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Hydrocarbon generation/expulsion modelling of the lower Paleozoic potential source rocks in the Gryfice and Kołobrzeg blocks (NW Poland)

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The lower Paleozoic source rocks in the offshore part of the Gryfice and Kołobrzeg blocks (NW Poland) were studied through geochemical data and numerical modelling. The geochemical study revealed a presence of effective source rocks in Caradocian strata, but with low hydrocarbon potential. The remaining lower Paleozoic source rock horizons were not documented by core samples. The timing of hydrocarbon generation and expulsion was modelled for the K1-1/86 and L2-1/87 boreholes located in the Gryfice and Kołobrzeg blocks, respectively. 1-D and 2-D modelling indicated that in the Kołobrzeg Block the onset of petroleum generation occurred at the end of the Silurian and the beginning of the Devonian. Source rocks in the Gryfice Block reached the early stage of oil generation at the beginning of the Permian and generation processes were completed by the end of the Triassic. Migration of hydrocarbons from source rocks began in the Carboniferous in both the Gryfice and Kołobrzeg blocks and lasted to the end of the Mesozoic. During hydrocarbon migration, an intensive dispersion process was observed, caused by leaking along the fault planes. The modelling revealed that hydrocarbons may have accumulated in Devonian reservoirs. The lack of any discovered accumulations could be the result of hydrocarbon dispersion caused by tectonic deformation and intense vertical fault block movements.

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Key words: Gryfice and Kołobrzeg blocks, lower Paleozoic, source rock, burial history, thermal evolution, petroleum processes.

INTRODUCTION

Characteristics of lower Paleozoic source rocks in the Pomeranian segment of the Trans-European Suture Zone (TESZ) and the petroleum processes in the offshore part of this area were examined.

The study area is the offshore parts of the Gryfice and Kołobrzeg blocks, located in the Pomeranian segment of the Trans-European Suture Zone (TESZ). Owing to few geologic data available from the lower Paleozoic succession, as well as a lack of representative results of geochemical analyses for the potential source rocks (only Caradocian shales were sampled), the investigation has the character of a generation test. Characteristics of source rocks of the lower Paleozoic strata and the model of kinetic transformations were adopted from the petroleum analysis of coeval strata in the Baltic region further east. Reconstructed lithostratigraphic sections in the offshore L2-1/87 and K1-1/86 boreholes were used for modelling of the hydrocarbon generation and expulsion processes (Fig. 1). Modelling of hydrocarbon migration and accumulation was performed along the regional 81032K-820 cross-section (Fig. 1).

To determine the thickness of strata removed during the late Paleozoic and Mesozoic, measured parameters of kerogen thermal maturity were used. The same data were used to model calibration of heat flow changes through time. Having the thermal and burial history constrained, the following basic generation conditions were established for each borehole:

– time and depth identification of the organic matter thermal maturity intervals;
– position of generation stages and degree of kerogen transformation;
– amount of generated and expelled hydrocarbon mass;
– time and range of hydrocarbon migration;
– time and amount of accumulation.

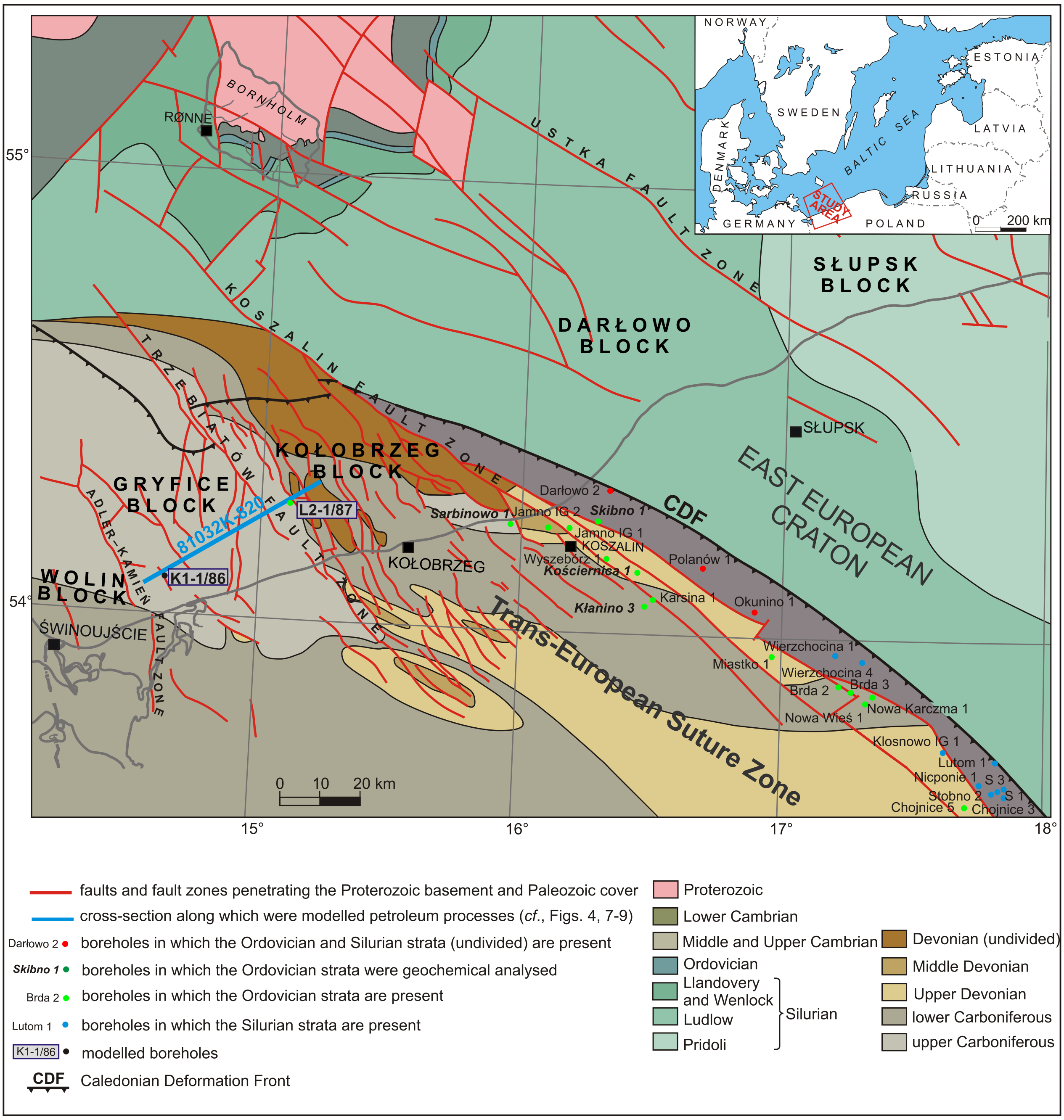

Fig. 1. Geological map of the Pomeranian part of the Caledonian Platform without Permian and younger deposits (after Pokorski and Modliński, 2007, modified) with location of the boreholes analysed

GEOLOGICAL SETTING

The study area is a part of the northern segment of the TESZ, located between two major fault zones, the Trzebiatów in the west and the Koszalin in the east (Fig. 1). The lower Paleozoic strata are tectonically deformed, folded and most probably also detached from their original basement (Dadlez, 2000). According to Pokorski and Jaworowski (2002), in the Kołobrzeg Block, beneath the overthrusted lower Paleozoic allochthonous strata, an autochthonous sedimentary cover of the East European Craton (EEC) might be expected, similar to that already recognized in the southern Skania outcrops. The basement of the Rugia, Wolin, Gryfice and Kołobrzeg blocks is either related to the East European Craton or to terrains accreted to the TESZ during the Caledonian collision.

The geological development of the area in early Paleozoic time was reconstructed mainly based on studies of the lower Paleozoic sedimentary rocks in the nearby Koszalin–Chojnice Zone (see Znosko, 1965; Teller and Korejwo, 1968; Dadlez, 1978; Podhalańska and Modliński, 2006; Poprawa, 2006). In the study area and its eastern vicinity the Ordovician strata, most frequently the Llandeillian–lower Caradocian, were found in the bottom part of the boreholes: Brda 2, Brda 3, Chojnice 5, L2-1/87, Jamno IG 1, Jamno IG 2, Karsina 1, Kościernica 1, Miastko 1, Nowa Karczma 1, Nowa Wieś 1, Sarbinowo 1, Skibno 1 and Wyszebórz 1 (Dadlez, 1978; Podhalańska and Modliński, 2006; Fig. 1). The folded Silurian strata were encountered in the boreholes: Chojnice 3, Klosnowo IG 1, Kłanino 3, Lutom 1, Nicponie 1, Stobno 1 (S 1), Stobno 2, Stobno 3 (S 3), Wierzchocina 1 and Wierzchocina 4 (Dadlez, 1978; Podhalańska and Modliński, 2006; Fig. 1).

The depth of recent burial of the lower Paleozoic strata ranges between 4000 and 7000 m. The lower Paleozoic strata, folded during the Caledonian orogeny (Znosko, 1965; Dadlez, 1978; Żaba and Poprawa, 2006), is overlain by a Devonian-Carboniferous cover which is presently over 1000 m thick (Matyja, 2006) and which was also was deformed during the Variscan orogeny. In the vicinity of the Sarbinowo and west of the Dygowo–Białogard Fault Zone, lower Permian extrusive rocks are present, being a final result of the Variscan orogeny, and which are covered by strata of the upper Rotliegend. Permian rocks are deposited unconformably on the Devonian and Carboniferous succession. Their total thickness in the specific profiles varies from a few to about 350 m. Permian deposition in the northern, Pomeranian segment of the Polish region continued through the Mesozoic. There is a succession about 1800 m thick near Sarbinowo and over 3000 m in the south-western part of Pomerania (Dadlez, 1974; Dadlez *et al*., 1995; Stephenson *et al*., 2003). Analogous to the Polish Lowland, the topmost part of the sedimentary cover is composed of Cenozoic unconsolidated deposits up to 200 m thick.

As the lower Paleozoic strata is poorly recognized in the study region, the downhole conditions of the lower Paleozoic are indirectly interpreted from seismic section analysis (see Pokorski, 2010). Only on this basis one can infer the evolution of the lower Paleozoic succession at the pre-Devonian stage of development of the basin. That the late Paleozoic stage of the area's evolution finished with tectonic deformation and uplift, and the late Permian–Mesozoic stage, terminated with inversion of the Polish Basin, has been generally well recognized and described in the literature (e.g., Dadlez, 1978; Karnkowski, 1999; Krzywiec, 2002; Lamarche and Schenk-Wenderoth, 2005*a*, *b*; Matyja, 2006).

The tectonic structure of the part of the Caledonian platform studied is a result of multiphase deformation related mainly to contractional and transpressional regimes (Znosko, 1965; Dadlez, 1978; Poprawa *et al*., 1999; Poprawa, 2006). A few phases of uplift and erosion accompanied the tectonic deformation, the main ones being: Early Devonian, late to post-Carboniferous, and post-Cretaceous. In the offshore part of study area the Early Devonian erosion event led to partial removal of Ordovician and Silurian strata with a total thickness of approximately 2000 m (Fig. 2). After the Carboniferous to early Permian phase of erosion, the Devonian and Carboniferous strata were partially denuded, with the thickness of the removed section determined to be up to 1200 m thick. The latest to post-Cretaceous erosion partially removed the Upper Cretaceous and Jurassic strata. The thickness of the eroded Mesozoic section was estimated at approximately 1300 m in the Gryfice Block (Fig. 2A) and 2300 m in the Kołobrzeg Block (Fig. 2B).

THERMAL EVOLUTION

The late Permian–Mesozoic stage of the study area's thermal history is relatively well understood, while the late Paleozoic thermal history is less well documented, despite the existence of geochemical data. The early Paleozoic stage is poorly recognized with little information.

Reconstruction of the heat flow during the geological evolution of the basin started with analysis of the recent thermal regime. The input data consisted of a map of temperatures for the top of the Zechstein Main Dolomite carbonates, i.e. the best recognized stratigraphic horizon of the study area (Karwasiecka, 2000). The reconstruction was based on direct measurements in boreholes in thermal equilibrium conditions similar to steady-state. Where there was an absence of such measurements, the downhole temperature was assessed below the observed horizon on the basis of published data on the magnitude of the heat flow (Karwasiecka and Bruszewska, 1997). The distribution of recent temperatures obtained at the top of the Main Dolomite strata in the area analysed revealed values predominantly in the range of 70–90°C. Geothermal gradients calculated for late Permian and Mesozoic time in the study area on the basis of the distribution of downhole temperatures range between 2.00 and 2.25°C/100 m. These temperatures indicated that the lower Paleozoic potential source rock, 1000–2000 m lower in the succession, was certainly able to generate hydrocarbons. Reconstruction of this process, however, requires determination of thermal changes over the entire time interval, from the deposition of the source rocks analysed to their current depth.

Currently available knowledge on changes in the thermal field comes only from regional studies. Several basic models of thermal evolution exist, and these were proposed by Majorowicz *et al*. (1984), Karnkowski (1999, 2003*a*), Poprawa and Grotek (2004), and Poprawa and Andriessen (2006). Though Majorowicz *et al*. (1984) in their model covered only the Lublin area and northern-western Fore-Sudetic Monocline, this material remains significant for the remaining part of the Polish Lowland. Based on analysed gradients of thermal maturity, Majorowicz *et al*. (1984) suggested that the Variscan orogen and its foreland were heated in late Paleozoic time and afterwards progressively cooled. This process continues till the present.

Karnkowski (1999, 2003*a*) suggested that the magnitude of the heat flow within the main depocentre of the Polish Basin was constant, with a positive thermal anomaly during the Permian, Triassic and Jurassic only, within the Fore-Sudetic Monocline. Poprawa and Grotek (2004) and Poprawa and Andriessen (2006) proposed two alternative models. In first, they proposed steady heat flow in the Cretaceous, and variable heat flow in the Permian and Triassic. The other model included a local increase of heat flow in the Permian and Triassic followed by a progressive decrease, with relatively lower values in Late Cretaceous time.

The modelling performed revealed that the observed thermal maturity of the lower Paleozoic succession analysed, with its upper Paleozoic and Permian-Mesozoic cover, requires

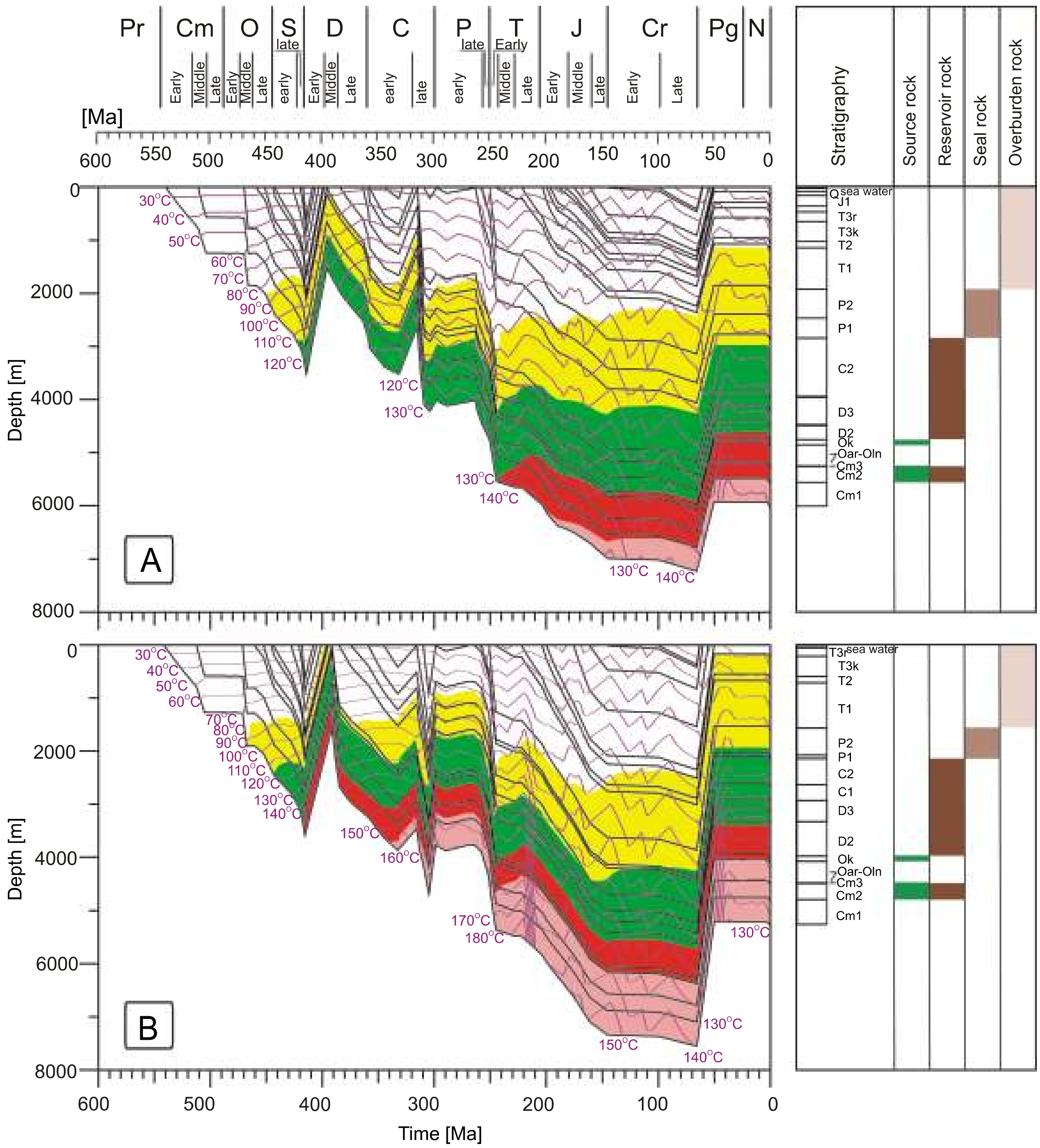

Fig. 2. Burial history curves for selected lithostratigraphic succession with thermal maturity zones in profiles: A – K-1/86 borehole in the Gryfice Block and B – L2-1/87 borehole in the Kołobrzeg Block

Pr – Precambrian, Cm – Cambrian, Cm1 – Lower Cambrian, Cm2 – Middle Cambrian, Cm3 – Upper Cambrian, O – Ordovician, Oar – Ordovician (Arenigian), Oln – Ordovician (Llanvirnian), Ok – Ordovician (Caradocian), S – Silurian, D – Devonian, D2 – Middle Devonian, D3 – Upper Devonian, C – Carboniferous, C1 – lower Carboniferous, C2 – upper Carboniferous, P – Permian, P1 – lower Permian, P2 – upper Permian, T – Triassic, T1 – Lower Triassic, T2 – Middle Triassic, T3k – Upper Triassic (Keuper), T3r – Upper Triassic (Rhaetian), J – Jurassic, J1 – Lower Jurassic, Cr – Cretaceous, Pg – Paleogene, N – Neogene, Q – Quaternary

lower heat flow during Mesozoic burial as compared to recent heat flow. This has been described previously with reference to the onshore part of the Mid-Polish Trough (Poprawa and Grotek, 2004; Poprawa and Andriessen, 2006).

Available data allowed reconstruction of the Variscian thermal and burial regime. Analysis of the thermal history on the onshore part of the Kołobrzeg and Gryfice blocks (Kosakowski *et al*., 2006) indicated that Variscian heat flow was slightly higher in comparison to recent heat flow. This difference gradually disappeared towards the marine part of these blocks. As in the Baltic Basin (Karnkowski, 2003*b*; Poprawa and Grotek, 2005; Kosakowski *et al*., 2010; Poprawa *et al*., 2010), the timing of the main phase of maturation in the offshore part of the Kołobrzeg and Gryfice blocks could not be determined with any precision. It is assumed that successive increases in heat flow took place from the beginning of Devonian to the late Carboniferous, i.e. to the time of maximum burial.

The present surface heat flow was calculated on the basis of heat conductivity values calculated from lithological proportions for each specific stratigraphic horizon of the section analysed. The reconstructed recent heat flow ranges from *ca.* 45 mW/m^2 in the western part of the analysed platform (Gryfice Block) to *ca.* 60 mW/m^2 in the eastern part (Kołobrzeg Block).

GENERAL CHARACTERISTICS OF THE LOWER PALEOZOIC SOURCE ROCKS

Potential source rock horizons in the eastern part of the study area have been geochemically documented only within the Caradocian strata. There were only 49 core samples collected from this horizon from the L2-1/87 borehole in the offshore part of study area, as well as from the Kłanino 3, Kościernica 1, Sarbinowo 1, and Skibno 1 boreholes in the onshore part (Fig. 1). Quantitative analysis reveals that the total organic carbon (TOC) content is low, usually below 0.3 wt.%, and the hydrocarbon potential does not exceed 250 mg HC/g TOC. Measured T_{max} values are variable and in the onshore part are within the initial phase of the low-temperature thermogenic processes ("oil window"), while in the offshore part they are within the late phase of the "oil window" (Fig. 3). Therefore, geochemical studies reveal the presence of effective source rocks in Caradocian strata, but with low hydrocarbon potential. However, by analogy with the Baltic region, the generation modelling was also completed for the Middle Cambrian and Upper Cambrian–Lower Ordovician strata as a synthetic section with geochemical characteristics of the boreholes from the Słupsk Block (Kosakowski *et al*., 2010; Więcław *et al*., 2010*a*).

T a b l e 1

Geochemical characteristics and hydrocarbon potential of the Caradocian strata of the Pomeranian part of Caledonian platform

Indices	Values
TOC [wt.%]	0.10 – 0.47 / 0.24 (49)/(5)
T_{max} [°C]	427 – 461 / 438 (22)/(4)
R_o [%]	1.27 and 1.29 (2)/(1)
$S_1 + S_2$	0.28 – 1.89 / 0.71 (40)/(5)
HI	38 – 405 / 219 (40)/(5)
Pristane/phytane	0.72 and 1.00 (2)
Pristane/*n*-C_{17}	0.48 (1)
Phytane/*n*-C_{18}	0.31 and 0.47 (2)

TOC – total organic carbon, T_{max} – temperature of maximum of S_2 peak, R_o – mean random reflectance of the vitrinite-like macerals, S_2 – residual petroleum potential (mg HC/g rock), S_1 – oil and gas yield (mg HC/g rock), HI – hydrogen index (mg HC/g TOC). Range of geochemical parameters is given as numerator; median values in denominator. In parentheses: number of samples from boreholes (numerator) and number of sampled boreholes (denominator)

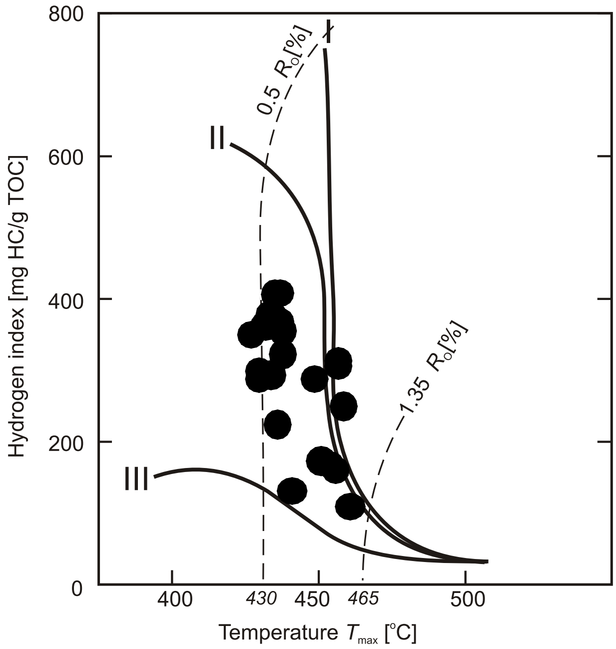

Fig. 3. Rock-Eval hydrogen index versus T_{max} temperature for Caradocian (Upper Ordovician) source rocks of the Koszalin–Chojnice Zone

Maturity paths of individual kerogen types after Espitalié *et al*. (1985*a*, *b*); R_o – vitrinite reflectance scale

MODELLING PROCEDURE

The principal aim of the 1-D numerical modelling was to determine the depth and timing of hydrocarbon generation and expulsion for sections of the L2-1/87 and K1-1/86 boreholes (Fig. 1). These processes were reconstructed by means of *BasinMod*™ 1-D (BMRM 1-D, 2006). To assess the amount of hydrocarbons generated and expelled from the lower Paleozoic source rocks, the following data were quantified: present and original thicknesses of individual stratigraphic units, thicknesses of missing sections, lithology of individual stratigraphic units, as well as present and palaeo-heat flow. Input data for modelling also include geochemical data such as reconstructed TOC and genetic type of kerogen. Maturity was calculated using the EASY%R_o model (Sweeney and Burnham, 1990). Generation and expulsion of hydrocarbons were calculated by the LLNL (Lawrence Livermore National Laboratory) model (Ungerer *et al*., 1988; Forbes *et al*., 1991; BMRM 1-D, 2006) and the use of kinetic parameters E_a = 57.5 (kcal/mol) and A_0 = 2.508E + 28 (1/m.y.) calculated by Więcław *et al*. (2010*b*) for source rocks in the Baltic region. Maturity modelling was calibrated with Rock-Eval T_{max} temperature and vitrinite reflectance.

Migration and accumulation of hydrocarbons was analysed with *BasinMod*™ 2-D software (BMRM 2-D, 2006) along the cross-section 81032K-820 situated between boreholes K1-1/86 and L2-1/87 (Fig. 1). The following horizons were input to the 2-D model based on seismic section interpretation: top of the Ordovician (Caradocian), top of the Devonian, top of the Carboniferous, the bottom and top of the Zechstein, the bottom of the Middle Triassic, the top of the Upper Triassic, and the bottom of the Jurassic intervals. Moreover, two additional horizons were input, the Middle and Upper Cambrian source rocks. These are "synthetic" horizons because this succession is beyond the resolution of seismic data, and not drilled in any borehole (Fig. 4). The thickness of the Middle Cambrian source rock is assumed to be approximately 45 m, with 0.5 wt.% TOC, while the Upper Cambrian source rock with 10 wt.% TOC is only 1 m thick. The Caradocian source rock is 60 m thick with 1.5 wt.% TOC. Porosity and permeability data were not available, so these parameters were calculated from the lithological type of each interval. These rock types were adequately defined in the region, in the west from the K1-1/86 boreholes, and in the east from the L2-1/87 boreholes. The same procedure was used for the thermal data input.

THERMAL MATURITY EVOLUTION OF THE LOWER PALEOZOIC STRATA

Modelling of thermal maturity, determined by the heat flow and burial conditions described above, revealed that the early stage of thermal maturity (0.5–0.7% R_o) was obtained by potential Middle Cambrian source rocks in the offshore part of the Gryfice and Kołobrzeg blocks at the end of the Ordovician and beginning of the Silurian. This occurred at burial depths of 1400–1900 m and temperatures over 80°C (Figs. 2 and 5). The increase of burial depth of source rocks resulted in their enter-

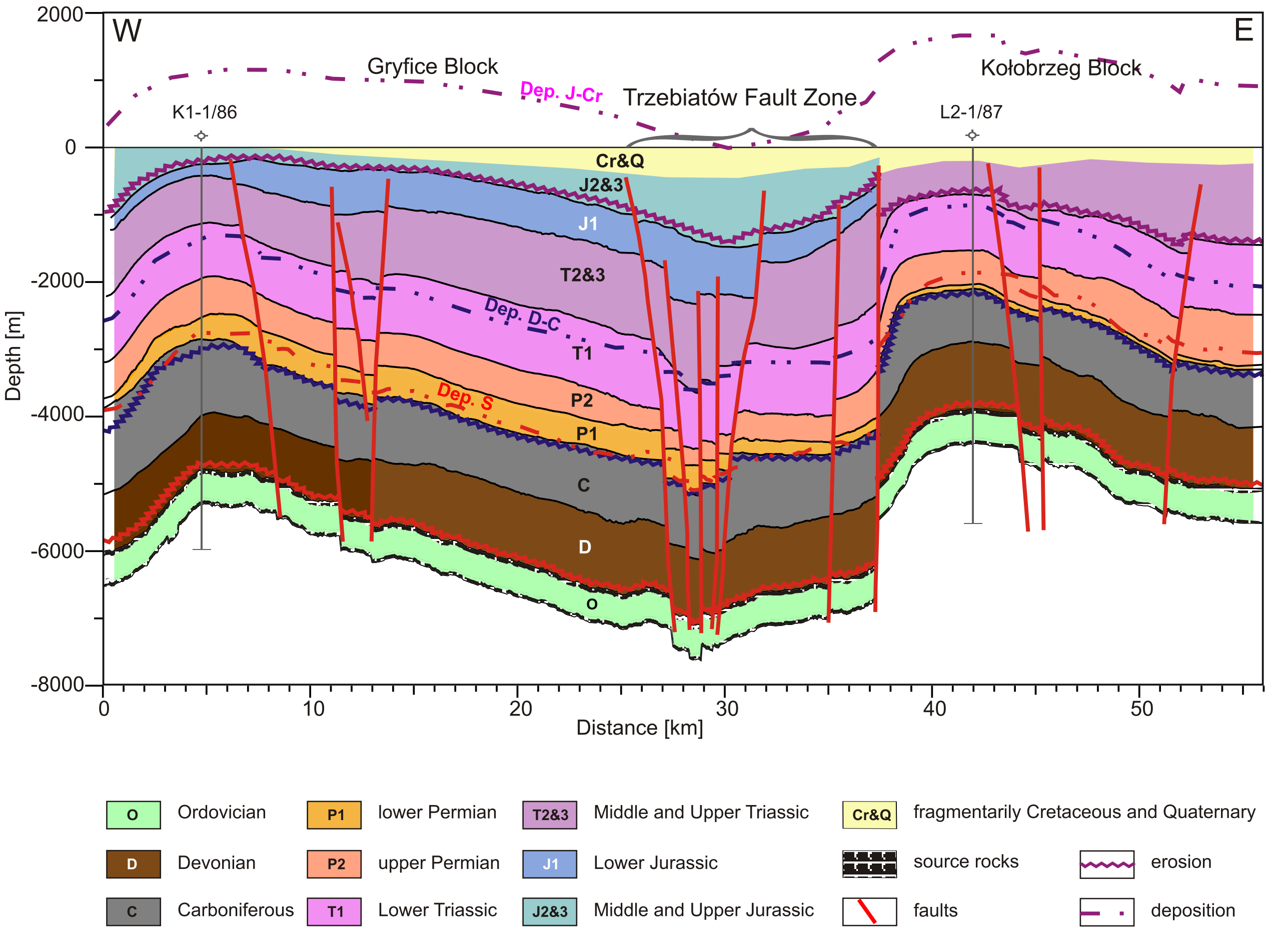

Fig. 4. The 81032K-820 cross-section along which 2-D modelling of generation, expulsion, migration and accumulation was completed

Dep. S – deposition of Silurian strata; Dep. D-C – deposition of Devonian and Carboniferous strata; Dep. J-Cr – deposition of Jurassic and Cretaceous strata; for location see Figure 1

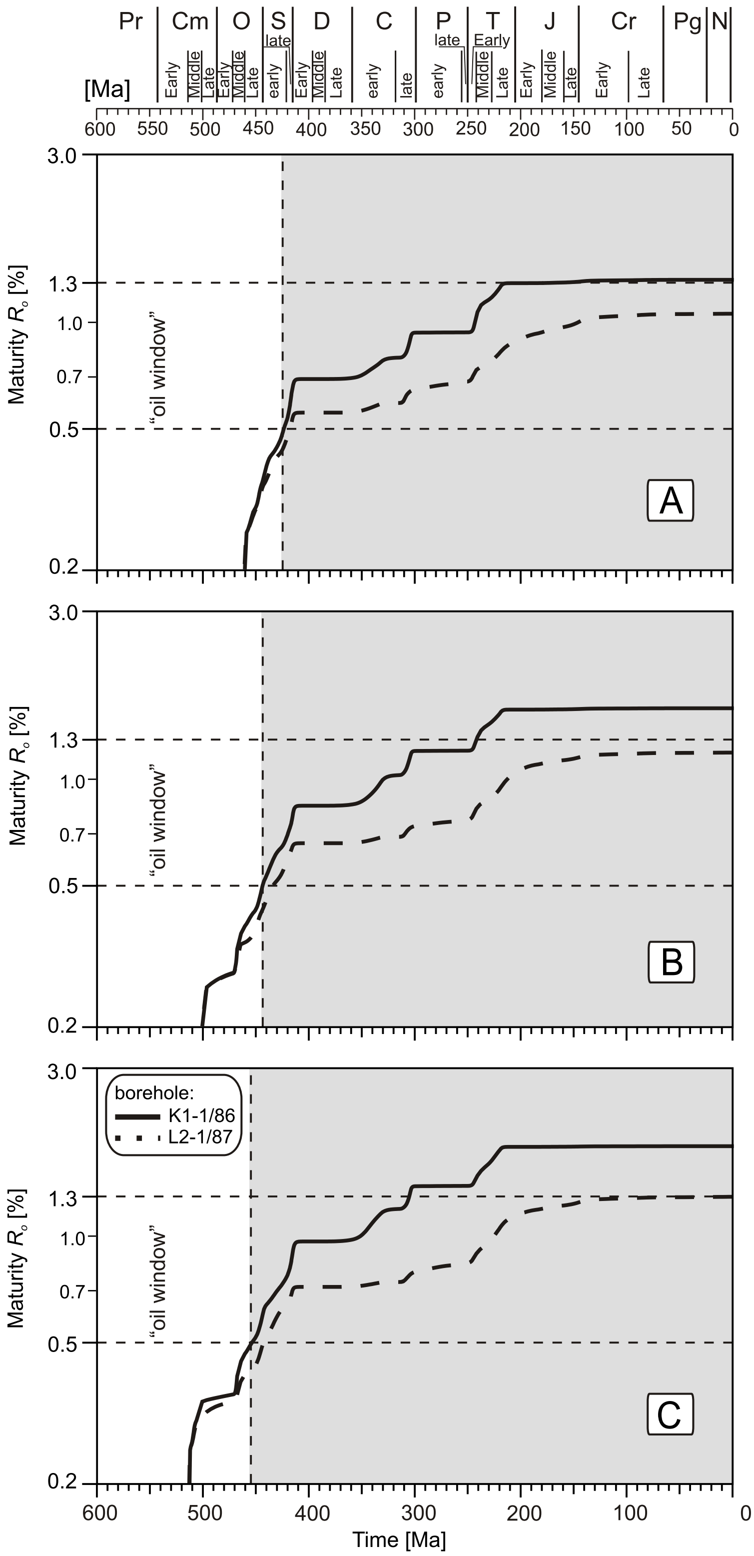

Fig. 5. Maturity evolution in lower Paleozoic source rocks in profiles of the K1-1/86 and L2-1/87 boreholes, analysed for A – Middle Cambrian, B – Upper Cambrian and C – Upper Ordovician (Caradocian)

R_o – vitrinite reflectance scale; for other abbreviations see Figure 2

ing the main thermal maturity stage within the "oil window" interval (0.7–1.0% R_o) prior to the Early Devonian uplift (Fig. 5). The erosion connected with the uplift hindered any increase of maturity of the kerogen. The deposition of Middle to Upper Devonian and Carboniferous sediments led to burial of the potential Middle Cambrian source rocks to the thermal conditions of the late stage of the "oil window" (1.0–1.3% R_o) (Figs. 2 and 5). Further deposition, especially of the Permian and Lower Triassic sediments, caused that potential source rock in part of the area to enter the "gas window" (1.3–2.6% R_o). The Middle Cambrian strata reached maximum thermal maturity prior to inversion at the end of the Cretaceous, at the maximum burial depth of 7000–7500 m and temperatures of 160–170°C (Fig. 2). Potential source horizons of Upper Cambrian age entered the early stage of the "oil window" at the end of the Ordovician and in the early Silurian (Figs. 2 and 5). The Upper Cambrian–Lower Ordovician source rocks reached the main stage of the "oil window" in the Kołobrzeg Block in the Ludlow and the final stage at the end of the Visean. In the Gryfice Block, the main stage was reached in the Famennian and the final stage in the early Permian (Fig. 5). An even bigger time difference between entering comparable maturation stages as regards the Middle and Upper Cambrian potential source rocks can be observed for thermal maturity in the "oil window". The Upper Cambrian in the Kołobrzeg Block entered this maturity interval in the Middle Triassic, i.e. *ca*. 60 m.y. later than the Middle Cambrian, at a depth of burial of about 4500 m and a temperature over 160°C (Fig. 2). The Upper Cambrian–Lower Ordovician source rocks in the Gryfice Block entered the stage of the "oil window" much later, in the Norian, at a burial depth below 6000 m and temperature over 150°C (Fig. 2).

In the Kołobrzeg and Gryfice blocks the potential Caradocian source horizons entered the early stage of the "oil window" in Wenlock–Pridoli time, at burial depths of 1400–1900 m and temperatures over 80°C (Figs. 2 and 5). The Early Devonian and late Carboniferous uplift and erosion events stopped further increase of maturity. Only deposition of Permian–Mesozoic strata, which caused a considerable increase of burial depth and temperature, led to entering the main stage of the "oil window". In the Kołobrzeg Block, this stage was reached by the Caradocian rocks at the beginning of the Tournaisian, and in the Gryfice Block at the turn of the Early and Middle Triassic (Figs. 2 and 5). The maturation history of the Caradocian strata also varies across both blocks. In the Kołobrzeg Block, the beginning of the "oil window" took place in the Middle Triassic, at a depth of burial near 4000 m and temperature over 150°C, while in the Gryfice Block this took place at the turn of the Jurassic and Cretaceous at a burial depth of 5850 m and temperature over 130°C (Fig. 2). Further

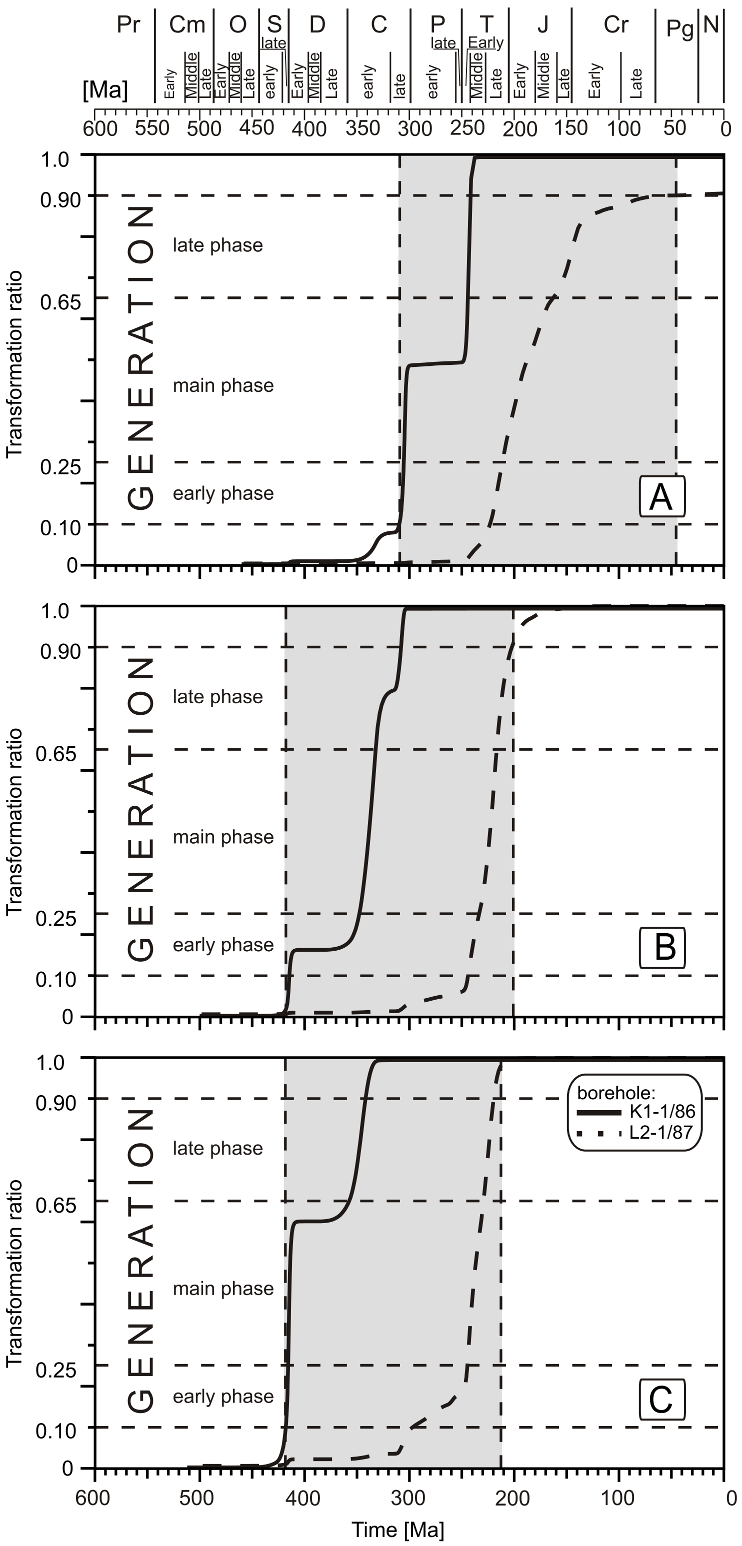

Fig. 6. Transformation ratio of kerogen in lower Paleozoic source rocks in the K-1/86 and L2-1/87 boreholes for A – Middle Cambrian, B – Upper Cambrian and C – Upper Ordovician (Caradocian)

For other abbreviations see Figure 2

increase of burial to *ca*. 6300 m in the L2-1/87 borehole and *ca*. 6150 m in the K1-1/86 borehole did not result in significant increase in maturity or entering of the stage of high-temperature gases (above 1.3% R_o) (Fig. 2).

GENERATION AND EXPULSION PROCESSES IN THE LOWER PALEOZOIC SUCCESSION

Modelling of hydrocarbon generation for the Middle Cambrian strata showed that the potential source rocks reached the entire generation potential range from the early to the final stage. In the Kołobrzeg Block, in the L2-1/87 borehole, the lowest parts of the potential Middle Cambrian source rocks reached the early stage (10–25% of generation potential) at the end of the Silurian and beginning of the Devonian at a depth of *ca*. 2700 m and temperature over 130°C (Fig. 6). The remaining part of the Middle Cambrian section reached that stage in a wide time range from the Devonian to the beginning of the Carboniferous. During the same time interval the source rocks reached the main stage (25–65% of generation potential), at a depth of burial below 2700 m (Fig. 6). The Early Devonian uplift and erosion interrupted the generation process. Deposition of a thick Middle and Upper Devonian succession led to resumption of this process and, in the early Carboniferous, to the final stage of generation (65–90%) (Fig. 6). The potential Middle Cambrian source horizons in the area around the L2-1/87 borehole exhausted their generation potential at the end of the Westphalian, reaching a total degree of organic matter transformation. In the Gryfice Block, in the K1-1/86 borehole, the Middle Cambrian potential source rocks reached the early stage only at the beginning of the Permian, at a depth of burial below 3600 m and temperature over 120°C (Fig. 6). The main stage was reached in the Early Triassic at a burial depth of *ca*. 5100 m and temperature over 130°C, and the final stage on the turn of the Mid and Late Triassic. The potential source rocks of the Middle Cambrian exhausted their generation potential at the end of the Triassic (Fig. 6). The specific generation stages of the potential Upper Cambrian–Lower Ordovician source rocks were reached in a broad time interval from the beginning of the Devonian to the end of the Triassic. The source rocks in the Kołobrzeg Block reached the early stage of hydrocarbon generation at the beginning of the Devonian, and totally exhausted their generation potential before the end of the Visean (Fig. 6). The source rocks in the Gryfice Block entered the early stage at the beginning of Permian, and the main stage on the turn of the Early and Mid Triassic. The final stage of hydrocarbon generation in the Gryfice Block was entered in the Late Triassic, at the end of the Carnian and beginning of the Norian (Fig. 6). Despite the time and depth differences of reaching specific generation stages in the Kołobrzeg and Gryfice tectonic blocks, the organic matter was completely transformed into hydrocarbons (Fig. 6). A similar range of time and depth was observed in kinetic modelling of Caradocian source rocks. In the Kołobrzeg Block, in L2-1/87 borehole, the source rocks reached the entire generation interval from the early to the final stage. The early and the main stages of hydrocarbon generation were reached in the Westphalian, at a depth of burial of 2700–3200 m and temperatures of 130–140°C (Fig. 6). The final generation stage was reached by the Caradocian organic matter only on the turn of the Early and Mid Triassic, with total transformation. In the Gryfice Block, in borehole K1-1/86, the Caradocian source rocks also entered the entire interval from the early to the final stage. The early and the main generation stages were entered in a narrow time interval of the Early Triassic (Carnian). The transformation degree obtained for kerogen was 90% (Fig. 6).

MIGRATION AND ACCUMULATION OF HYDROCARBONS IN THE LOWER PALEOZOIC STRATA

Modelling of hydrocarbon migration and accumulation performed along the 81032K-820 cross-section for the the lower Paleozoic succession allowed constraint of the timing and lateral extent of these processes in the region discussed. The Cambrian source rocks achieved total transformation ratio at the end of the Carboniferous in the Kołobrzeg Block and in the Trzebiatów Fault Zone. At the same time the Caradocian source rocks in that region achieved between 30 and 50% of kerogen transformation. In the Gryfice Block at the end of the Carboniferous, the transformation ratio for the Middle Cambrian and Upper Cambrian–Lower Ordovician source rocks was 40%, and for the Caradocian about 20%. At the end of the Triassic the Cambrian source rocks were completely transformed. At the same time the Caradocian source rock was also totally transformed, except for a few places in the Kołobrzeg Block and near the K1-1/86 borehole, where the final transformation ratio of 90% was achieved at the end of the Cretaceous. In the area between nine and twelve kilometres of the cross-section analysed, the Caradocian source rocks did not exceed 30% transformation. Hydrocarbon generation from the Cambrian source rocks in the Kołobrzeg Block and in the Trzebiatów Fault Zone began in the Visean. During the Namurian the Caradocian source rocks started hydrocarbon generation in the Kołobrzeg Block. In the Gryfice Block hydrocarbon generation from the Cambrian source rocks began at the end of Carboniferous, and from the Caradocian rocks in the Mid Triassic (Fig. 7). The end of hydrocarbon generation from the Cambrian source horizons in the Kołobrzeg Block and Trzebiatów Fault Zone took place at the end of Carboniferous, and for the Caradocian rocks in the Late Triassic. The generation process in the Gryfice Block was terminated at the end of Triassic for the Cambrian source rock and at the end of the Jurassic for the Caradocian rocks (Fig. 7). The total amount of oil generated from the Middle Cambrian source rocks was up to 350 mg/g TOC, for the Upper Cambrian it was 400 mg/g TOC, and for the Caradocian 300 mg/g TOC (Fig. 7). The total amount of gas generated was on average 50 mg/g TOC for all three source rocks. Expulsion of hydrocarbons was observed mainly from the Upper Cambrian–Lower Ordovician interval, as the Caradocian expelled only residual amounts of hydrocarbons. Oil expulsion from the Upper Cambrian interval was initiated in Namurian time in the Kołobrzeg Block and Trzebiatów Fault Zone, while in the Gryfice Block expulsion occurred during the Late Triassic. The end of oil expulsion from the Upper Cambrian–Lower Ordovician interval was in the Early Jurassic in the Trzebiatów Fault Zone, in the Cretaceous in the Kołobrzeg Block and in the Jurassic in the Gryfice Block. Expulsion from the Caradocian source rocks took place in the Triassic. The volume of expelled oil varies from 0.03 m^3/m^3 rock for the Caradocian to 0.12 m^3/m^3 rock for the Upper Cambrian–Lower Ordovician source intervals. Gas expulsion from the Upper Cambrian source rocks in the Gryfice and Kołobrzeg blocks took place during the time interval between the end of the Carboniferous and the beginning of the Triassic. Expulsion of gas from the Caradocian started at the end of the Mid Triassic in the eastern part of the study area and in the Late Triassic in the western part. It lasted until the Early Cretaceous. The volume of expelled gas varied from 0.006 m^3/m^3 rock for the Caradocian to 0.016 m^3/m^3 rock for the Upper Cambrian–Lower Ordovician source intervals. Hydrocarbon migration and accumulation modelling carried out for the lower Paleozoic potential source rocks revealed the possibility of hydrocarbon accumulation in the study area. Hydrocarbons, expelled mainly from the Upper Cambrian–Lower Ordovician source rocks, may have accumulated in the Devonian reservoirs in both the Gryfice and Kołobrzeg blocks near anticlinal structures along faults. Accumulation began at the end of the Carboniferous. In the Kołobrzeg Block, faults between 45 and 50 km of the cross-section (Fig. 8), were pathways for dispersion of existing hydrocarbons. This dispersion stopped at the end of the Permian and beginning of the Triassic and accumulation began again in the Devonian reservoir near the L2-1/87 borehole (Fig. 8). Migration of oil in the Kołobrzeg Block lasted until the Paleogene, however only a part of the migrated hydrocarbons were accumulated and some were dispersed. In the traps involving Devonian reservoirs in the Kołobrzeg Block 0.095 m^3/m^3 rock of oil accumulated (Fig. 8). In the Gryfice Block, accumulation took part in east from the K1-1/86 borehole and began at the end of the Carboniferous and lasted to the end of the Permian. At the end of the Permian and beginning of the Triassic some dispersion occurred there, and finally about 0.02 m^3/m^3 rock of oil accumulated (Fig. 8). In the Gryfice and Kołobrzeg blocks, gas migration and accumulation occurred in Devonian strata, mainly in the Trzebiatów Fault Zone and in the Kołobrzeg Block. This accumulation in the Trzebiatów Fault Zone began at the end of the Carboniferous and lasted until Triassic time, while in the Kołobrzeg Block it took place at the beginning of the Jurassic. Some dispersions of accumulated gas were observed, mainly due to vertical migration along the faults. The volume of accumulated gas it the Trzebiatów Fault Zone achieved 0.008 m^3/m^3 rock, and in the Kołobrzeg Block 0.027 m^3/m^3 rock (Fig. 9).

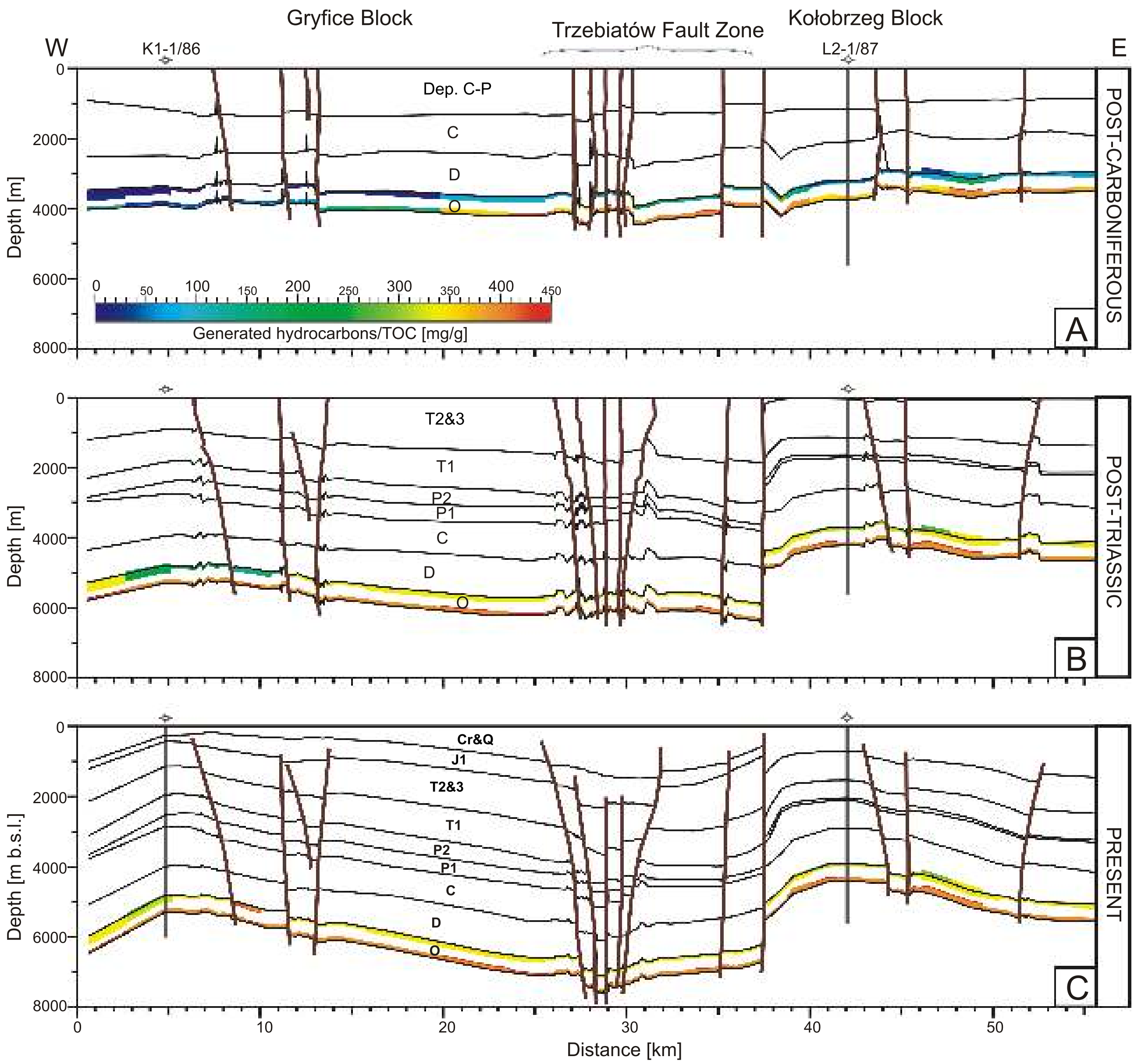

Fig. 7. Amount of generated hydrocarbons along the cross-section 81032K-820: A – after Carboniferous sedimentation, B – after Triassic sedimentation and C – present

Dep. C-P – deposition of Carboniferous and Permian strata; for other abbreviations see Figure 4

The expelled hydrocarbons migrated from the source rocks into Devonian sandstones. The connection between older source rocks and younger reservoir rocks was facilitated by a number of faults. However, it is important to note that the Middle and Upper Cambrian source rocks were included in the model as a synthetic succession, and have not been documented in boreholes, and are poorly documented by seismic analysis; therefore, changes in the exact position of the succession within the section might result in changes in time and range of the petroleum processes discussed.

CONCLUSIONS

The analysis of hydrocarbon generation and expulsion processes in the lower Paleozoic strata in the Gryfice and Kołobrzeg blocks showed that:

1. Middle Cambrian potential source rocks reached the entire hydrocarbon generation interval, from early to late phases, in both the Kołobrzeg and Gryfice blocks and the timing of reaching of those phases was practically the same. The early stage of hydrocarbon generation was reached by source rocks at the end of the Silurian and beginning of the Devo-

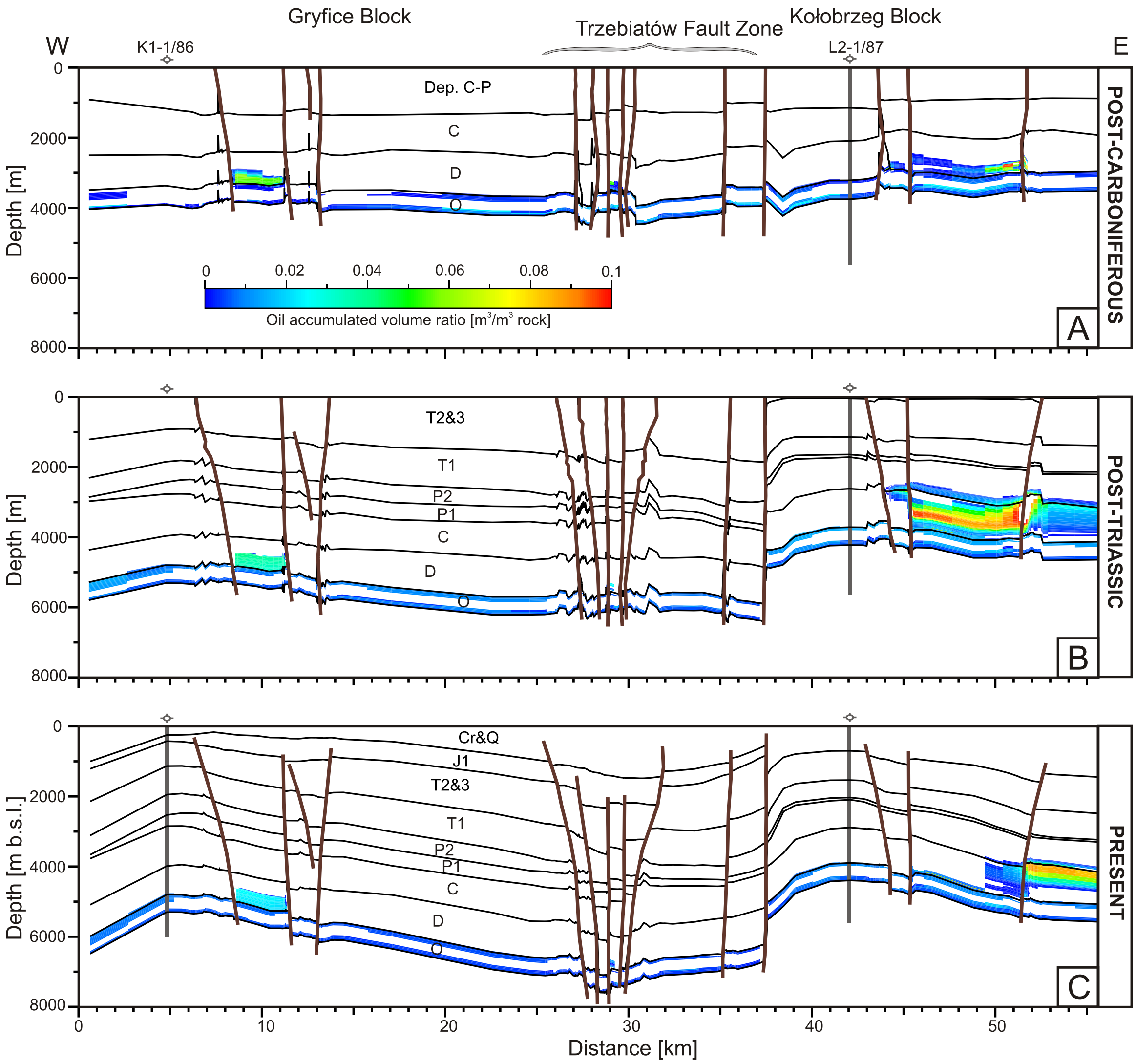

Fig. 8. Oil accumulated volume ratio along the cross-section 81032K-820: A – after Carboniferous sedimentation, B – after Triassic sedimentation and C – present

Abbreviations as in Figures 4 and 7

nian, and the main stage in the Lochkovian. The Early Devonian erosion event interrupted hydrocarbon generation. The successive increase in depth and temperature during the Mid and Late Devonian and early Carboniferous caused the source rocks to enter the final stage of hydrocarbon generation at the beginning of the Tournaisian. The potential Middle Cambrian source rocks depleted their generation potential at the end of the Westphalian, reaching a complete degree of organic matter transformation. In the Gryfice Block, the potential Middle Cambrian source rocks reached the early stage of hydrocarbon generation at the beginning of the Permian, the main stage being reached during Late Triassic time, and the late stage at the turn of the Mid and Late Triassic. Potential Middle Cambrian source rocks depleted their generation potential at the end of the Triassic and beginning of the Jurassic.

2. Upper Cambrian–Lower Ordovician potential source rocks in the Kołobrzeg Block reached the early stage of hydrocarbon generation at the beginning of the Devonian. Prior to the end of the Westphalian they entered the final stage of hydrocarbon generation, completely depleting their generation potential. In the Gryfice Block, the source rocks reached their early generation stage at the end of the Carboniferous and the main generation stage at the turn of the Early and Mid Triassic. The final stage of hydrocarbon generation in that tectonic block was reached during the Late Triassic. Hydrocarbon expulsion in both blocks began during the Namurian, and finished in Jurassic time. In the Kołobrzeg Block at some locations, expulsion of hydrocarbons continued until the Cretaceous.

3. Caradocian source rocks in the Kołobrzeg Block also reached the entire hydrocarbon generation interval from the early to the final stage. The early and main stages of hydrocarbon generation were reached by the Caradocian rocks during the Westphalian, and the final stage on the turn of the Early and

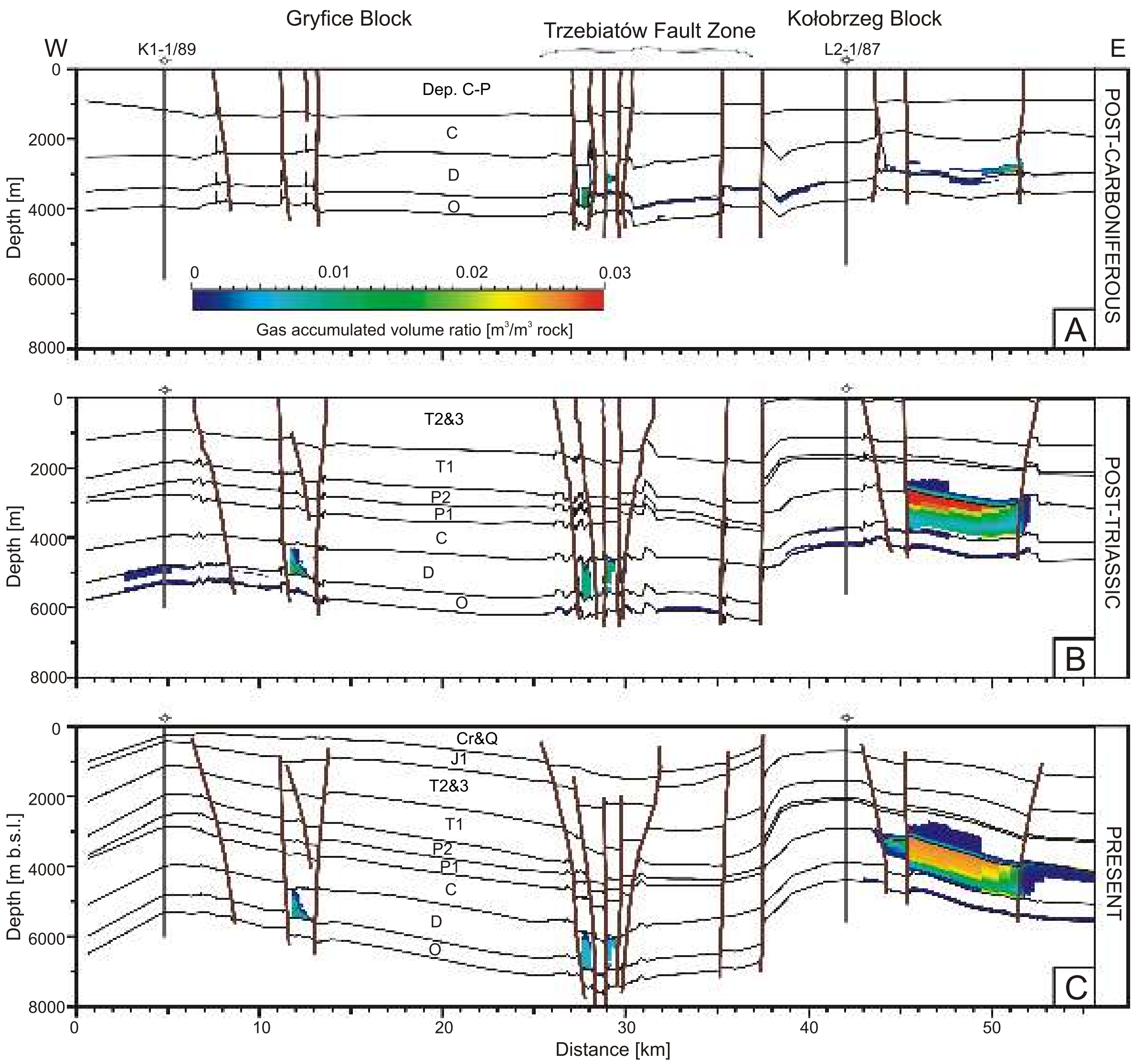

Fig. 9. Gas accumulated volume ratio along the cross-section 81032K-820: A – after Carboniferous sedimentation, B – after Triassic sedimentation and C – present

Abbreviations as in Figures 4 and 7

Mid Triassic. Organic matter of the Caradocian source rocks was completely transformed by the end of the Mid Triassic. In the Gryfice Block, the Caradocian source rocks also reached the entire generation interval from the early to the final stage. The early and main stages of generation were reached in a narrow time interval of the Early Triassic, while the final stage was reached on the turn of the Mid and Late Jurassic. The processes of hydrocarbon expulsion from the Caradocian took place in the Kołobrzeg Block in the time interval of Mid and Late Triassic, and in the Gryfice Block during the Late Triassic.

4. Migration of expelled hydrocarbons from the Upper Cambrian–Lower Ordovician and the Caradocian source rocks to Devonian reservoirs started during Carboniferous time in both the Gryfice and Kołobrzeg blocks and lasted until the end of the Mesozoic. Faults enhanced the good vertical migration pathways. During hydrocarbon migration intense hydrocarbon dispersion was observed. The hydrocarbons accumulated mostly during the Permian and Triassic, while during the Jurassic and Cretaceous some dispersion of that accumulation was observed. On the cross-section analysed, migration took place mainly along the Trzebiatów Fault Zone and in the Kołobrzeg Block, in the anticlinal zones of near-fault elevations.

Lack of discovered accumulations within Devonian reservoirs in the study area is related to hydrocarbon dispersion caused by tectonic uplift and deformation. Moreover, high temperatures and pressures caused oil cracking and formed a gas phase that readily migrated from the reservoir and was dispersed.

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