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2-D modelling of petroleum processes of the lower Paleozoic strata in the Polish part of the Baltic region

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2-D modelling of hydrocarbon generation, expulsion, migration and accumulation processes was carried out for the four (Middle Cambrian, Upper Cambrian–Tremadocian, Caradocian and Llandovery) source rock horizons. The petroleum potential of these source rocks is different, the highest being observed in the Upper Cambrian–Tremadocian horizon and the lowest in the Middle Cambrian one. The maturity of organic matter within these source units increases from the north-east to the south-west of the Polish part of Baltic region. The petroleum generation from these source rocks was highest in the Darłowo and Słupsk blocks as well as in the onshore part of the Łeba Block. Expulsion took place mainly from the Upper Cambrian–Tremadocian source rocks and these rocks sourced almost all hydrocarbons accumulated within the Middle Cambrian sandstone reservoirs. Migration of hydrocarbons proceeded along fault zones. Almost all petroleum processes in the study area took place between the end of the Pridoli and the end of the Carboniferous. Moreover, during the Permian and the Mesozoic, part of the hydrocarbons remigrated within the reservoir. This process changed the setting and the volume of hydrocarbon accumulations. It was caused by the tectonic rebuilding of the basin and, in most cases, it led to the modification of accumulation range or to the dispersion of hydrocarbons.

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INTRODUCTION

Petroleum processes in the lower Paleozoic strata were modelled along two regional cross-sections (Fig. 1), located in the western Polish part of the Baltic region. These studies aimed to reconstruct the depositional history of the sequence of rock units and to predict their behaviour and petroleum properties. The main task was to reconstruct the oil and gas generation, expulsion and migration. As a result, we determined the composition and amount of generated, expelled and accumulated hydrocarbons in each time in each level as displayed in cross-sections. Additionally, the 2-D modelling indicated the direction and rate of hydrocarbon migration. It should be mentioned that some of geological and physical data needed in that kind of reconstruction could not be measured hence, we had to use assumptions. Some previous studies of petroleum processes in the Baltic region carried out by Górecki *et al*. (1979), Witkowski (1989), Karnkowski (2003) and Zdanaviciute and Lazauskiene (2004) were excellent sources of information (interpreted seismic sections, geological, geochemical, porosity and permeability data).

The modelling of petroleum processes is, as Waples (1994) said "...a compromise between what we would like to do and what our limited knowledge permits...".

GEOLOGICAL SETTING

In the study part of the Baltic region, the Precambrian crystalline basement is covered by lower Paleozoic strata, including Cambrian, Ordovician and Silurian rocks. In the southern part, Permian, Triassic and Jurassic sedimentary rocks are also present.

Descriptions of basin geology and evolution were published by Witkowski (1989), Poprawa *et al*., (1999) and Poprawa *et al*., (2010).

According to Poprawa *et al*. (2010) and Kosakowski *et al*. (2010), two main erosion events had an important impact on the evolutionary history of the region. The Devonian and Carboniferous strata were eroded during Carboniferous uplift and are absent from the study area. In the offshore part, the Upper Silurian strata were also partly eroded during a Late Carbonif-

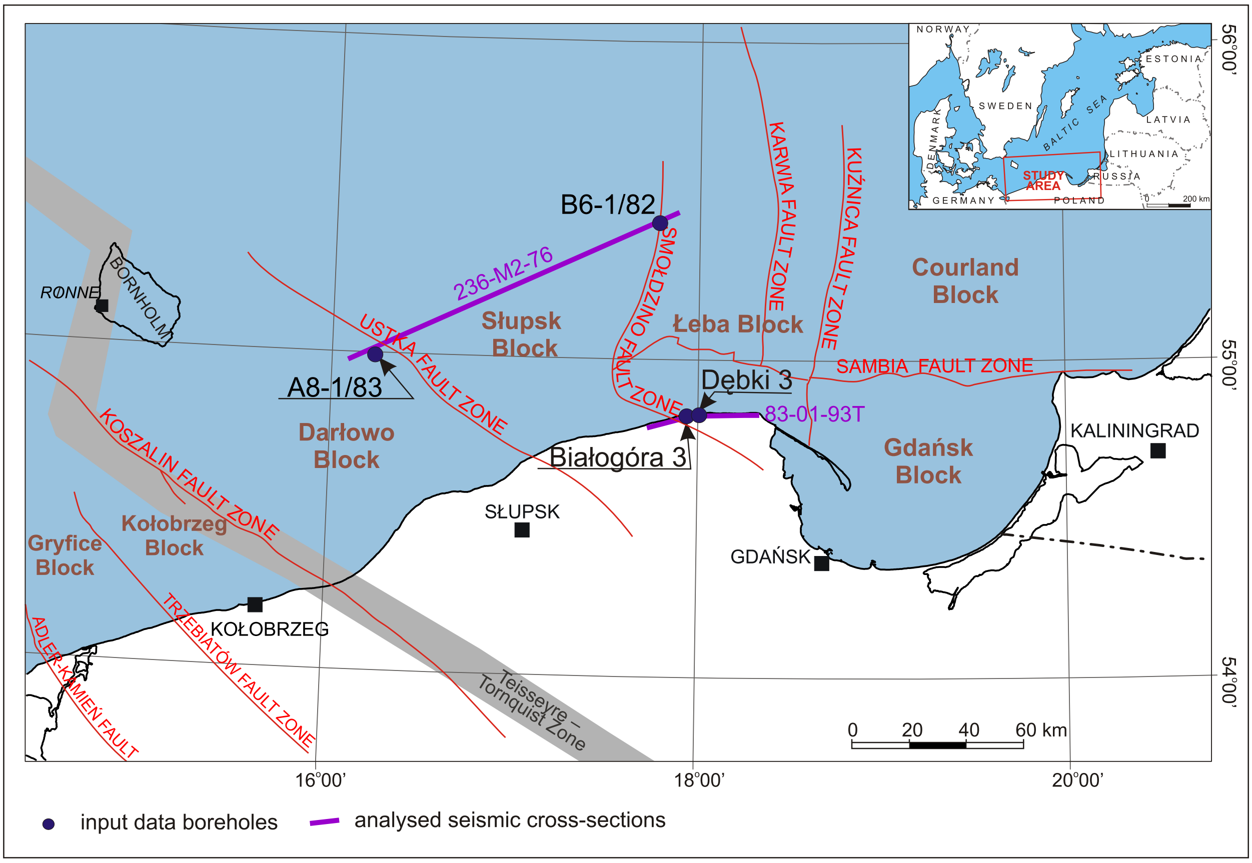

Fig. 1. Sketch tectonic map of the Polish Baltic region and location of analysed boreholes and cross-sections for 2-D modelling

Fault system after Pokorski (2010)

erous–Early Permian erosional event. The magnitude of this erosion was determined to be 1350 m in the eastern part and 1600 m in the western part of the study area. Both the post-Triassic and post-Cretaceous erosion events reduced the Triassic and Cretaceous deposits by approximately 300 m in the south to 450 m in the north of the Baltic region.

MATERIAL AND METHODS

Modelling of petroleum processes was carried out by *BasinMod*™ 2-D software (BMRM 2-D, 2006). A review of the methodology of *BasinMod*™ 2-D was presented by Wróbel *et al*. (2008).

The 236-M2-76 cross-section between the A8-1/83 and the B6-1/82 boreholes is 127.3 km long and located in the offshore, northern part of the Darłowo, Słupsk and Łeba blocks (Fig. 1). The interpretation of seismic sections identified the top surfaces of the Proterozoic, the Lower Cambrian, and the Ordovician successions as well as reflections from within the Silurian succession. Independently of seismic section interpretations, the top of the Upper Cambrian strata was positioned in the cross-section on the basis of depth data from boreholes.

The 39.5 km long 83-01-93T cross-section is located onshore, in the southern parts of the Słupsk and the Łeba blocks. It includes the Białogóra 3 and the Dębki 3 boreholes (Fig. 1). The interpretation of seismic sections identified the top surfaces of crystalline basement, and the Lower Cambrian succession, the base of the Upper Cambrian and the top of the Ordovician sequences, the reflections within the Silurian succession as well as the base of the Zechstein, the Triassic and the Lower Jurassic successions. The ages of the horizons and faults are based on Gradstein *et al*. (2004).

It should be mentioned that geological models created from interpreted seismic sections are not as accurate as geological profiles based on data from boreholes. This is caused by the low resolution of the seismic sections and problematic velocity models due to the old source data (Pokorski, 2010).

The geochemical, porosity and kinetic data were interpolated between the boreholes in which parameters were determined. A similar approach was applied to the location of the source rocks where particular sectors were assigned adequate thicknesses and TOC contents.

LITHOLOGICAL MODEL

Lithological differences recognized from borehole profiles and lithofacies maps (Modliński and Podhalańska, 2010) provided the input to the models for each stratigraphic formation as a percentage of sandstones, siltstones, shales, limestones, dolomites and evaporites. In the eastern part of the 236-M2-76 cross-section, formation lithologies were taken from the B6-1/82 borehole profile and in western part from the A8-1/83 borehole. Lithologies were defined as percentages of particular types of rocks. Analogously to the offshore cross-section, lithologies were set out on the 83-01-93T cross-section, where the eastern part of section was defined by lithological information from the Dębki 3 borehole, and the western part from that of the Białogóra 3 borehole.

The Middle Cambrian, Upper Cambrian–Tremadocian, Caradocian and Llandovery source rocks were determined and characterized by Więcław *et al*. (2010*a*). These source rocks were introduced into the model at the base of relevant stratigraphic horizons. Geochemical data for source rocks were taken from the B6-1/82 and the A8-1/83 boreholes in the eastern and western parts of the 236-M2-76 cross-section, respectively. A similar approach was applied to the 83-01-93T cross-section, where the eastern part was described by geochemical parameters from the Dębki 3 borehole and the western part from these derived from the Białogóra 3 borehole.

PHYSICAL MODEL

Thermal conditions described by Poprawa *et al*. (2010) and Kosakowski *et al*. (2010) were applied to the 2-D models by interpolation between boreholes. The modelling also used kinetic parameters calculated for the lower Paleozoic strata of the Baltic region by Więcław *et al*. (2010*b*).

Porosity and permeability data on the Middle Cambrian sandstones were described by Najdionow *et al*. (1984), Weil (1990) and Semyrka *et al*. (2010). For the Middle Cambrian reservoirs in the offshore part, the porosity varies between 1.2 and 2.2% in the A8-1/83 borehole and between 1.5 and 26.7% in the B6-1/82 borehole. In the B6-1/82 borehole the median value of porosity is 10.1%. Porosity in the onshore areas varies from 1.4 to 8.5% in the Białogóra 3 borehole and from 1 to 9.6% in the Dębki 3 borehole (Semyrka *et al*., 2010).

The thickness of reservoir was taken as the difference between the total thickness of the Middle Cambrian strata and the thickness of shales and mudstones in that formation. The main factor influencing the reservoir quality of the Middle Cambrian sandstones is the quartz cement, which reduces both the porosity and the permeability (Domżalski *et al*., 2004; Molenaar *et al*., 2007).

The aspects of petroleum migration modelling were described by Ungerer *et al*. (1990) and Welte *et al*. (2000), and the role of faults in hydrocarbon migration and entrapment was discussed by Aydin (2000) and Lopatin *et al*. (2003).

REGIONAL TRANSFORMATION RATIO OF THE LOWER PALEOZOIC SOURCE ROCKS

The maturity of dispersed organic matter depends on the location in the Baltic region (Karnkowski, 2003; Zdanaviciute and Lazauskiene, 2004; Kosakowski *et al*., 2010; Więcław *et al*., 2010*a*). Source rock maturity changes considerably from the north-east to the south-west of the Polish part of the Baltic region, as shown by values of the transformation ratio.

The changes in the value of transformation ratio are noticeable in the 236-M2-76 cross-section, which includes three blocks and which provides an insight into the areas where maturity was at different levels. At the end of the Tournaisian, in the offshore part of the Darłowo and partly of the Słupsk block, the transformation ratio reached 50% for the Middle Cambrian, 30% for the Upper Cambrian–Tremadocian and did not exceed 20% for the Caradocian and the Llandovery source rocks. At the same time, in the eastern part of the Słupsk Block and in the Łeba Block the transformation ratio for all source rocks was below 10%. In the Visean, in the western part of the 236-M2-76 cross-section the transformation ratio increased and in the eastern part of the Słupsk Block, and in the Łeba Block, it did not exceed 15% for all source rocks. At the end of the early Carboniferous all source rocks in the west reached complete transformation, while in the east transformation did not exceed 20%. These conditions have not changed until the present.

In onshore part of the Słupsk and Łeba blocks, along the 83-01-93T cross-section, time and values of transformation ratio differ considerably from those of the offshore part. In the eastern part of the Łeba Block and partly in the Słupsk Block the total transformation ratio was reached by the Middle Cambrian source rocks at the end of the Silurian. At the same time the younger source rocks reached transformation ratios of up to 80 and 70% in the Łeba Block and in the Słupsk Block, respectively. The Middle Cambrian source rocks reached total transformation ratio along the entire 83-01-93T cross-section at the end of the Emsian. The Upper Cambrian, Caradocian and Llandovery source rocks reached total transformation ratio along the whole cross-section in the Famennian.

Concluding the results of maturity and kinetic modelling along these two cross-sections, in the northern part of the Łeba Block source rocks are immature and in its southern part these are mature. Due to this difference, transformation ratio ranges from 15% in north to 100% in south. In both the Darłowo and the Słupsk blocks the source rocks reached almost total transformation in the Devonian in the onshore part and in the Carboniferous in the offshore part.

ARRANGEMENT AND TIMING OF REGIONAL HYDROCARBON GENERATION

In the northern offshore part of the study area, reconstruction of the hydrocarbon generation process for the Middle Cambrian source rocks revealed that in the Darłowo and Słupsk blocks its initiation took place at the beginning of the Tournaisian (355 Ma) and has lasted until the end of the Visean (326 Ma) (Fig. 2), totalling up to 400 mg HC/g TOC. Maximum generation of oil and gas took place in the Darłowo Block, near the A8-1/83 borehole and in the central part of the cross-section, in the Słupsk Block (Fig. 2). In the eastern part of the Słupsk Block and in the Łeba Block generation from the Middle Cambrian source rock did not exceed 100 mg HC/g TOC (Fig. 2). In the onshore part the same source rock horizon, along the 83-01-93T cross-section, started hydrocarbon gener-

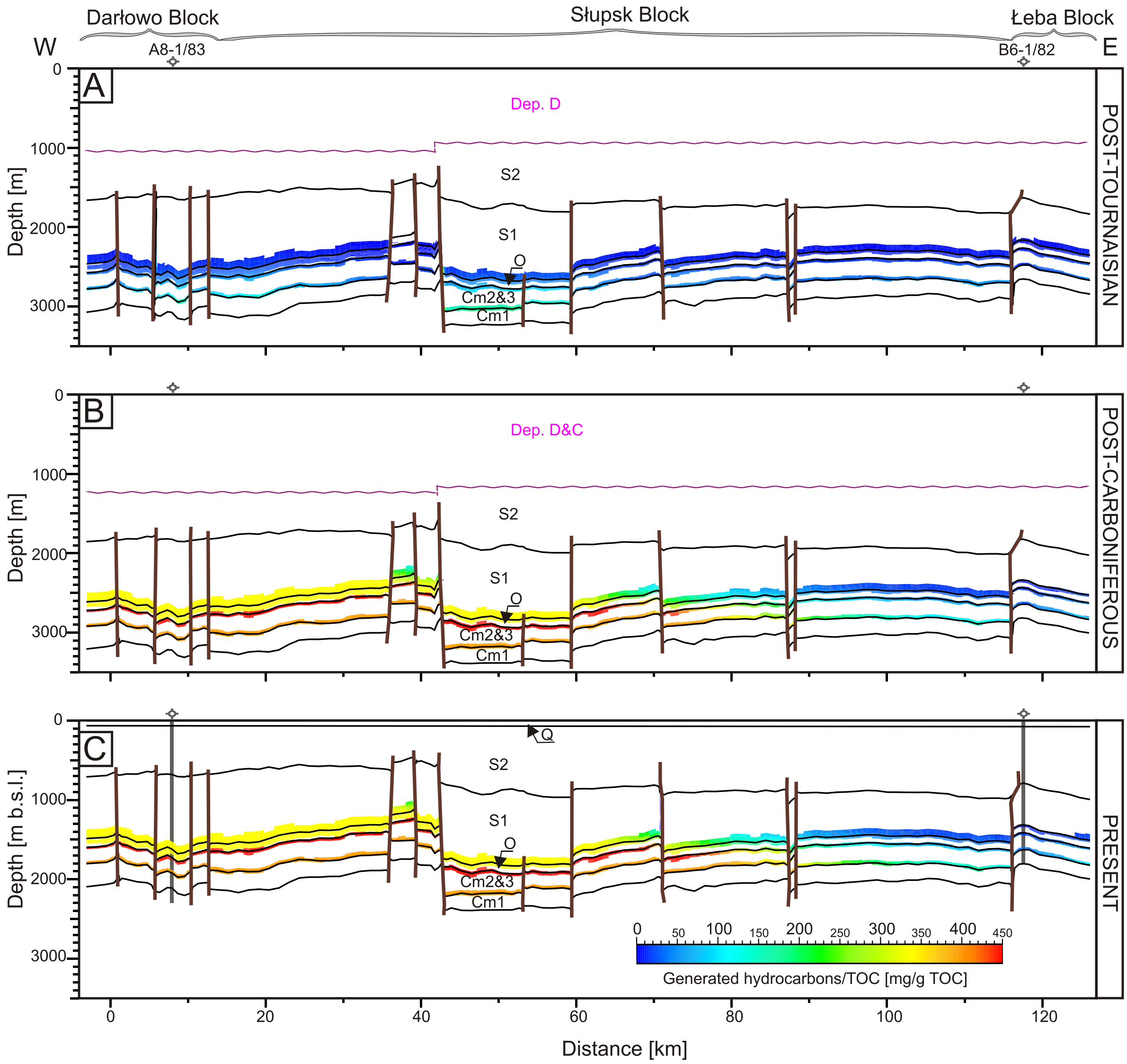

Fig. 2. Amount of hydrocarbons generated along the 236-M2-76 cross-section in particular time steps: A – after Tournaisian sedimentation, B – after Carboniferous sedimentation and C – present

Cm1 – Lower Cambrian, Cm2&3 – Middle and Upper Cambrian, O – Ordovician, S1 – Llandovery and Wenlock, S2 – Ludlow and Pridoli, Dep. D – Devonian deposits, Dep. D&C – Devonian and Carboniferous deposits, Q – Quaternary, wavy violet line – base of deposited sediments reconstructed in model

ation in the Ludlow (419 Ma) and the process lasted until the Lochkovian (414 Ma), near fault zones in the neighbourhood of the Białogóra 3 borehole and in the Słupsk Block. However, an exception was found near the fault zones, where generation ended at the beginning of the Tournaisian (460 Ma). The total amount of oil generated from the Middle Cambrian horizon reached 350 mg HC/g TOC and that of gas reached 50 mg HC/g TOC.

In the offshore area within the Upper Cambrian–Tremadocian, Caradocian and Llandovery source rocks, the hydrocarbon generation process started in the Tournaisian (352 Ma) and ended in the Visean (326 Ma). The amount of hydrocarbons generated varied from 350 mg HC/g TOC for the Caradocian and Llandovery source rocks to 450 mg HC/g TOC for the Upper Cambrian–Tremadocian source rocks (Fig. 2). In the eastern part of the 236-M2-76 cross-section the amount of hydrocarbons generated did not exceed 50 mg HC/g TOC (Fig. 2). In the onshore part only the Upper Cambrian source rocks are present whereas the Tremadocian strata have not been preserved. Generation of hydrocarbons within the Upper Cambrian, Caradocian and Llandovery source rocks started at the end of the Ludlow (419 Ma) in the eastern part of the 83-01-93T cross-section and reached a maximum in the mid Lochkovian (414 Ma). In the remaining area generation lasted until the beginning of the Tournaisian (360 Ma). Along the entire 83-01-93T cross-section the volume of hydrocarbons generated in the onshore part reached a maximum of 450 mg HC/g TOC for the Upper Cambrian source rock, and 350 mg HC/g TOC for the Caradocian and Llandovery source rocks.

The Darłowo, Słupsk and Łeba blocks differ in the amounts of hydrocarbons generated and in the time of the generation process. The best conditions for hydrocarbon generation existed in the Darłowo and Słupsk blocks, and in the onshore part of the Łeba Block. The offshore part of the Łeba Block and eastern part of the Słupsk Block seem not to be generative enough to include them in the mass balance of hydrocarbons in this part of the Baltic region.

EXPULSION, MIGRATION AND ACCUMULATION OF HYDROCARBONS

Expulsion modelling revealed that all the hydrocarbons generated in the Upper Cambrian–Tremadocian source rocks saturated the Middle Cambrian reservoirs. Fault systems provided the connection between an older reservoir and younger source rocks. As for the hydrocarbon generation process, the expulsion, migration and accumulation processes have been studied separately for the offshore and onshore parts of the Polish part of the Baltic region.

In offshore part, the main phase of oil and gas expulsion and migration took place between the mid (345 Ma) and the late Visean (326 Ma). Tectonic events occurring during the Permian and the Mesozoic caused some movements of hydrocarbons within the reservoir and changed their position in the basin (Fig. 3). The studies of petroleum processes along the 236-M2-76 cross-section revealed that the expelled oil in the Darłowo and Słupsk blocks migrated to the Middle Cambrian sandstones through the faults. These faults show thrust movements from 50 to 200 m, which guarantees connections between the source and the reservoir rocks. The fault with the highest thrust movement (about 500 m, over 42 km; Fig. 3) forms a barrier for hydrocarbon migrations from the eastern part of the Słupsk Block. In the uplifted part of the Słupsk Block expelled hydrocarbons migrated to the west. The analysis of oil migration in the offshore part show that the migration distance varied from a few to even 30–40 km, at an oil expulsion volume of up to 0.15 m^3/m^3 rock. Accumulation of oil took place mainly in the Słupsk and the Łeba blocks. The volume of oil accumulated in the Middle Cambrian sandstones varied from 0.13 m^3/m^3 rock in the western part of the Słupsk Block to 0.16 m^3/m^3 rock at the B6-1/82 (i.e. B6 field) in the Łeba Block (Fig. 3). The expulsion of gas occurred everywhere except for the Łeba Block, and its maximum volume reached 0.027 m^3/m^3 rock. In the central part of the Słupsk Block expelled gas migrated to the east towards the Łeba Block. Gas migrated along the 236-M2-76 cross-section partly underwent dispersion. Gas losses were caused by vertical migration through the faults, mainly during and after Carboniferous inversion of the Baltic region. Domżalski *et al*. (2004) described this process as a result of gas diffusion or effusion. Gas was accumulated in the reservoir in the amount of 0.02 m^3/m^3 rock with 20% losses (Fig. 4). Anticlinal traps along the Smołdzino Fault formed reservoirs for the gas accumulations. Gas yielded from the source rocks in the Darłowo Block and in the western part of the Słupsk Block migrated to the east, towards the fault with the largest thrust movement. This fault created a barrier to further hydrocarbon flow to the east and, as a consequence, substantial gas accumulation was disclosed in the 236-M2-76 model (Fig. 4).

In the onshore part of the study area, expulsion was observed mainly in Upper Cambrian strata. Oil expulsion processes started at the end of the Pridoli (416 Ma), and lasted to the end of the early Carboniferous (326 Ma). First, at the end of the Pridoli expulsion started in the eastern part of the 83-01-93T cross-section, and in the Famenian (375 Ma) expulsion began in the central and western parts of the cross-section. The volume of oil expulsion varied from 0.04 m^3/m^3 rock in the western part, to a maximum of 0.065 m^3/m^3 rock in the eastern part. Gas expulsion in the onshore part started at the end of the Ludlow (418 Ma) in the eastern part of the 83-01-93T cross-section and in the Lochkovian the expulsion began in the western part of this cross-section. At the end of the Pridoli (417 Ma) gas expulsion ended in the eastern part, but in the rest of the cross-section it lasted to the Frasnian (380 Ma). In the onshore part gas expulsion was observed also in the Caradocian source rock, over a wide time span, from the Frasnian (382 Ma) to the Cretaceous (70 Ma). It is worth noting that expulsion from the Middle Cambrian source rock appeared in small amounts in the onshore part. Oil migration from source rocks to the reservoir in the Middle Cambrian sandstones through faults began in the Pridoli (418 Ma) and lasted to the Cretaceous (65.5 Ma). However, the main stage of that process took place at the end of the Carboniferous (299 Ma). Later only 20% of hydrocarbons changed position within the reservoir (Fig. 5). Both the Permian and the Mesozoic oil migration was connected with filling of already existing Białogóra and Dębki traps. The accumulation process began in the Pridoli (417 Ma), mainly near faults in the vicinity of the Białogóra 3 and Dębki 3 boreholes in the Łeba Block and in the Słupsk Block (Fig. 5). In both the Devonian and the Carboniferous the already existing Białogóra field was supplied with oil migrating from the east and the west (Fig. 5). Finally, oil was entrapped in the Łeba Block near the Białogóra 3 borehole and in the eastern onshore part of the Słupsk Block. The volume of oil accumulation varied from 0.11 m^3/m^3 rock to 0.13 m^3/m^3 rock (Fig. 5). Gas migration was observed mainly in the Paleozoic, but as mentioned above it also took place in the Mesozoic. The main phase of gas migration lasted from the Pridoli (418 Ma) to the end of the Famennian (359 Ma). During the Carboniferous gas losses were observed in the reservoir, reaching 25% of the initial gas volume (Fig. 6). During the next stages of basin evolution further losses took place, mainly from the traps around the Białogóra 3 and the Dębki 3 boreholes until almost total dispersion of gas in this region took place (Fig. 6). In the Słupsk Block only slight losses of gas volume were observed, however, the range of this accumulation was reduced. Finally, the volume of entrapped gas in the eastern onshore part of the Słupsk Block, amounted up to 0.027 m^3/m^3 rock (Fig. 6).

CONCLUSIONS

Regional analysis of petroleum processes in the Polish part of the Baltic region indicated that almost all hydrocarbons were generated and expelled from Upper Cambrian–Tremadocian

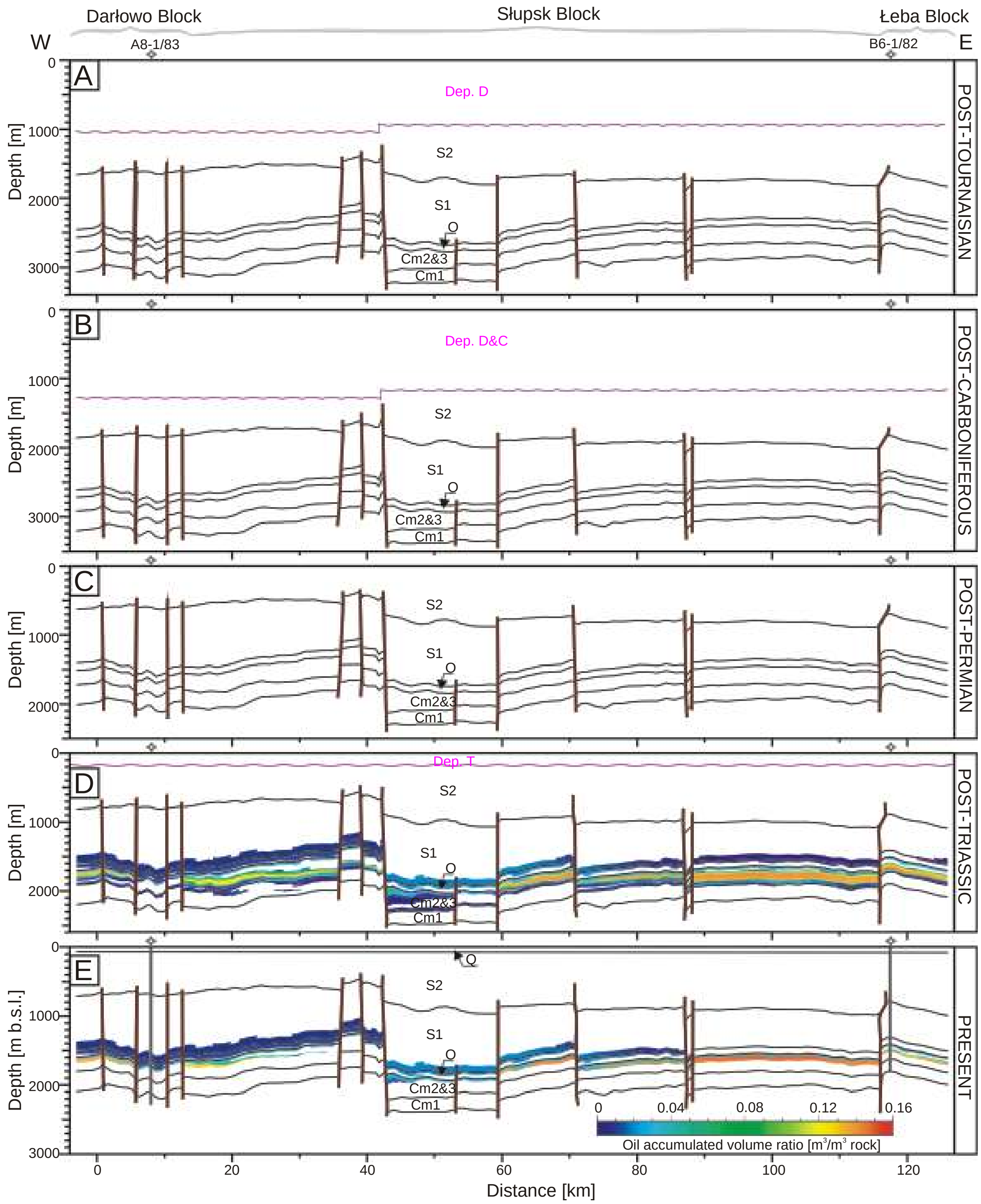

Fig. 3. Volume of the oil accumulated along the 236-M2-76 cross-section in particular time steps: A – after Tournaisian sedimentation, B – after Carboniferous sedimentation, C – after Permian sedimentation, D – before Jurassic sedimentation and E – present

Dep. T – Triassic deposits; for other abbreviations see Figure 2

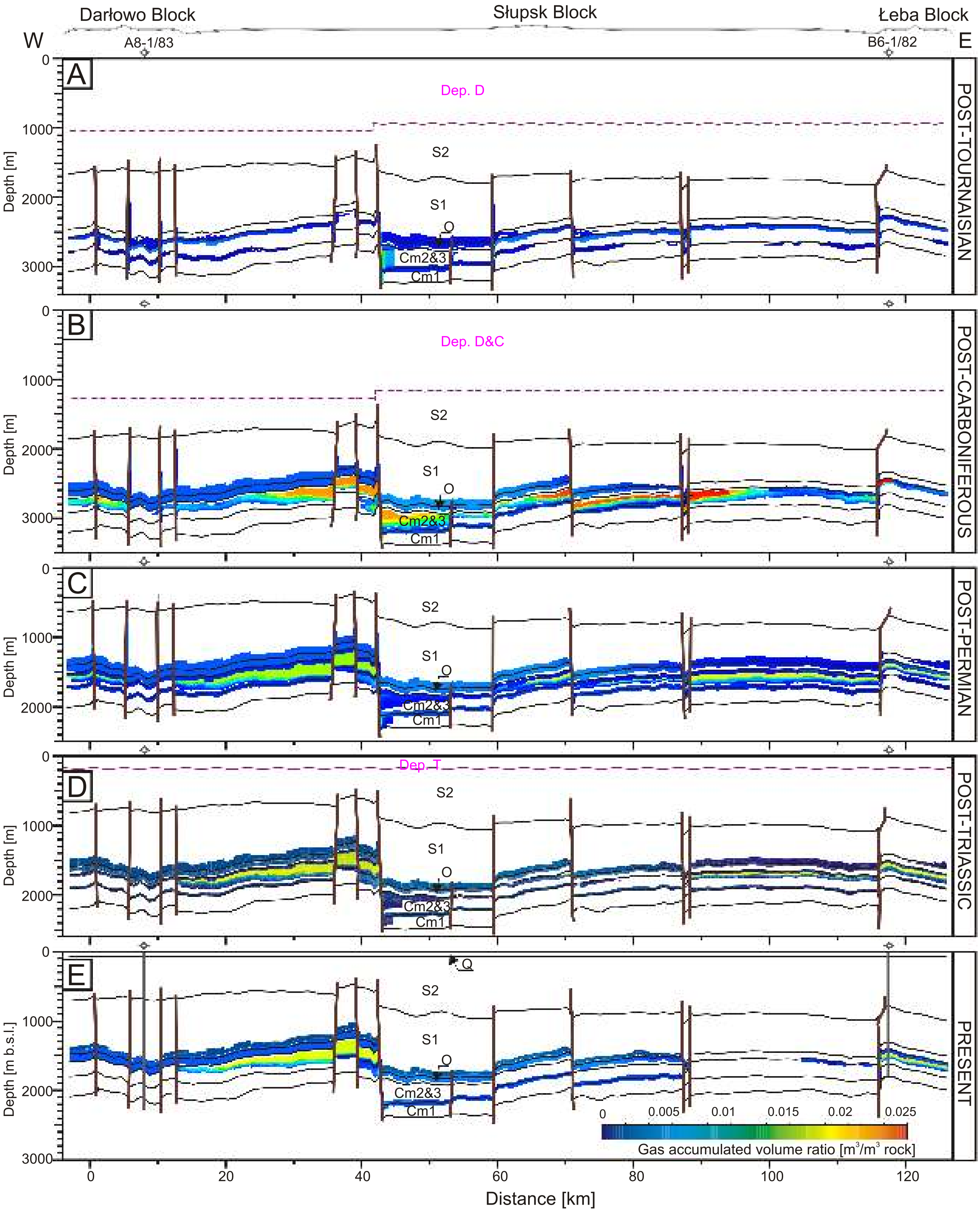

Fig. 4. Volume of the gas accumulated along the 236-M2-76 cross-section in particular time steps: A – after Tournaisian sedimentation, B – after Carboniferous sedimentation, C – after Permian sedimentation, D – before Jurassic sedimentation and E – present

For other abbreviations as in Figures 2 and 3

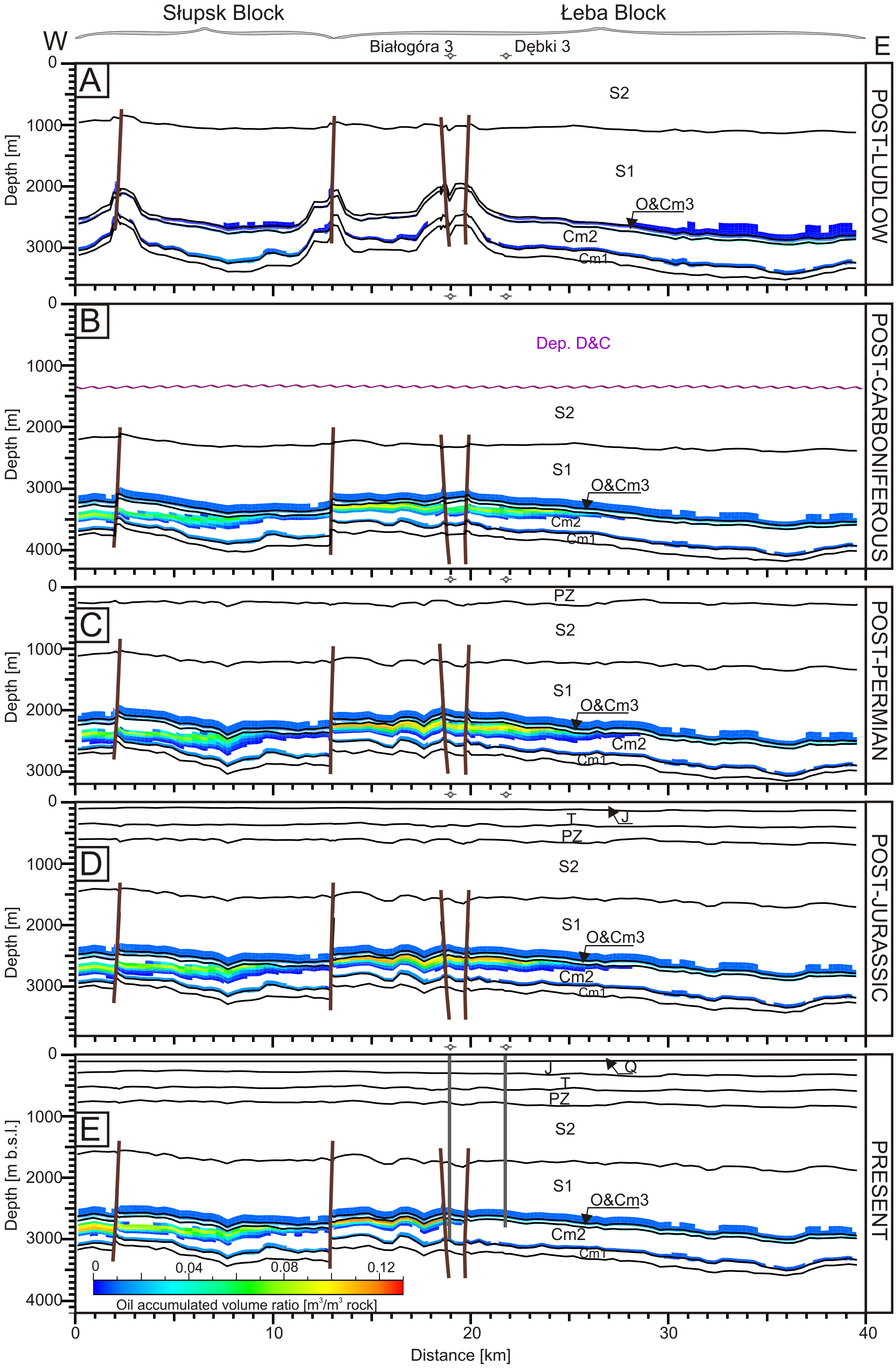

Fig. 5. Volume of the oil accumulated along the 83-01-93T cross-section in particular time steps: A – after Ludlow sedimentation, B – after Carboniferous sedimentation, C – after Permian sedimentation, D – after Jurassic sedimentation and E – present

Cm2 – Middle Cambrian, O&Cm3 – Ordovician and Upper Cambrian, PZ – Permian (Zechstein), T – Triassic, J – Jurassic; abbreviations as in Figure 2

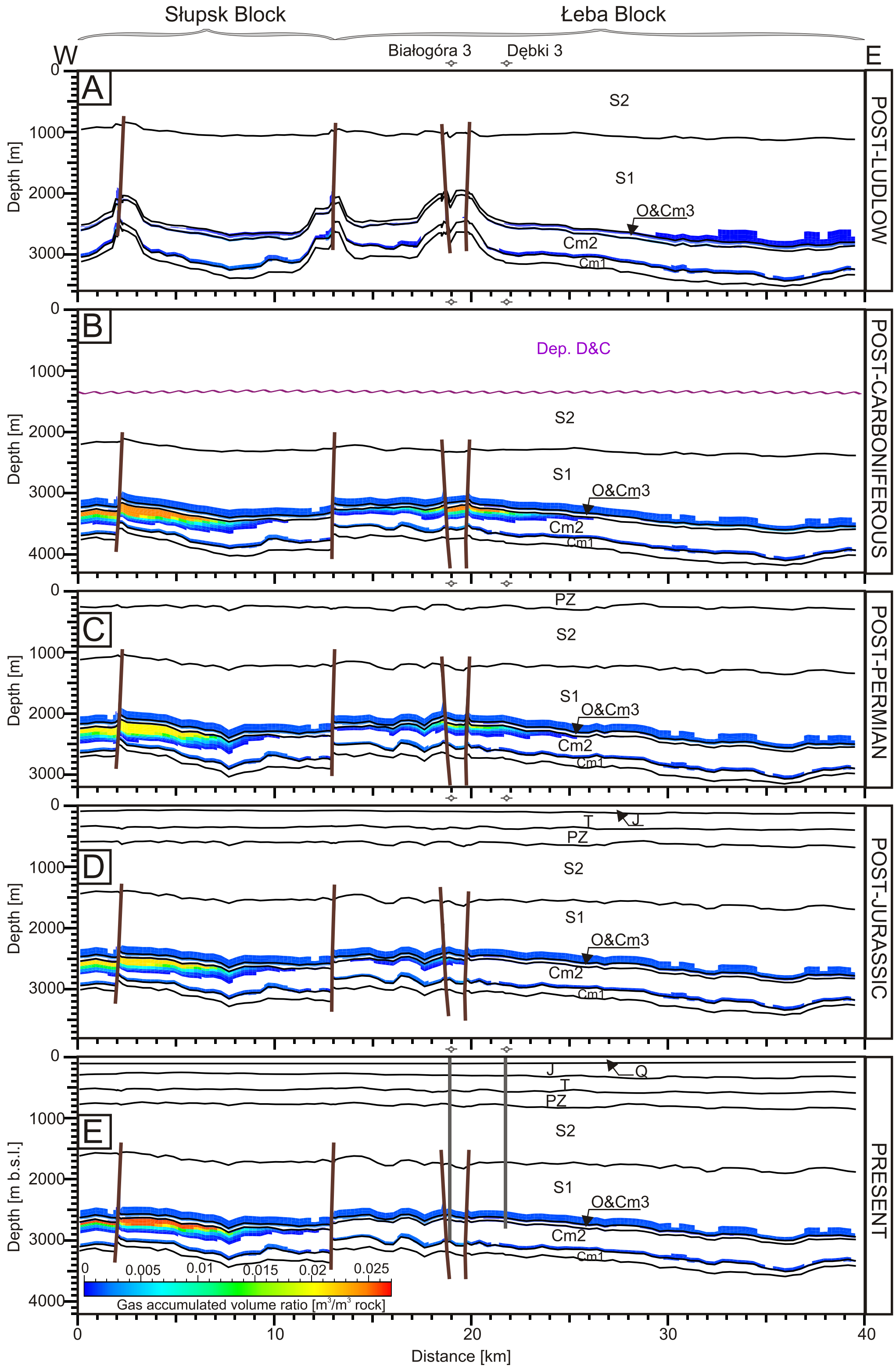

Fig. 6. Volume of the gas accumulated along the 83-01-93T cross-section in particular time steps: A – after Ludlow sedimentation, B – after Carboniferous sedimentation, C – after Permian sedimentation, D – after Jurassic sedimentation and E – present

Abbreviations as in Figures 2 and 5

source rocks. Only in the onshore area did Caradocian source rocks expel some hydrocarbons. The period of expulsion process depends on the region; in the offshore region it took place between the Visean and the end of the Carboniferous, while in the onshore region the expulsion began earlier, at the end of the Silurian and lasted to the end of the Carboniferous. It should be emphasized that in the Permian and the Mesozoic slight migration of hydrocarbons took place in the Middle Cambrian reservoirs, resulting either in the filling of the traps or in dispersion of hydrocarbons. Accumulation was nearly concurrent with migration. Hydrocarbons were entrapped in the Middle Cambrian traps described as structural traps, e.g. faulted anticlines. Migration from the younger, Upper Cambrian–Tremadocian source rocks to the older, Middle Cambrian reservoirs was guaranteed by many faults with throws creating connection between these horizons. Expelled hydrocarbons were entrapped with insignificant losses as only gas yielded in the onshore part of the region underwent dispersion.

2-D modelling of petroleum processes revealed perspectives of the discovery of new oil and gas fields in the study area of the Baltic region. The most generative are the Upper Cambrian–Tremadocian source rocks, located in the Darłowo and the Słupsk blocks, and in the onshore part of the Łeba Block where favourable thermal conditions were achieved. The study indicated a dominant west-east migration pathway, hence the Słupsk and the Łeba blocks are perspective for petroleum discoveries.

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