latitude changes of the European plate with global climate changes (*cf.* Wygrala, 1989).

The thermal modelling was significantly limited by those factors influencing the thermal maturity, which were not connected with burial or conductive heat flow. In the case of the area analysed such factors could include migration of fluids that are anomalously hot or anomalously cool as compared to the ambient rocks, or potential palaeooverpressures (Poprawa and Grotek, 2005).

SUBSIDENCE HISTORY OF THE WESTERN BALTIC REGION

Development of sedimentary basin in the studied of the Baltic region part begun during latest Ediacaran to earliest Cambrian time with the phase of relatively rapid subsidence continuing until the Mid Cambrian (Figs. 2–4). Afterwards, the rate of tectonic subsidence decreased through time until the Mid Ordovician, creating an overall subsidence pattern characteristic of an extensional regime. These results compared to the regional subsidence pattern suggest a model of latest Ediacaran rifting, related to Precambrian supercontinent break-up, and subsequent thermal sag of the passive margin of southwestern Baltica (Poprawa *et al*., 1999; Jaworowski, 2000; Poprawa, 2006*a*).

The characteristic phenomenon is Mid Cambrian tectonic reactivation of the basin, expressed as a phase of more rapid subsidence (Figs. 3 and 4). The origin of this subsidence event is difficult to establish from available subsidence data, however, previously it was interpreted as extensional reactivation of the basin (Poprawa *et al*., 1999).

The rift model for the Baltic region requires extensional faulting, which apparently is not common. However, Martinsson (1968) and Floden (1980) reported the presence of Cambrian synsedimentary faults and fissures, being an expression of regional extension. Further west, on the western margin of Baltica, syn-rift extensional structures are better expressed, as documented by seismic data (Lassen *et al*., 2001).

During the Late Cambrian to the Middle Ordovician, the rates of subsidence and deposition rate were very low in the area analysed. At the same time the basin was laterally expanding and lateral facies variations were relatively small. This is suggestive of a thermal sag stage of basin development, and to lesser degree it might also be related to a high eustatic sea level.

Backstripping results allow us to conclude that the next stage of the basin's tectonic development began in Late Ordovician time and continued until the end of the Silurian. This stage was characterized by subsidence and deposition rates accelerating in time, with their maximum during the late Silurian, creating a convex-up type of tectonic subsidence curve (Figs. 2–4). This type of subsidence pattern is characteristic of compressional regime, and together with results of sediment provenance area analysis supports a model of the flexural foredeep of the North-German–Polish Caledonides which has been applied to the Upper Ordovician–Silurian Baltic Basin (Poprawa *et al*., 1999; Poprawa, 2006*b*, 2007*a*; Nawrocki and Poprawa, 2006). The tectonic loading of the plate at its western margin is responsible for a general westwards increase of sedimentary cover thickness.

A similar type of subsidence is observed further south along the East European Craton margin (Poprawa and Pacześna, 2002), and also towards the north-west in the Danish sector of the western Baltic Sea (Vejbæk *et al*., 1994) and in the Silurian basins of Eastern Avalonia (King, 1994) and Western Avalonia (Waldron *et al*., 1996). This all together indicates conversion from a Cambrian to Mid Ordovician passive margin geotectonic context into the Late Ordovician–Silurian convergent plate boundary related to Baltica-Avalonia oblique collision (comp. e.g., Cocks, 2000; Beier *et al*., 2000; Samuelsson *et al*., 2002; Torsvik and Rehnström, 2003; Nawrocki and Poprawa, 2006).

The foreland basin entered a shallow-marine and ultimately a continental stage only during the mid-Early Devonian in the Eastern Baltic region. Judging from development of the Silu-

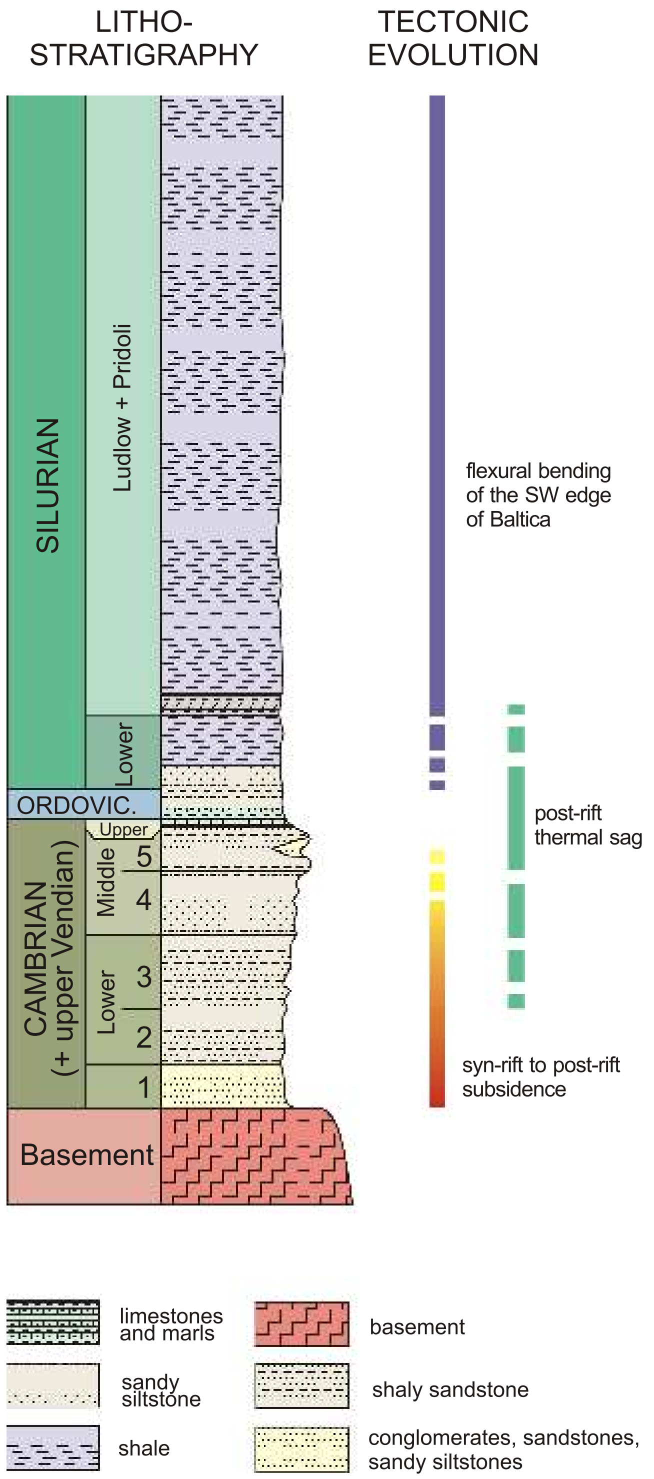


Fig. 2. Generalized lithostratigraphic section of the lower Paleozoic successions of the western part of the Baltic region and the main stages of tectonic evolution of the basin after Poprawa *et al*. (1999) and Poprawa and Pacześna (2002)

Lower and Middle Cambrian: 1 – Żarnowiec Fm. (upper Vendian–lowermost Cambrian), 2 – lower part of Lower Cambrian (including *Rusophycus parallelum*, *Platysolenites*, *Schmidtiellus mickwitzi* and *Mobergella*), 3 – upper part of Lower Cambrian (*Holmia–Protolenus*), 4 – *Eccaparadoxides oelandicus*, 5 – *Paradoxides paradoxissimus*

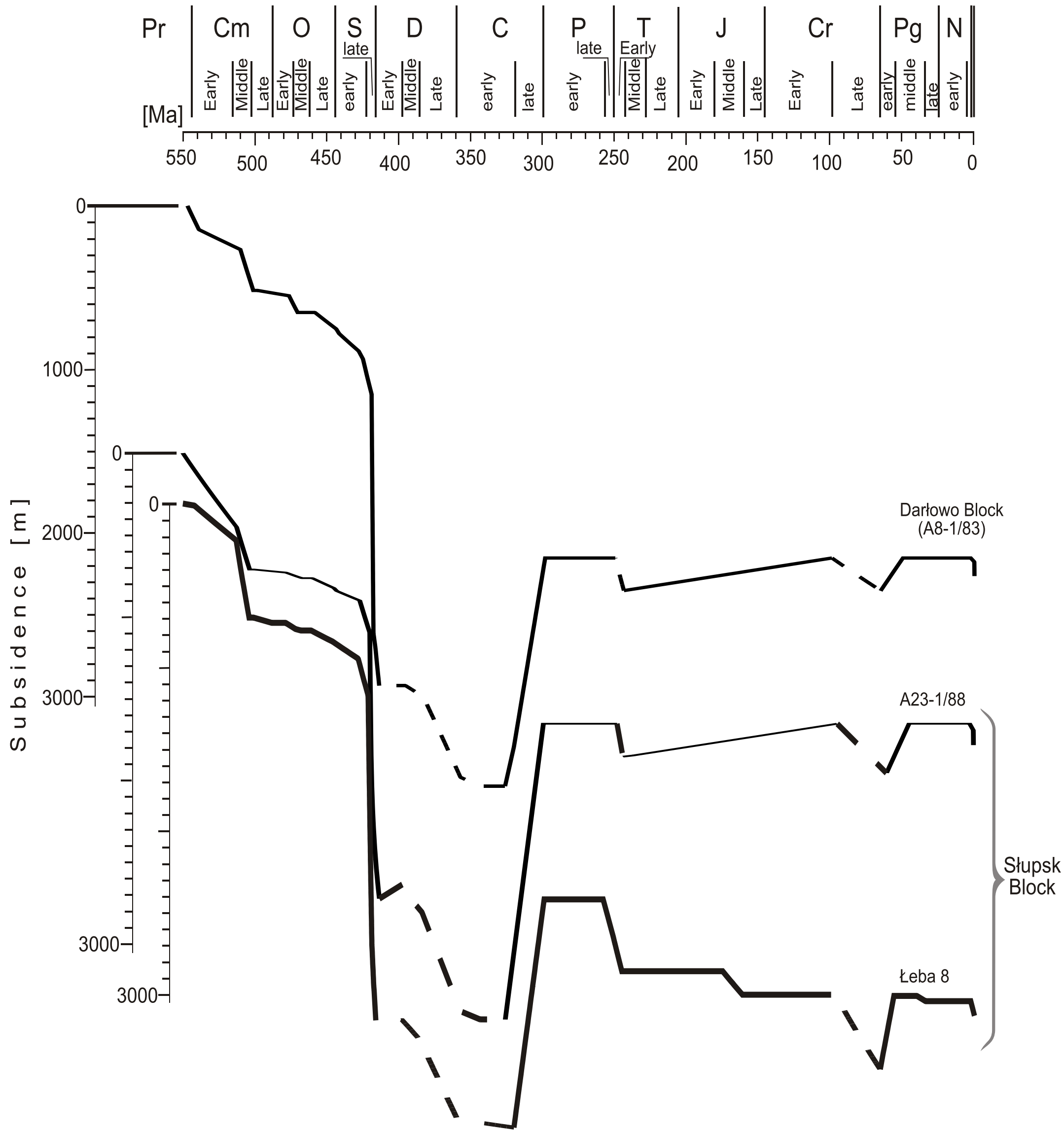


Fig. 3. Total subsidence curves of the bottom of the lower Paleozoic strata for the boreholes investigated in the Baltic region

Pr – Precambrian, Cm – Cambrian, O – Ordovician, S – Silurian, D – Devonian, C – Carboniferous, P – Permian, T – Triassic, J – Jurassic, Cr – Cretaceous, Pg – Paleogene, N – Neogene

rian/Devonian unconformity in the Koszalin–Chojnice Zone west of the analysed sector of the Baltic region as an equivalent, the western part of the basin was uplifted and eroded during Early Devonian time. This was at least partly related to post-collisional isostatic uplift. Taking into account the facies development of the Middle Devonian to lower Carboniferous strata in the Koszalin–Chojnice Zone, as well as in strata in the eastern part of the Baltic Basin (Matyja, 2006), the presence of strata of the same age in the area studied might be assumed. Quantitative subsidence development of that basin is, however, very difficult to reconstruct. The Devonian to lower Carboniferous deposits, were completely removed during post-Variscan (late Carboniferous to late Permian) uplift and erosion, caused mainly by tectonic stressess induced by strike-slip translation and/or collisions in the Trans-European Suture Zone, converted into a sinistral mega-shear zone (Ziegler, 1989, 1990).

During Early Devonian and late Carboniferous–late Permian phases of erosion, part of the upper Silurian section was also removed. Therefore, currently the upper Permian: Rotliegend and Zechstein facies sediments of the NE Polish region rest directly on Ludlow or Pridoli strata. Permian sediments were deposited at the beginning of the phase of rapid subsidence, continuing until the Early Triassic (Figs. 3 and 4), which correlates with a tectonic event in the Polish Trough interpreted as a rift event (e.g., Dadlez *et al*., 1995; Karnkowski, 1999). For most of the remaining part of Triassic, Jurassic and Early Cretaceous, limited subsidence or uplift is observed (Figs. 3 and 4).

During the Late Cretaceous, at a late stage of the Polish region development, the area analysed become a part of the Pomeranian marginal trough. As in the other marginal troughs of the Polish region, Late Cretaceous tectonic subsidence event is observed here. This event was interpreted as a result of regional

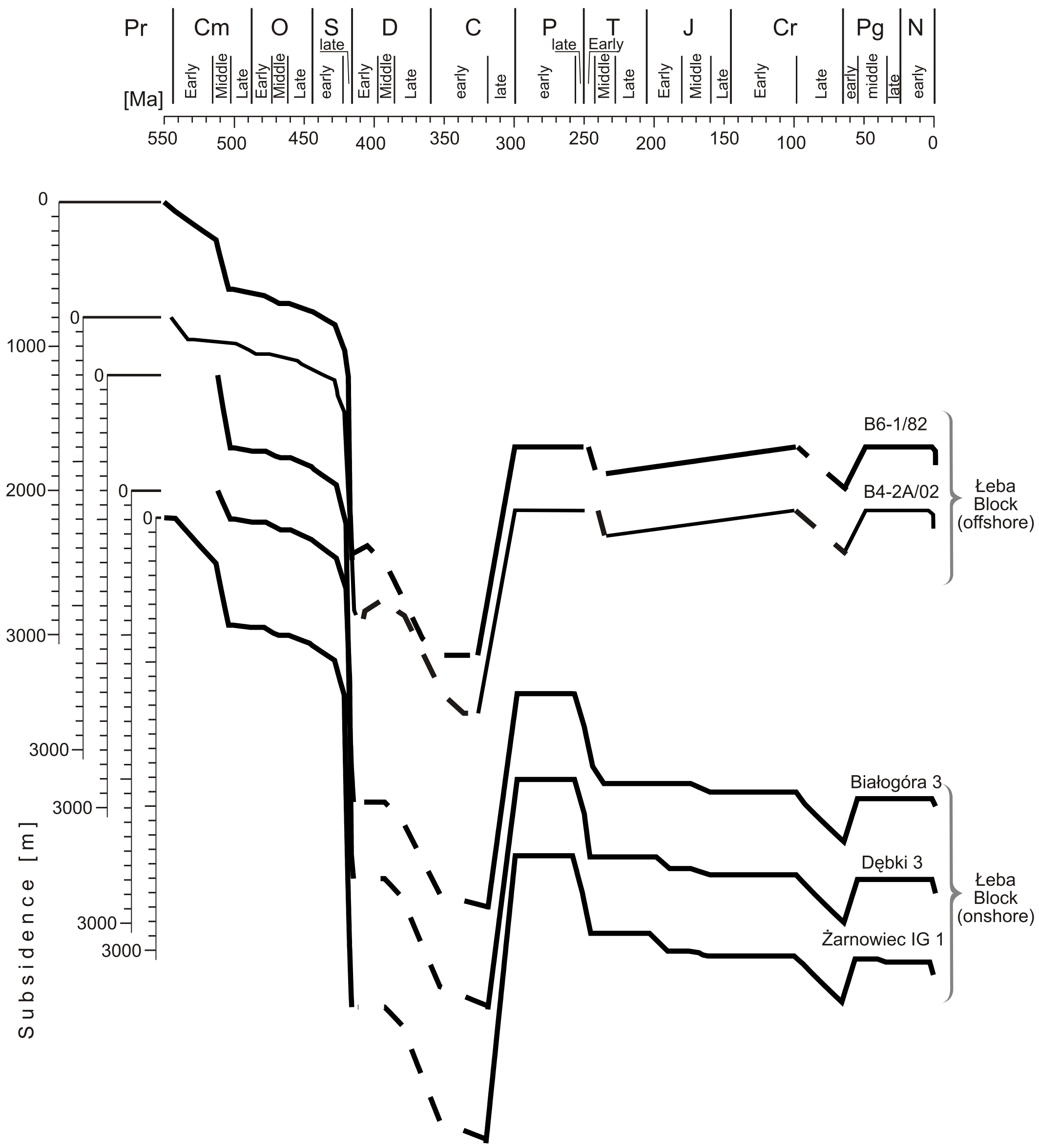


Fig. 4. Total subsidence curves of the bottom of the lower Paleozoic strata for the boreholes investigated on the Łeba Block (Baltic region)

Abbreviations as in Figure 3

compression based on the character of the subsidence curves (Dadlez *et al*., 1995), which is consistent with a kinematic and genetic interpretation of Cretaceous synsedimentary faults (Krzywiec, 2002).

THERMAL AND BURIAL HISTORY OF THE WESTERN BALTIC REGION – RESULTS AND DISCUSSION

1-D maturity modelling and a thermal and burial history reconstruction was conducted for 8 boreholes. These were the Łeba 8, Białogóra 3, Dębki 3 and Żarnowiec IG 1 in the onshore part, and boreholes A8-1/83, A23-1/88, B6-1/82 and B4-2A/02 in the offshore part of the study area (Fig. 1). The model of the recent thermal regime was calibrated with either well temperature logs (e.g., Żarnowiec IG 1 borehole) or indirectly with data obtained from maps of temperatures at the given depth horizons (Karwasiecka and Bruszewska, 1997). Calculated values of recent heat flow varies across the area analysed from *ca*. 38 mW/m^2 in its eastern and central part to *ca*. 50 mW/m^2 in the northwestern part (Figs. 5 and 6). These do not differ significantly from the data published previously (e.g., Karwasiecka and Bruszewska, 1997), and any discrepancies between recent heat flow values obtained in this study and previously published ones are result of different assumptions of thermal conductivity.

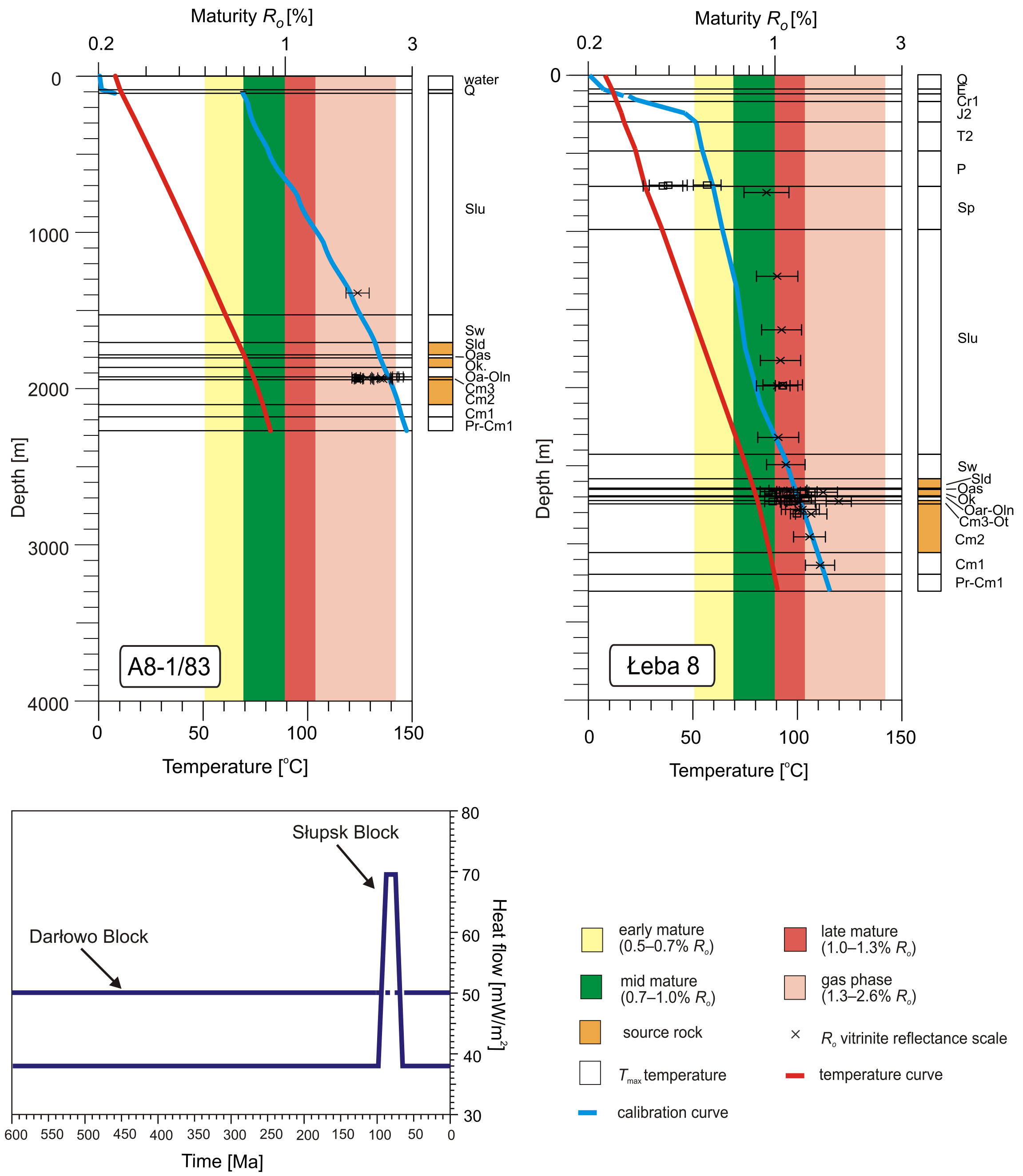
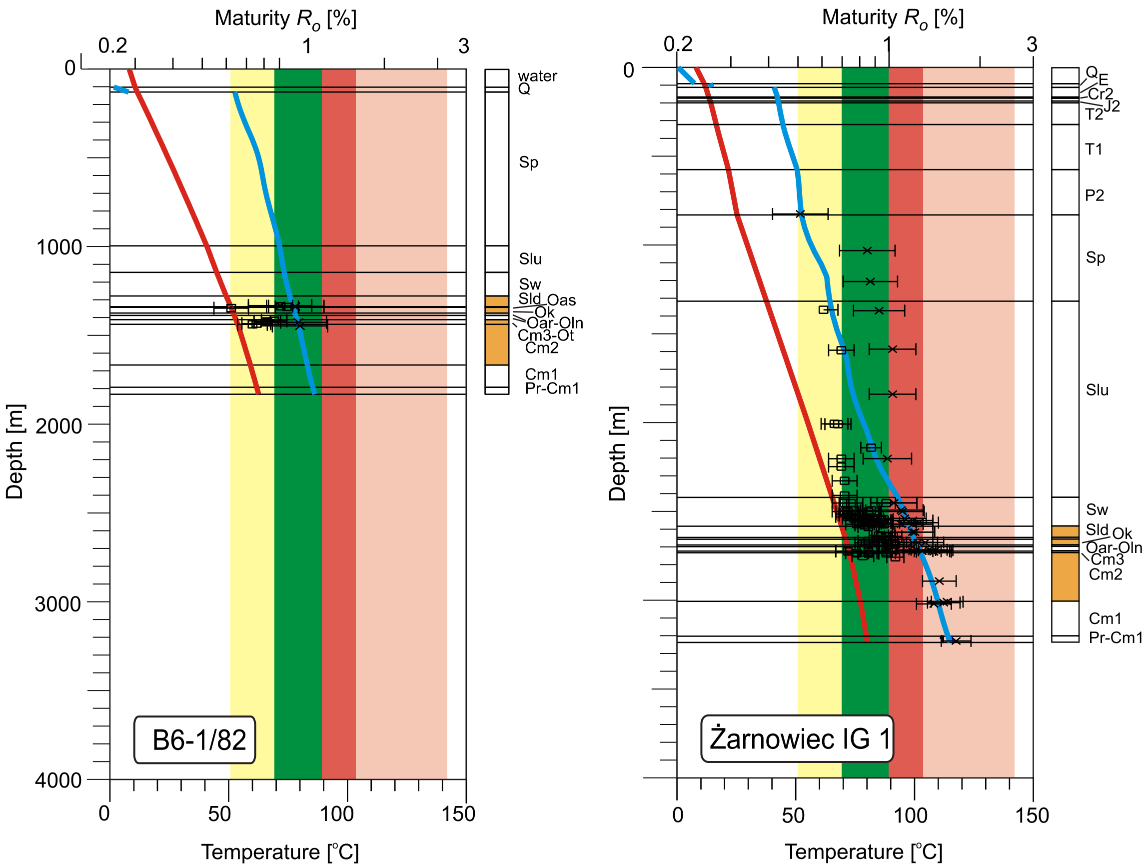


Fig. 5. Modelled maturity and temperature trends in the A8-1/83 and Łeba 8 boreholes using the heat flow history on the Darłowo and Słupsk blocks (western part of Baltic region)

Q – Quaternary; E – Eocne; Cr1 – Lower Cretaceous; J2 – Middle Jurassic, T2 – Middle Triassic; P – Permian; Sp – Silurian (Pridoli); Slu – Silurian (Ludlow); Sw – Silurian (Wenlock); Sld – Silurian (Llandovery); Oas – Ordovician (Ashgillian); Ok – Ordovician (Caradocian); Oln – Ordovician (Llanvirnian); Oar – Ordovician (Arenigian); Ot – Ordovician (Tremadocian); Cm3 – Upper Cambrian; Cm2 – Middle Cambrian; Cm1 – Lower Cambrian; Pr – Precambrian

The maturity modelling was calibrated by thermal maturity measurements, mainly reflectance of vitrinite-like macerals and Rock-Eval pyrolytic T_{max} temperature. In most cases the quantity of thermal maturity measurements, and particularly their distribution across the section, are insufficient to obtain a unique solution from the modelling. For some sections (Łeba 8 and Żarnowiec IG 1 boreholes) numerous thermal maturity measurements properly distributed across the section were available, however, the very complex character of the thermal maturity profile caused difficulties in proper calibration of the model.

Given these limitations of the maturity modelling, a few thermal and burial scenarios were analyzed. These included a scenario of heat flow constant in time, an Early Cambrian



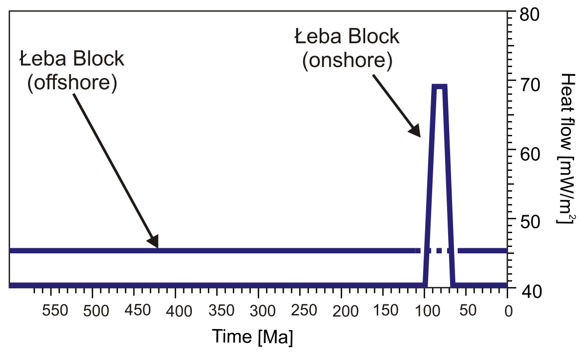


Fig. 6. Modelled maturity and temperature trends in the B6-1/82 and Żarnowiec IG 1 boreholes using the heat flow history on the Łeba Block (western part of Baltic region)

T1 – Lower Triassic, Cr2 – Upper Cambrian; other explanations as in Figure 5

syn-rift heat flow elevation (Kosakowski *et al*., 1999), a heat flow elevation during maximum Variscan burial (Majorowicz *et al*., 1984; Kosakowski *et al*., 1998; Poprawa *et al*., 2002; Karnkowski, 2003; Poprawa and Grotek, 2005; Poprawa, 2007*b*) and a model of a late Mesozoic themal event (Poprawa and Grotek, 2005).

The Early Cambrian syn-rift heat flow elevation in the Baltic region, followed a systematic decrease in heat flow through time, related to a post-rift stage of basin development, was proposed by Kosakowski *et al*. (1999). This was based exclusively on a tectonic model of the basin (Poprawa *et al*., 1999). However, results of the current study indicate that, due to subsequent deep burial of strata which might have previously experienced syn-rift temperature elevation, the model cannot be constrained by maturity modelling.

A model of heat flow constant in time and equal to the recent one is sufficient to explain available thermal maturity measurements in part of the offshore Baltic region analysed B6-1/82 and B4-2A/02 boreholes). This model requires adoption of relatively small thickness of upper Silurian strata which were removed during Early Devonian uplift and erosion, not exceeding ~100–200 m. The remaining part of the currently missing Silurian section would have been removed during late Carboniferous to early Permian time, together with the Middle and Upper Devonian and lower Carboniferous deposits (Figs. 2–4). This model implies that the maximum burial of the lower Paleozoic succession during the early Carboniferous was relatively high, allowing it to achieve the currently observed maturity. The cumulative thickness of the missing Paleozoic section in the cases of these boreholes would be in the range of approximately 1400 m.

Farther west (A8-1/83 and A23-1/88 boreholes), where the thermal maturity of the lower Paleozoic succession increases, the model of heat flow constant in time would allow explanation of the observed maturation only if one were to assume a large thickness of missing Paleozoic strata, in the range of 3000 m (Figs. 3 and 5). If one was to assume that this value is unrealistically high, then either a Variscan or a late Mesozoic thermal event is required in models of these boreholes. With little maturity data currently available for model calibration located within the thin interval of the well section, differentiation between these two alternative scenarios is not possible.

In the onshore part of the area analysed there are two boreholes with very poor data control on the maturity profile (Białogóra 3 and Dębki 3 boreholes) with maturity measurements available only for the Middle Cambrian to Ordovician section. There are also two boreholes with good maturity data coverage across a major part of the section (Łeba 8 and Żarnowiec IG 1 boreholes; Figs. 5 and 6). In the case of the Białogóra 3 and Dębki 3 boreholes limited maturity data allows for alternative thermal and burial history models. The scenario of heat flow constant through time requires a very large thickness of missing section, exceeding 3000 m (Fig. 4). Development of the upper Silurian, Middle to Upper Ordovician and lower Carboniferous in locations with better preserved sections in the vicinity of the area studied indicate that that this value is hardly realistic. Therefore either a Variscan or a late Mesozoic thermal event must be adopted into a model. Again, with current data it is not possible to identify one unique model solution among these two options.

In the case of boreholes Łeba 8 and Żarnowiec IG 1, good coverage of the section with thermal maturity measurements allows one to reveal the palaeothermal regimes in more detail. Overall maturity profiles have, however, a very complex character creating significant difficulties in the reconstruction of heat flow history and burial conditions. In both boreholes, thermal maturity measurements for the Permian–Mesozoic strata above the major unconformity reveal relatively high maximum palaeotemperatures in the burial history of these deposits, indicating the presence of a late Mesozoic thermal event (Poprawa and Grotek, 2005). This maturity excess is more significant in the case of the Żarnowiec IG 1 borehole (Fig. 6). The nature of this event is uncertain, and because of the limited amount of data it is not discussed here.

The model of late Mesozoic heating allows also for proper calibration with maturity data in the lower part of the lower Paleozoic sequence. However, the upper part of this sequence is characterized by a thermal maturity higher than predicted in the model and is characterized by specific a sub-vertical maturity profile, which might be attributed to a thermal anomaly, caused e.g., by hot fluids.

In case of the Żarnowiec IG 1 borehole a zone of thermal maturity lower than the background maturity profile is observed within the lower Silurian and Ludlow section (Fig. 6). This characteristic pattern of maturity profile is observed commonly in the Baltic Basin and was related by Poprawa and Grotek (2005) to maturation retardation by palaeo-overpressure. Overpressure retards chemical coalification reactions (e.g., Horvath, 1983) and sustain undercompacted zones with anomalously high porosity and low thermal conductivity, which could act as thermal insulators to the flow of heat (e.g., Mello and Karner, 1996). Development of the overpressures might be related to very high deposition rates of the thick pile of upper Silurian argillaceous sediments, which in the western part of the basin exceeded 1000 m/My (Poprawa *et al.* 1999; Poprawa, 2006*b*).

It might be summarized that for the majority of the boreholes analysed, except for B6-1/82 and B4-2A/02, some sort of positive thermal event is required to explain the existing thermal maturity data. This might be either a late Mesozoic event or a Variscan event, or both in uncertain proportions. In most of the cases analysed the limited amount of maturity data per well for the model calibration does not allow one to study these events in proper detail, therefore data from the broad surroundings of the area studied might be useful for better understanding of these thermal events.

According to Poprawa and Grotek (2005) the late Variscan thermal event, characterized by an increase of palaeo-heat flow towards the south and east, i.e. outwards of the most deeply buried zones, was related partly to lithosphere-scale heating of the Variscan orogen broad foreland, but also to migration of hot fluids. The western and northern parts of the Baltic region experienced only a limited increase in Variscan heat flow (*op. cit.*). Precise timing of the thermal event is difficult to constrain, however, to affect the thermal maturity of the lower Paleozoic succession it must have lasted at least until the maximum burial time, which most probably was the early Carboniferous. The Variscan thermal event in the Baltic region might be regarded as a part of a much broader process of heating of the sedimentary basins in the foreland of the Variscan orogen as far as the East European Craton (e.g., Majorowicz *et al*., 1984), allowing one to extend the model of "hot" Variscan orogeny to the very broad foreland of the orogen.

In the area studied, however, only a limited increase in Variscan heat flow might be revealed from maturity data. In the case of the Białogóra 3 and Żarnowiecc IG 1 boreholes, a heat flow higher by 10% in relation to the recent one causes in the model an increase in Upper Cambrian stratal maturity from 1.2 to 1.3% R_o, and from 1.4 to 1.6% R_o, respectively. Increase of heat flow by 20% leads to increases in the thermal maturity to 1.5 and 1.85% R_o in the Białogóra 3 and Żarnowiec IG 1 boreholes, respectively (Fig. 6). The increase in thermal maturity results in the Upper Cambrian source rock entering the gas window during Carboniferous time. Thermal maturity data available for the model's calibration therefore limits the intensity of the Variscan heating in the area studied.

In the case of the late Mesozoic thermal event, its reconstructed intensity increases across the Baltic Basin from east to west (Poprawa and Grotek, 2005). Also in this case, precise reconstruction of the timing of the thermal event is not possible; however, taking into account the stratigraphic age of the strata affected by elevated temperatures, it might be estimated as being within the Late Jurassic to Late Cretaceous interval. The complex maturity profile of the Mesozoic succession, with its relatively high values in the upper part of succession and sub-vertical profiles, indicate an advectional/convectional mechanism of heat transfer. It is, however, important to note that other studies resulted in reconstruction of low Mesozoic heat flow in the Baltic Basin, equal to the recent one (Karnkowski, 2003); therefore, this issue still requires more study.

CONCLUSIONS

1. In the cases of most of the boreholes analysed, the low quantity of thermal maturity measurements, and their location in the section in a relatively low thickness interval of the Upper Cambrian to Ordovician, does not allow one to obtain a unique solution to the maturity modelling. For the boreholes Łeba 8 and Żarnowiec IG 1 numerous thermal maturity measurements favourably distributed across the whole section were available; however, the very complex character of the thermal maturity profile causes difficulties in proper calibration of the model.

2. During latest Ediacaran to earliest Cambrian time, rifting took place in the western part of the Baltic Basin, followed by Cambrian to Mid Ordovician post-rift thermal sag (Poprawa *et al*., 1999). The rifting presumably resulted in syn-rift heat flow elevation (Kosakowski *et al*., 1999), which cannot be, however proved with results of the maturity modelling conducted due to subsequent deep burial of the strata, which might have previously experience syn-rift temperature elevation.

3. From the Late Ordovician to the end of the Silurian the western Baltic region constituted the flexural foredeep of the North-German–Polish Caledonides (Poprawa *et al*., 1999). Rapid subsidence and deposition in the foredeep basin caused significant burial of the Upper Cambrian to lower Silurian source rock by the end of the Silurian.

4. Within the time period represented by the major unconformity two uplift and erosion events took place: the Early Devonian, and in the late Carboniferous to mid Permian. The quantitative proportion between the two is difficult to determine.

5. Maximum Paleozoic burial in the western Baltic region took place during early Carboniferous time. In the Baltic region a relatively high heat flow is observed for that time (Kosakowski *et al*., 1998; Poprawa *et al*., 2002; Karnkowski, 2003; Poprawa and Grotek, 2005), however within the part of the basin studied here, only a limited increase of heat flow has been reconstructed.

6. During late Mesozoic time an advectional/convectional thermal event took place in the Baltic Basin (Poprawa and Grotek, 2005). A lack of thermal maturity data for the Mesozoic strata in most of the boreholes analysed does not allow one to test this concept. Exceptions are the Łeba 8 and Żarnowiec IG 1 boreholes, with maturity data for the Permian–Mesozoic succession indicative of late Mesozoic heating.

7. In the northern part of the study area a model of heat flow constant in time is sufficient to explain available thermal maturity measurements.

8. Recent heat flow varies across the study area from *ca*. 38 mW/m^2 in its eastern and central parts, to *ca*. 50 mW/m^2 in its northwestern part.

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