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PETROLEUM PROCESSES IN THE PALAEOZOIC AND MESOZOIC STRATA BETWEEN TARNÓW AND RZESZÓW (SE POLAND): 2-D MODELLING APPROACH

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Abstract: Two-dimensional modelling of hydrocarbon generation, expulsion, migration and accumulation processes in SE Poland between Tarnów and Rzeszów was carried out for five source rock horizons, *i.e.* the Ordovician, Silurian, Middle Devonian–Lower Carboniferous carbonates, Lower Carboniferous clastics, and Middle Jurassic. Five cross-sections in the study area allowed the reconstruction of timing and range of petroleum processes. The best source rocks related to the Ordovician and Silurian shales and mudstones reached "oil window" maturity within the entire study area and locally also reached the "gas window". Generation of hydrocarbons was observed from all five source rocks, but the Ordovician and Silurian source rocks generated two and three times more hydrocarbons than the Lower Carboniferous and Jurassic source rocks, respectively. Expulsion took place only in case of the Lower Palaeozoic source rocks, but the volume of expelled hydrocarbons differed across the area. Hydrocarbons migrated from the Ordovician and Silurian source rocks to the Upper Jurassic (carbonates) and Upper Cretaceous (sandstones) reservoirs or to the Upper Palaeozoic carbonates in connection with the emplacement of the Carpathian thrust belt during the Miocene. Faults formed main migration pathways and hydrocarbons accumulated in structural and stratigraphic traps, located in the vicinity of faults. In places, traps are associated with a deep Miocene erosion surface. The onset of hydrocarbon generation took place during the Neogene, mainly the Miocene, but in the north, generation and expulsion started earlier – at the end of the Mesozoic.

Key words: petroleum processes, 2-D modelling, Mesozoic, Palaeozoic, Tarnów–Rzeszów area, SE Poland.

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INTRODUCTION

Reconstruction (modelling) of hydrocarbon generation, migration and entrapment within the Palaeozoic and Mesozoic succession has been carried out for the western part of the Carpathian Foredeep (Fig. 1). The geological section of the Palaeozoic and Mesozoic strata in the study area, located between Tarnów and Rzeszów (Fig. 1), is most completely developed and best preserved (Karnkowski, 1974; 1999; Myśliwiec *et al.*, 2006; Oszczypko *et al.*, 2006). The sedimentary succession here begins with Precambrian rocks, covered by Ordovician, Silurian, Devonian, Lower Carboniferous, locally Triassic, Jurassic and Cretaceous strata. In the Rzeszów area, Mesozoic deposits are absent. The Palaeozoic and/or Mesozoic successions are covered by the autochthonous Miocene siliciclastics of the Carpathian Foredeep and, partly, by the frontal part of the Carpathian foreland fold-and-thrust belt (Karnkowski, 1974; 1999; Myśliwiec *et al.*, 2006; Oszczypko *et al.*, 2006).

The 2-D petroleum modelling carried out along five regional cross-sections (Fig. 1) was aimed at reconstruction of the depositional history of the sequence of rock units and assessment of their prospectivity with respect to petroleum exploration. Similar 2-D modelling studies focused on the Outer (Flysch) Carpathians have been completed in this area by Maćkowski *et al.* (2009). 1-D modelling studies of the Palaeozoic and Mesozoic petroleum systems have been published by Kotarba *et al.* (2003), Kotarba *et al.* (2004), Kosakowski *et al.* (2010), and Kosakowski and Wróbel (2011, in press). The influence of the synsedimentary thrusts and folds on the results of 2-D petroleum modelling was presented by Kuśmierek *et al.* (2001). No regional 2-D modelling of petroleum processes for the Palaeozoic and Mesozoic substratum of the Carpathian Foredeep in the Tarnów–Rzeszów area has been made so far. Investigations presented in this paper are the first published attempt at reconstructing oil and gas gen-

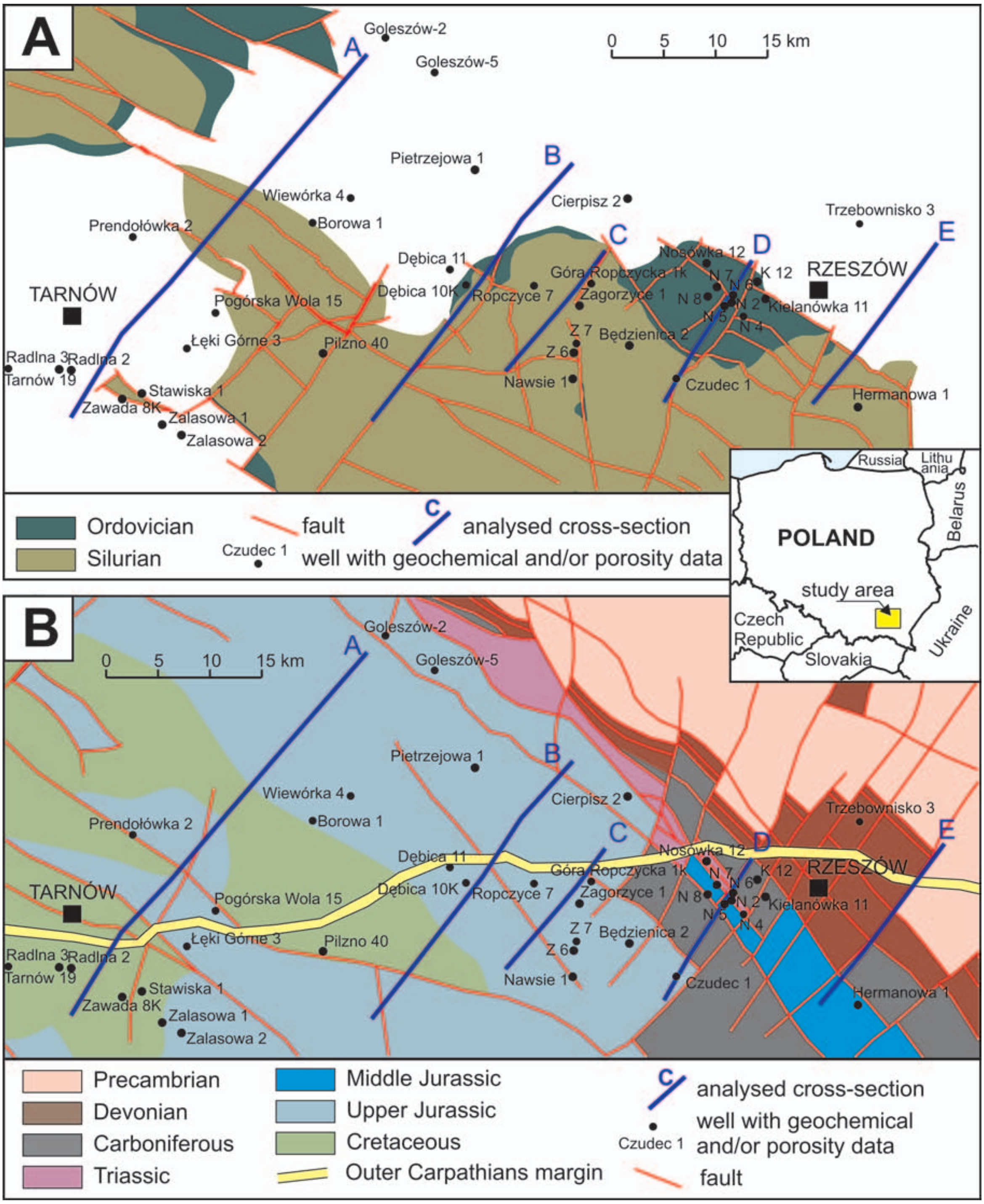

Fig. 1. Geological map of the **(A)** top surface of the Lower Palaeozoic after Buła and Habryn, *eds*. (2008) and Buła and Habryn (2011), **(B)** top surface of the Mesozoic after Poprawa and Nemčok (1989)

eration, expulsion, migration and accumulation in the Palaeozoic and Mesozoic succession of this area. Reconstruction of basin evolution, thermal changes and identification of the effective source rocks allowed us to determine the composition and amount of generated, expelled and accumulated hydrocarbons in each period and their position in the stratigraphic section. Additionally, the results of completed 2-D modelling study indicated the direction and rate of hydrocarbon migration and pointed to additional petroleum prospectives.

GEOLOGICAL SETTING

The study area is located in the southern part of Poland. The Carpathian Foredeep was formed as a flexural basin during the Miocene emplacement of the Carpathian thrust belt (*e.g.*, Krzywiec, 2001; Oszczypko *et al.*, 2006). The basement of this sedimentary basin represents the so-called epi-Variscan platform that consists of deformed Palaeozoic rocks and their Mesozoic cover (*e.g.*, Oszczypko *et al.*, 2006 and references therein).

The Palaeozoic and Mesozoic sedimentary succession in this area is characterized by numerous erosional gaps, and consists of Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic and Cretaceous strata (Fig. 1) that are buried beneath the Miocene infill of the Carpathian Foredeep basin and, partly, by the Carpathian thrust sheets. Details of the geological structure of the Tarnów–Rzeszów area were presented by Karnkowski (1974, 1999), Jawor and Baran (2004), Oszczypko *et al.* (2006), Buła *et al.* (2008), Buła and Habryn *eds*. (2008), Buła and Habryn (2011), Kosakowski and Wróbel (2011, in press), and Krajewski *et al.* (2011).

The oldest structural element of the crystalline basement belongs to the Małopolska Block, with Kraków–Lubliniec Fault Zone as its western margin. The northern margin of this block is commonly drawn along the Holy Cross Fault Zone (Buła *et al.*, 2008; Buła & Habryn, *eds*., 2008). The sedimentary cover of the Małopolska Block is divided into three structural stages: Caledonian, Variscan and Alpine (Jawor & Baran, 2004). In the western part of this block, the Caledonian stage is composed of Ordovician and Silurian formations. The Cambrian formations are not present in the study area. The Ordovician and Silurian strata rest directly above the Ediacaran anchimetamorphic complex (Buła & Habryn *eds*., 2008). A hiatus exists between the deposits of the Caledonian and Variscan structural stages. The Variscan structural stage is formed by the earliest Lower Devonian, and/or the Middle Devonian–Lower Carboniferous carbonate and Lower Carboniferous clastic complexes (Jawor & Baran, 2004; Narkiewicz, 2007; Buła & Habryn, *eds*., 2008; Kosakowski & Wróbel, 2011). Locally, Mesozoic strata rest directly on Silurian deposits.

The Permian–Mesozoic sedimentary cover of the Alpine structural stage is represented by the Permian–Triassic complex, the Middle Jurassic–Lower Cretaceous complex and the Upper Cretaceous complex. Their present areal extent and mutual relationships were determined by multistage processes of uplift and erosion (*cf.* Krajewski *et al.*, 2011). The Kimmerian and Laramian tectonic movements led to significant erosion of the Mesozoic cover and reduction in the areal distribution of particular complexes, especially the Permian–Triassic complex (Jawor & Baran, 2004). The section of the next structural complex starts only with the Middle Jurassic formations. The overlying complex is most widely distributed and consists of Middle Jurassic, Upper Jurassic as well as Lower Cretaceous formations. The Upper Cretaceous formations are separated from the underlying strata by an erosional unconformity corresponding to the Austrian phase of regional deformation during Aptian and Albian times (Jawor & Baran, 2004; Kosakowski & Wróbel, in press).

INTERPRETATION OF SEISMIC DATA

In order to prepare five geological transects necessary for 2-D modelling, several seismic profiles aligned along five regional transects have been interpreted (Fig. 1). The regional transects were assembled from seismic profiles, acquired by Geofizyka Kraków Ltd. for the Polish Oil and Gas Company (PGNiG S.A.). Several wells that were drilled through the Outer Carpathian nappes and sub-Carpathian autochthonous Miocene strata of the Carpathian Foredeep basin into the sub-Miocene basement were used to calibrate seismic data. In order to tie depth well data (stratigraphy) to time seismic data, time-depth tables were constructed using check-shot data available for selected wells. Check-shot data and sonic logs have also been used for depth-conversion of interpreted seismic horizons and faults, in order to create depth geological profiles, used for modelling of the petroleum system.

Palaeozoic and Mesozoic successions in the Zagorzyce area have been influenced by several episodes of subsidence and uplift associated with erosion (*cf.* Buła & Habryn, 2011; Krajewski *et al.*, 2011). Palaeozoic and Mesozoic strike-slip movements, generally aligned along the Teisseyre–Tornquist Zone, have been proposed farther to the north, within the Holy Cross Mts. and along the north-eastern boundary of the Mid-Polish Trough (Lewandowski, 1994, 2003; Lamarche *et al.*, 1998, 1999, 2002, 2003; Nawrocki, 2000; Gutowski & Koyi, 2007; Krzywiec *et al.*, 2009). Hence, it seems probable that within the study area Palaeozoic and Mesozoic strike-slip movements might also have played some role in shaping of the present-day geological structure of the Carpathian sub-Miocene basement.

In the southwesternmost part of the C seismic transect, a deep palaeovalley that cuts through the Mesozoic and most of the Palaeozoic cover, is noted (*cf.* Krzywiec *et al.*, 2009; Zubrzycka *et al.*, 2009). This palaeovalley belongs to the system of palaeovalleys formed due to the inversion of the Mid-Polish Trough that plunges to the south beneath the Carpathian Foredeep basin and the Outer Carpathians.

MODELLING OF HYDROCARBON GENERATION AND MIGRATION – METHODS AND DATA

The modelling of petroleum processes was carried out using BasinMod^{TM} 2-D software (BMRM 2-D, 2006). The methodology was based on four basic steps (Wróbel *et al.*, 2008; Wróbel & Kosakowski, 2010). The first step consisted of construction of a geological model including lithology of each horizon and basin evolution, especially the range and the thickness of eroded strata. The second step was the establishment of a thermal model, based on the history of the change of the surface temperature and heat flow. The third step was the compilation of geochemical and physical data measured in rock samples. The last step involved calibration of the model and the selection of calculation options.

For this study, five SW–NE trending cross-sections were used for reconstructing petroleum processes in the Palaeozoic and Mesozoic source rocks (Fig. 1). The A cross-section is 45 km long and located in the western part of the study area between Tarnów and Mielec. The B and C cross-sections are 31.5 km and 26.5 km long, respectively, and cover the central part of the analysed area, from Dębica to Sędziszów Małopolski. The D and E cross sections, located in the eastern part of the analysed area, near Rzeszów, are 16 and 19.6 km long, respectively (Fig. 1).

GEOLOGICAL MODEL

The lithological model was created from borehole profiles and interpreted well logs. Lithological composition served as input for the models for each stratigraphic formation as a percentage of sandstones, siltstones, shales, limestones, dolomites and evaporites. The oldest Palaeozoic rocks present are Ordovician in age (Buła & Habryn *eds.*, 2008; Buła & Habryn, 2011).

The Ordovician strata have been preserved in a few areas within fold, fold and block and block structures (Fig. 1). The dominant lithologies are carbonates and fine-grained siliciclastics (claystones and mudstones) and some glauconitic sandstones (Buła & Habryn, 2008; Buła & Habryn, 2011).

Similarly to the Ordovician strata, the Silurian section does not form a continuous cover (Fig. 1). The Silurian is represented mainly by fine-grained clastics, *e.g.*, claystones and mudstones (Buła & Habryn, 2008; Buła & Habryn, 2011).

The Devonian and part of the Lower Carboniferous strata, known as the Devonian–Carboniferous carbonate complex, are composed of fine crystalline dolomites with marls and limestones. Sometimes the limestones contain thin claystone and mudstone interbeds as well as streaks (Buła & Habryn, 2008; Buła & Habryn, 2011). The Carboniferous clastic complex is the youngest lithologic-stratigraphic unit of the Palaeozoic cover in the Małopolska Block. The rocks have been preserved within small depressions developed in block and fold structures (Buła & Habryn, 2008). This complex is composed of claystones and mudstones accompanied by fine- to medium-grained sandstones.

The oldest Mesozoic rocks are Permian strata represented mainly by conglomerates and sandstones with claystones and mudstones in the uppermost part of the section. The Permian strata have been deposited in fault-controlled grabens, and their thickness rarely exceeds a few tens of metres (Jawor & Baran, 2004). They are covered by the Lower Triassic variegated conglomerates, sandstones and claystones (*cf.* Oszczypko *et al.*, 2006; Krajewski *et al.*, 2011). They are covered by the Middle Jurassic sandstones, dark clays and mudstones, sometimes limestones. The Middle Jurassic succession is, in turn, covered by the Upper Jurassic–Lower Cretaceous marly and limestone series and by the Upper Cretaceous sandstones and carbonates (Maksym *et al.*, 2001; Zdanowski *et al.*, 2001; Oszczypko *et al.*, 2006; Krajewski *et al.*, 2011).

Several erosional events varying in timing and extending from the southwest to the northeast across the study area were included in the geological model. Both the post-Silurian and the post-Ordovician erosional events were associated with 200 m of erosion. Moreover, 150–600 m of Devonian–Carboniferous strata were eroded (Kosakowski & Wróbel, 2011). Triassic strata, amounting up to 350 m of section, have been almost completely eroded during the late period of early Jurassic times. From the late Cretaceous to the Miocene, approximately 2,000 m of Jurassic and Cretaceous section was eroded (Marek & Pajchlowa, 1997; Dadlez *et al.*, 1998). The assessed thickness of eroded strata was checked against the regional geology and thermal parameters (Kosakowski & Wróbel, 2011; Kosakowski & Wróbel, in press).

The thermal conditions and calculated kinetic parameters were applied to the 2-D models by interpolation between the boreholes, and were described in detail in the 1-D modelling papers by Kosakowski and Wróbel (2011, in press). The 2-D thermal model is simply an interpolation of profile information set in the wells such as heat flow and surface temperature. As input for the 2-D thermal model, the literature data including maps of the temperature distribution and heat flow values calibrated with temperature logs were used (Majorowicz & Plewa, 1979; Majorowicz, 1984; Plewa, 1994; Karwasiecka & Bruszewska, 1997). Due to some differences in these values averages were used.

Regional changes in the present heat flow values in the study area of the Małopolska block range from 50 to 40 mW/m^2 (Majorowicz & Plewa, 1979; Belka, 1993a, b; Karwasiecka, 2001; Kotarba *et al.*, 2004). Geological models of the Caledonian stage of development prepared using results of Narkiewicz (2002, 2007), Poprawa *et al.* (1997) and Poprawa (2006a, b) did not indicate a significant thermal events during this period. Overheating occurred during Variscan orogeny, and during Permian, Mesozoic and Cenozoic times the deposited strata underwent cooling (Majorowicz, 1984).

GEOCHEMICAL AND PHYSICAL MODEL

The geochemical characteristics of the Palaeozoic and Mesozoic strata in the Kraków–Rzeszów area published by Więcław *et al.* (2011) and Kosakowski *et al.* (in press) formed the basis for distribution of thickness and original total organic carbon (TOC_o) content along the cross-sections used in the modelling. These authors concluded that excellent source rocks were present in the Ordovician, Silurian and Middle Jurassic successions, whereas the Middle Devonian–Lower Carboniferous carbonates and the Lower Carboniferous clastics could be classified as "fair" source rocks (Peters & Cassa, 1994). In the regional approach, necessary in 2-D modelling, the source rocks were put into the model as thin beds in the bottom of each stratigraphic horizon. The thickness of effective Ordovician source rocks varied from 40 to 140 m, and the TOC_o content ranged from 1 to 2.5 wt%. The lowest TOC_o in the Ordovician source rocks was found in the eastern part of the study area (the D and E cross-sections), and the highest in the western part (the B and C cross-sections). The Silurian source rocks had the same TOC_o content along all the cross-sections on average 3 wt%, but their thickness varied, from 40 m along the A, C and D cross-sections to 80 m along the B and E cross-sections. The Middle Devonian–Lower Carboniferous carbonate source rock was rather thin, not exceeding 30 m, and the TOC_o content varied from 0.5 to 0.8 wt%. For the Lower Carboniferous clastic source rocks the TOC_o was found to be 1 wt% on average, while the thickness ranged widely, from few tens of metres to even 120 m.

Characteristics of reservoirs including the basement of the Carpathian Foredeep were published by Myśliwiec *et al.* (2006). Kosakowski *et al.* (2012) made a wide research of porosity and permeability in selected reservoir rocks in the Kraków–Lubaczów area. The results of petrophysical analysis realized by Kosakowski *et al.* (2012) and reservoir properties in each gas and oil fields published by Karnkowski (1999) and Myśliwiec *et al.* (2006) were the data base for physical model used in the presented petroleum modelling.

The porosity of the Lower Carboniferous clastic rocks ranges from less than 1% to even 17%, with a median value of about 3%. It suggests poor conditions for accumulation of hydrocarbons, but some horizons were defined as highly porous. Higher porosity was observed mainly in the Nosówka and Łowczów wells (Kosakowski *et al.*, 2012). Potential reservoirs in the Mesozoic also showed variable porosity; the best being Upper Jurassic carbonates. The Upper Jurassic strata showed porosities from 5 to 16%. Good porosities were also found in the Upper Cretaceous strata (Kosakowski *et al.*, 2012).

RESULTS OF PETROLEUM MODELLING

The differences in the range of sedimentation and erosion of each geological epoch in the study area were significant enough to split the study Tarnów–Rzeszów area into three compartments: the zone between Tarnów and Ropczyce, which includes the A, B and C cross-sections, the zone located southwest of the Nosówka field, covered by the D cross-section, and the area east of the Hermanowa zone where the E cross-section is located. The diversified burial history influenced on petroleum processes both in time and range. These three zones present diversity of reservoirs age, migration style and timing in the Tarnów–Rzeszów area.

Tarnów–Ropczyce zone

The Tarnów–Ropczyce zone was analysed through the A, B, C cross-sections (Fig. 1). In this zone, subsidence during the Jurassic and Cretaceous times exerted important influence on the maturation of the Palaeozoic and Middle Jurassic source rocks.

The Ordovician source rocks along the B and C cross-sections reached late “oil window” maturity (1–1.3% R_o) in the late Jurassic, and in the late Cretaceous the maturity increased further to 1.3–2.6% R_o. The Silurian and Middle Devonian–Lower Carboniferous carbonate as well as the Lower Carboniferous clastic source horizons, present in three cross-sections in this zone, reached the main phase of “oil window” maturity (0.7–1% R_o) at the end of the early Jurassic. Later, their maturity increased to a maximum of the 1.3% R_o in the most deeply buried parts of the cross-section.

The Middle Jurassic source rocks analysed along the C cross-section underwent maturation principally during the late Cretaceous, and at present they have reached mid- to late “oil window” maturity.

The Ordovician source rocks were exhausted and fully transformed already in late Jurassic–early Cretaceous times.

The Silurian source rocks are presently exhausted and fully transformed. The main phase of maturation transpired during the early Cretaceous whereas during the late Cretaceous and the Palaeogene only a further increase in kerogen transformation ratio amounting to 10–20% took place.

The Devonian–Carboniferous source rocks show significant spatial variation in kerogen transformation ratio. Along the A cross-section, kerogen transformation varies from 60% in the south-western part to 80% in the north-eastern part. Along the B cross-section kerogen transformation is only about 30%, whereas along the C cross-section the transformation ratio ranges from 30% in the south-western part to 80% in the north-eastern part. The main phase of kerogen transformation in the Devonian–Carboniferous source rocks took place in late Cretaceous times.

Petroleum processes in Tarnów–Ropczyce zone

In the Tarnów–Ropczyce zone, the Ordovician and Silurian source rocks are the main sources of accumulated hydrocarbons, conformable with the data of Więcław *et al.* (2011) that showed good petroleum potential in these units.

The main phase of petroleum generation from the Ordovician and Silurian source horizons took place in the early Cretaceous with a minor resumption during the Neogene. The Ordovician source rocks along the B and C cross-sections generated from 300 to 350 mg/g TOC of oil and from 70 to almost 200 mg/g TOC of gas (Fig. 2). The volume of oil generated from the Silurian source rocks was similar over the entire Tarnów–Ropczyce zone and amounted to 350 mg/g TOC (Fig. 2). The volume of gas generated from the Silurian source rocks ranges from about 70 mg/g TOC along the A and B cross-sections to even 190 mg/g TOC in the north-eastern part of the C cross-section (Fig. 3).

The hydrocarbon generation from the Middle Devonian–Lower Carboniferous carbonate and the Lower Carboniferous clastic source rocks transpired in the Neogene, but the process had already begun in the Jurassic.

The gas prone kerogen present in the Devonian–Carboniferous source horizons generated up to 100 mg/g TOC of oil along all the three cross-sections in this zone (Fig. 2). The volume of gas generated from these source rocks is variable. Along section A, the volume of generated gas amounted to approximately 80 mg/g TOC and along section B it amounted to 30 mg/g TOC (Fig. 3). Along the C cross-section, the Carboniferous source rocks generated gas in amounts ranging from 30 to 120 mg/g TOC (Fig. 3).

Petroleum generation from the Middle Jurassic source rocks started at the end of the Oligocene and lasted to the end of the middle Miocene. The amounts of oil did not exceed 100 mg/g TOC whereas the amounts of gas ranged from 50 to 120 mg/g TOC (Figs 2, 3).

Expulsion took place almost exclusively from the Ordovician and Silurian source rocks along the A, B and C cross sections, and began in the early Cretaceous, with maximum expulsion in the Palaeogene.

The maximum volume of oil expulsion from the Ordovician source rocks along the B and C cross-sections ranged from 0.0006 m^3/m^3 rock along the B cross-section to 0.04 m^3/m^3 rock in the north-eastern part of the C cross-section

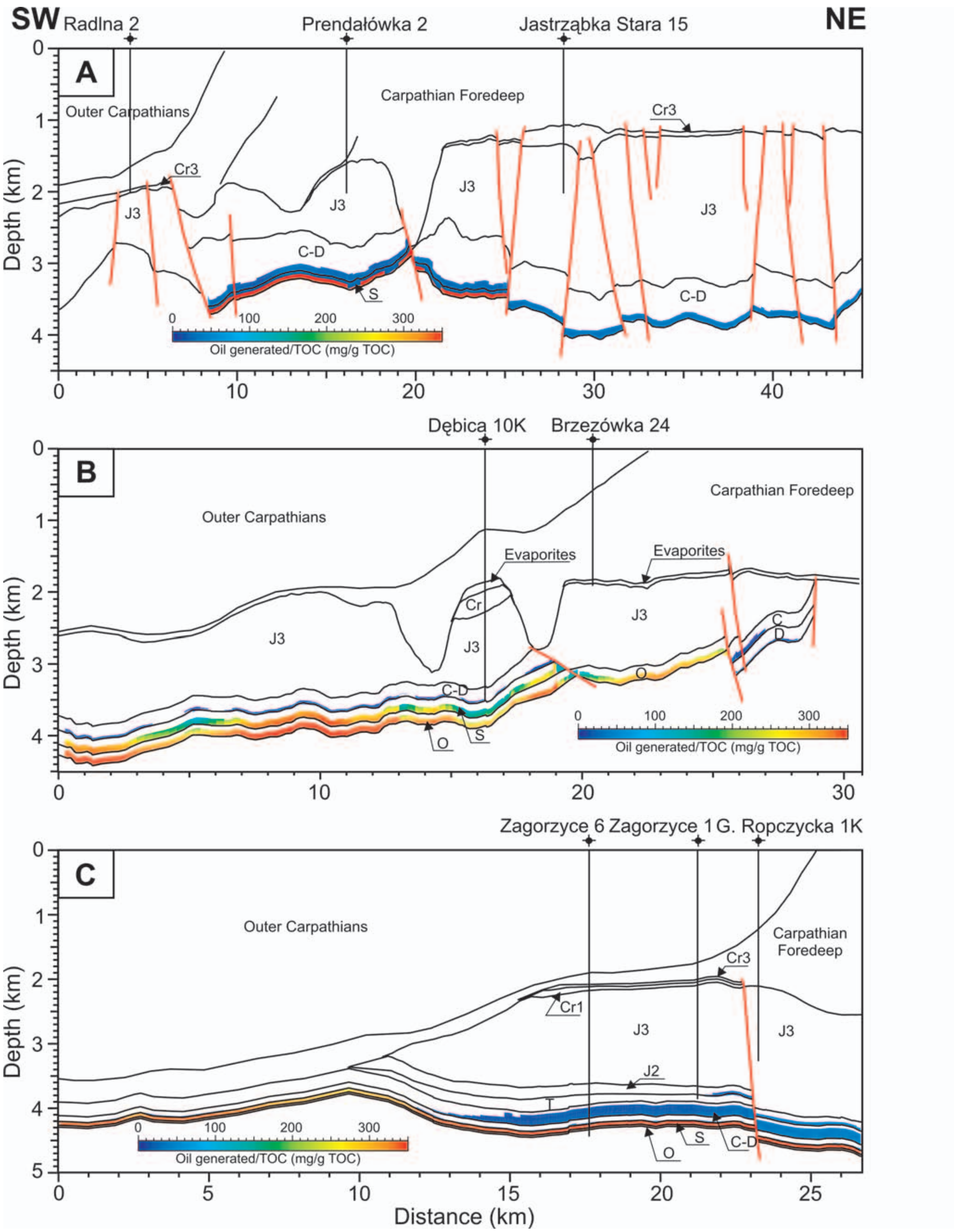

Fig. 2. Amount of generated oil along the **A**, **B** and **C** cross-sections. Cr – Cretaceous, Cr3 – Upper Cretaceous, Cr1 – Lower Cretaceous, J3 – Upper Jurassic, J2 – Middle Jurassic, T – Triassic, C – Carboniferous, D – Devonian, S – Silurian, O – Ordovician. Some of the wells were projected onto cross-sections. See Fig. 1 for location

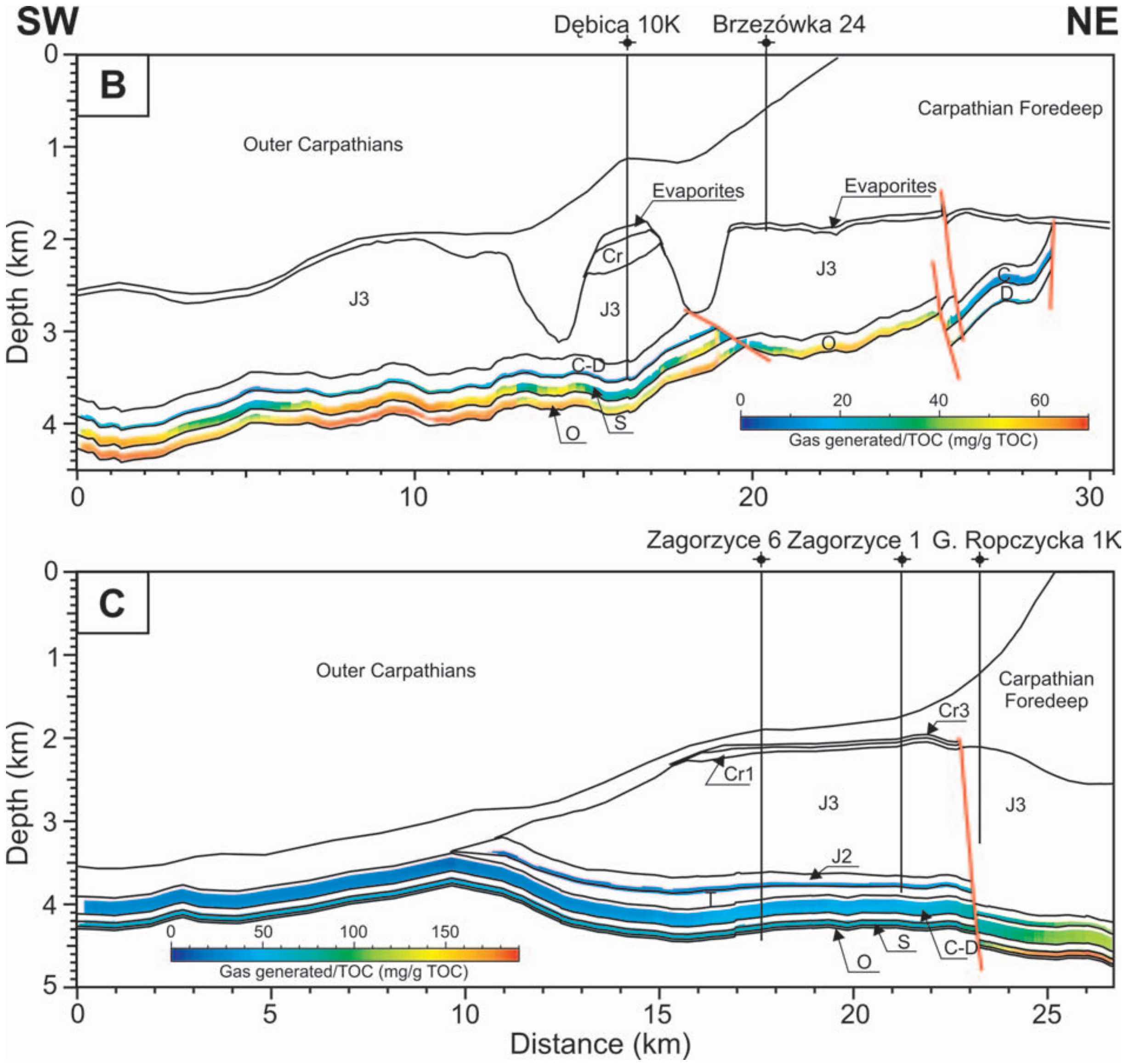

Fig. 3. Amount of generated gas along the **B** and **C** cross-sections. For abbreviations see Fig. 2

(Fig. 4). The volume of gas expulsion along the B and C cross-sections ranged from 0.0007 to 0.1 m^3/m^3 rock, respectively. The oil expulsion from the Ordovician source rock appeared along the entire interpreted horizon along the B cross-section, while along the C cross-section, the expulsion was observed almost exclusively in its north-eastern part. Expulsion of gas took place along the entire C cross-section.

Along the A cross-section, expulsion from the Silurian source rock took place with the same intensity along the entire horizon. The volume of the expelled oil ranged from about 0.0005 m^3/m^3 rock along the A and B cross-sections, to 0.04 m^3/m^3 rock in the north-eastern part of the C cross-section (Fig. 4). The volume of the expelled gas did not exceed 0.01 m^3/m^3 rock along the A, B and C cross-sections.

Migration of hydrocarbons was exclusively associated with the fault system and the Carpathian Overthrust. Carpathian overthrusting changed the pressure and tectonic regimes, which allowed hydrocarbon migration from the Lower Palaeozoic source rocks to the Upper Jurassic carbonate and the Upper Cretaceous sandstone reservoirs. Along all three cross-sections in the Tarnów–Ropczyce zone, hydrocarbons are accumulated in structural traps, *e.g.* faulted anticlines. Migration from the source rocks to the traps took place in the Miocene.

Along the A cross-section, oil and gas from the Silurian source rock migrated to the late Jurassic and late Cretaceous reservoirs following a short migration pathway, about 5 km. Hydrocarbons accumulated in the upper part of the Upper Jurassic carbonates and in the lower part of the Upper Cretaceous sandstones to create the Jastrząbka Stara oil field (Fig. 5). The volume of accumulated oil did not exceed 0.05 m^3/m^3 rock, and the volume of accumulated gas was less than 0.04 m^3/m^3 rock (Figs 5, 6).

Similarly to the A cross-section, oil and gas accumulations along the B cross-section are associated with Upper Jurassic carbonates and Upper Cretaceous sandstones. The accumulation located around the Brzezówka 24 well re-

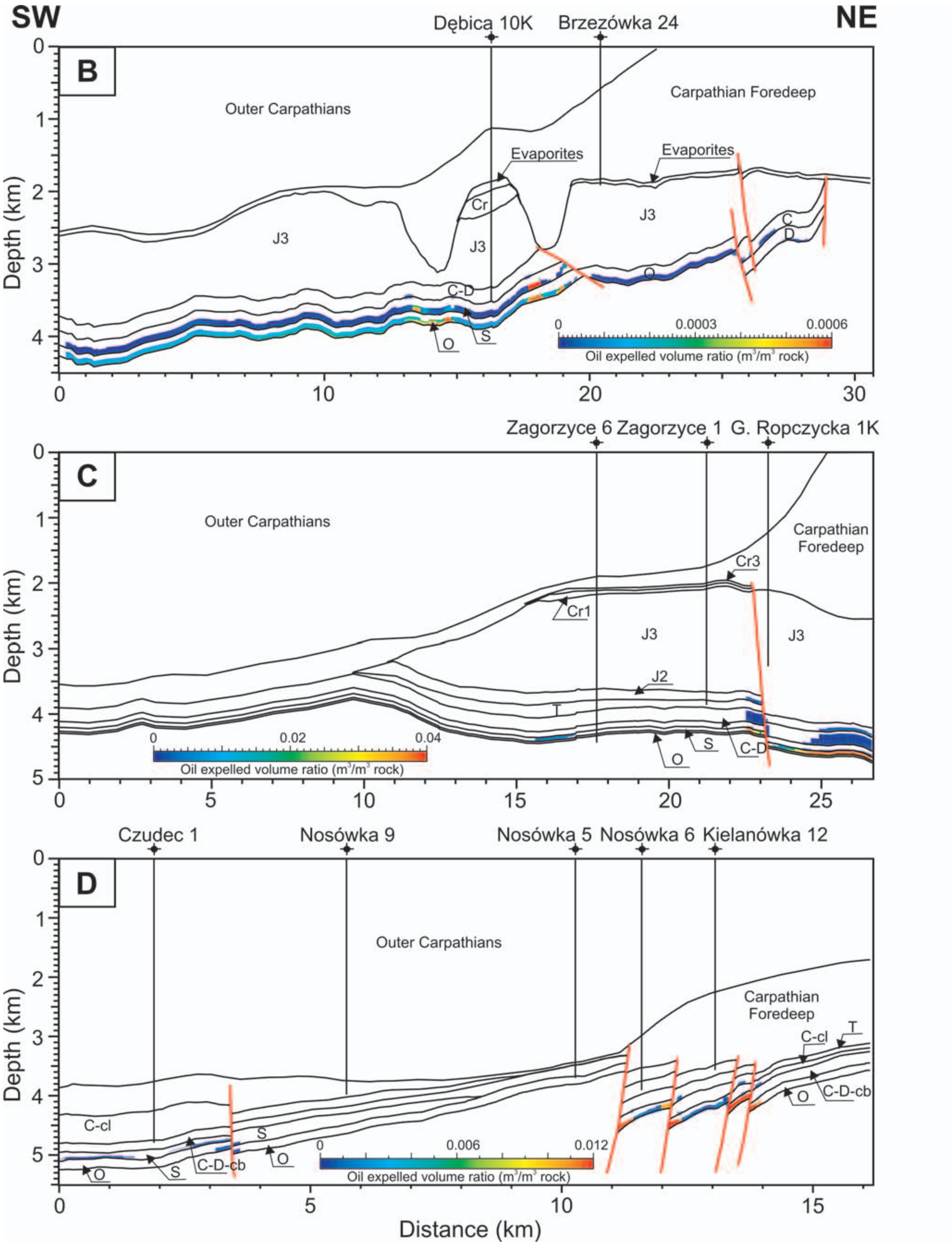

Fig. 4. The volume of the oil expulsion along the **B, C** and **D** cross-sections. See Fig. 1 for location and Figs 2 and 7 for abbreviations

sulted from migration of hydrocarbons from Ordovician and Silurian source rocks through a fault to the Jurassic-age reservoirs sealed by the Miocene-age fill of a deeply incised valley. The volume of oil accumulated around the Brzezówka 24 well reached 0.25 m^3/m^3 rock, and the gas accumulation did not exceed 0.04 m^3/m^3 rock (Figs 5, 6).

Accumulations present along the C cross-section resulted from petroleum migration from the Ordovician and Silurian source rocks along a fault surface to the top of an anticlinal structure in the Upper Jurassic carbonates in the Góra Ropczycka 1K area. The maximum volume of the accumulation of oil reached 0.11 m^3/m^3 rock, and the volume of gas amounted to 0.05 m^3/m^3 rock (Figs 5, 6).

In conclusion, the main source rocks in the Tarnów–Ropczyce zone are Ordovician and Silurian shales, which reached the late "oil window" maturity in late Jurassic–early Cretaceous times. The amount of generated oil reached the maximum of 350 mg/g TOC and generated gas went up to 200 mg/g TOC. Along the C cross-section, the expulsion from the Lower Palaeozoic source rocks amounted to 0.04 m^3/m^3 rock for oil and to 0.01 m^3/m^3 rock for gas. The migration of oil and gas took place during the Miocene, and resulted in accumulation of hydrocarbons in the Upper Jurassic carbonate and Upper Cretaceous sandstone reservoirs, forming structural, anticlinal traps during the Carpathian overthrusting. The amount of oil accumulation ranged from 0.05 to 0.25 m^3/m^3 rock, and the gas accumulation volume did not exceed 0.05 m^3/m^3 rock.

Nosówka zone

The Nosówka zone was analysed through the D cross-section located between the Czudec 1 and Kielanówka 12 wells (Fig. 1).

The maturity of the Ordovician, Silurian and Devonian–Carboniferous source rocks increased progressively through the Palaeozoic and Mesozoic to reach the end of "oil window". During the Neogene, further increases in maturity brought the Ordovician source rocks into the "gas window".

The Ordovician source rocks reached the early phase of "oil window" during the early Carboniferous; whereas the Silurian and Devonian–Carboniferous source rocks reached the same level of maturity during the Triassic. During the middle Jurassic, the Ordovician source rocks reached a maturity level corresponding to 1–1.3% R_o in the north-western part of the D cross-section, while the Devonian–Carboniferous source horizons reached the main stage of "oil window". At the same time, in the south-eastern part of the cross-section, source rocks reached the early "oil window". The Late Miocene subsidence caused a further increase in maturity in the northeast even to the "gas window" for the Ordovician source rocks, and to about 1% R_o for all source rocks in the south-eastern part of the cross-section.

In the Ordovician, source rocks kerogen transformation reached 100% in the north-eastern part of the cross-section, and about 80% in the south-western part. 60% of the Silurian source rocks transformed as did Devonian–Carboniferous source rocks in the north-eastern part of the area. In the south-western part of the D cross-section, the transformation ratio of the Devonian–Carboniferous source rocks did not exceed 40%. Kerogen transformation took place mainly in the middle Jurassic times, but resumed in the late Miocene.

Petroleum processes in Nosówka zone

Generation of hydrocarbons took place in two stages. The first transpired during middle Jurassic times in the north-eastern part of the D cross-section, and the second one during the late Neogene in the south-western part. The most generative source rocks were the Ordovician and Silurian shales. The volume of oil generated from the Ordovician source horizon varied from 300 mg/g TOC in the south-western part to 350 mg/g TOC in the north-eastern part of the cross-section (Fig. 7). The amount of generated gas was 90 mg/g TOC on average (Fig. 8). The Silurian source rocks, which are present only in the south-western part, generated up to 200 mg/g TOC of oil and 50 mg/g TOC of gas (Figs 7, 8). The Devonian–Carboniferous source rocks generated maximum of 100 mg/g TOC of oil and from 40 to 80 mg/ g TOC of gas in the north-eastern part (Figs 7, 8).

The expulsion took place at the end of the middle Jurassic and the beginning of the late Jurassic periods in the north-eastern part of the D cross-section and in the late Miocene in the south-western part. The Ordovician source rocks expelled almost 0.012 m^3/m^3 rock of oil and 0.004 m^3/m^3 rock of gas (Fig. 4). The Silurian source rocks expelled only 0.002 m^3/m^3 rock of oil, while the gas expulsion exceeded 0.004 m^3/m^3 rock (Fig. 4). In the north-eastern part of the cross-section, gas expulsion occurred locally from the Devonian–Carboniferous carbonate source rocks, however, it did not exceed 0.002 m^3/m^3 rock (Fig. 4).

Migration of oil and gas from the Ordovician and Silurian source rocks resulted in the oil and gas accumulation in partly eroded carbonate strata of early Carboniferous age. This migration event started at the turn of the middle and late Jurassic, but it was volumetrically insignificant. The migration event that created the present accumulations of oil and gas took place during the late Miocene and the Pliocene times.

The oil accumulation located around the Nosówka 5 well reaches 0.15 m^3/m^3 rock, and was probably sourced from Ordovician source rocks in the north-eastern part of the zone (Fig. 9). The gas accumulation present in the Carboniferous carbonates was created from the gas expelled in the north-eastern part of the cross-section from the Ordovician and partly from the Devonian–Carboniferous source rocks. A small gas accumulation exists together with the oil field near Nosówka 5 well. The volume of the accumulated gas varies from 0.015 m^3/m^3 rock in the eroded part of the cross-section near Nosówka 5 well, to 0.04 m^3/m^3 rock near Nosówka 6 well (Fig. 10).

In summary, in the Nosówka zone, two main stages of petroleum generation took place: during the Jurassic and during the Neogene. In the north-eastern part of the area, source rocks reached a high level of maturity already in the Jurassic, whereas in the south-eastern part the main phase of petroleum generation was not reached until the end of the Neogene. As in the Tarnów–Ropczyce zone, petroleum generation took place in the Ordovician and Silurian source rocks, and averaged 350 mg/g TOC of oil and 70 mg/g TOC

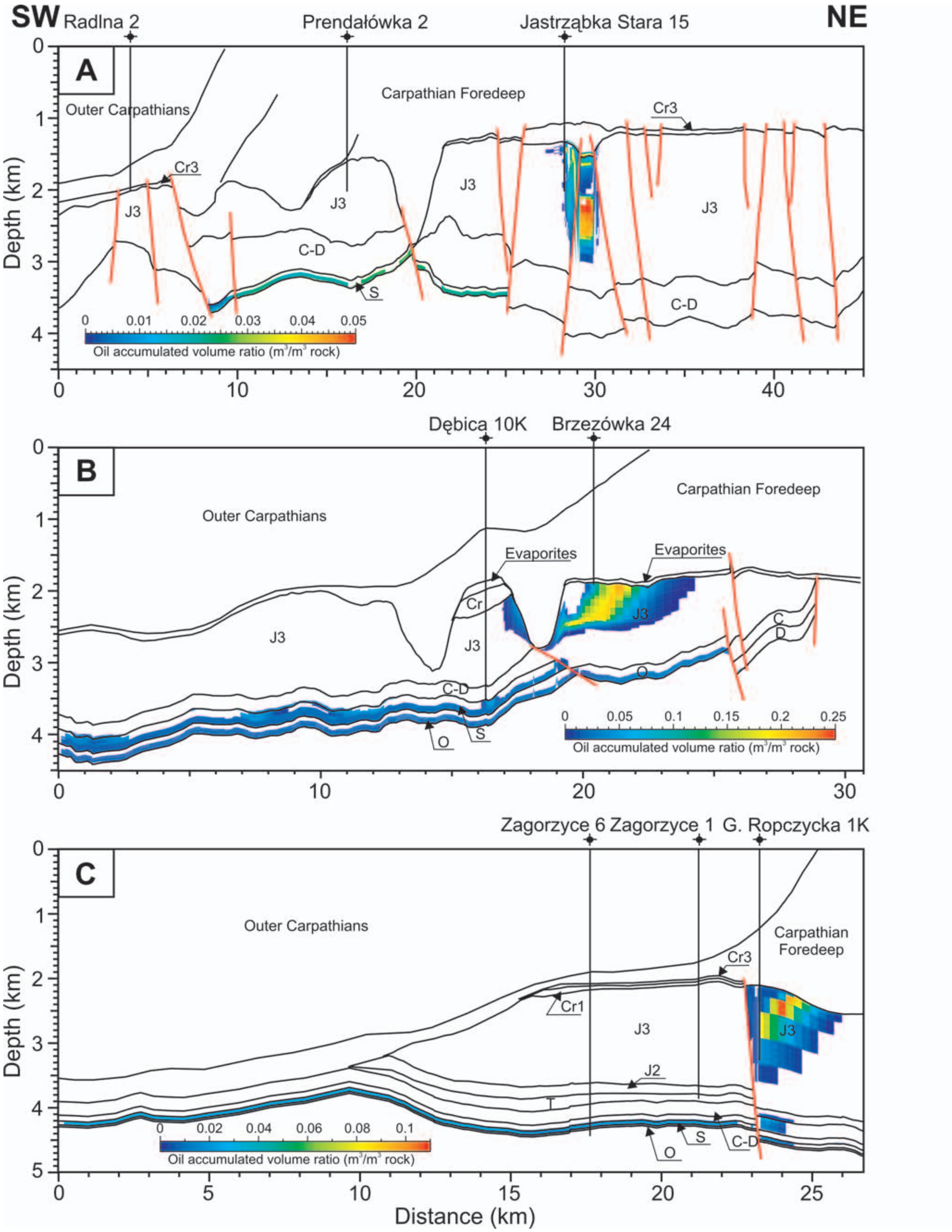

Fig. 5. The volume of the oil accumulation along the **A, B** and **C** cross-sections. See Fig. 1 for location and Fig. 2 for abbreviations

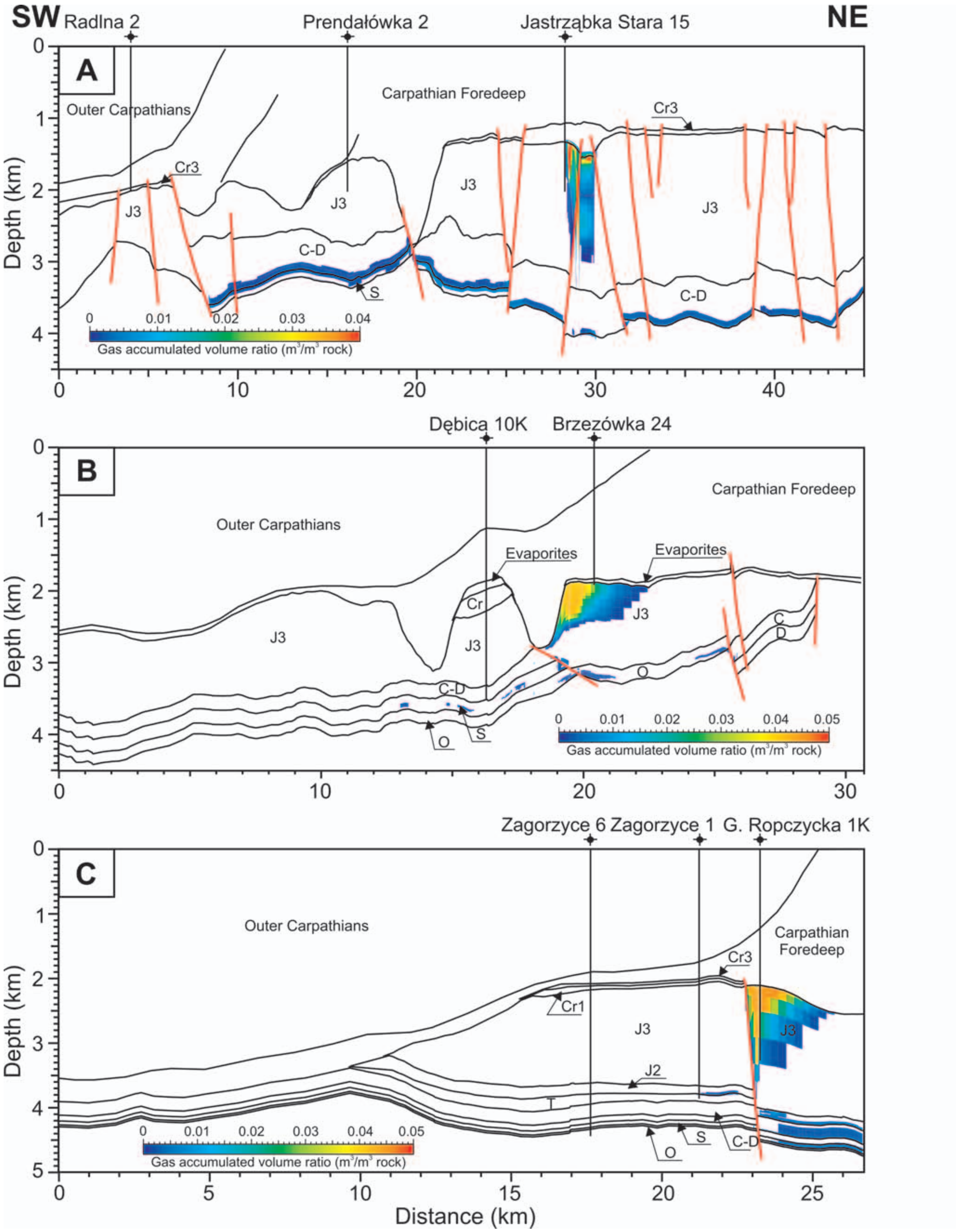

Fig. 6. The volume of the gas accumulation along the **A, B** and **C** cross-sections. See Fig. 1 for location and Fig. 2 for abbreviations

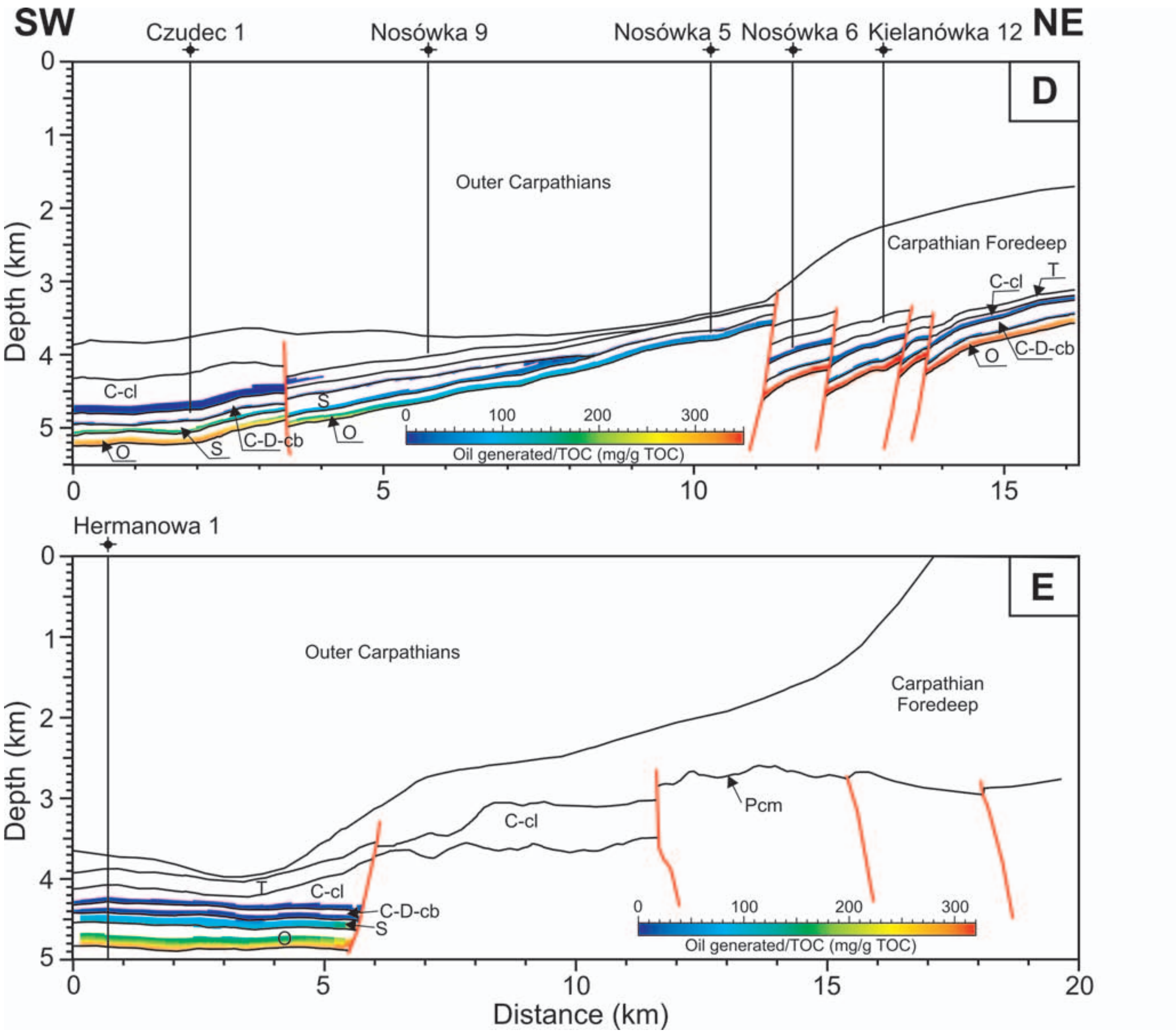

Fig. 7. Amount of generated oil along the **D** and **E** cross-sections. T – Triassic, Ccl – clastic strata of the Carboniferous, C-D-cb – carbonate strata of the Devonian and Carboniferous, S – Silurian, O – Ordovician, Pcm – Precambrian. Some of the wells were projected onto cross-sections. See Fig. 1 for location

of gas. The hydrocarbons were expelled almost exclusively from the Ordovician and Silurian source horizons. The oil expulsion did not exceed 0.012 m^3/m^3 rock and the gas expulsion was about 0.004 m^3/m^3 rock. Hydrocarbons accumulated in carbonate strata of Carboniferous age, and the main phase of migration took place during the Carpathian overthrusting. The volume of accumulated oil and gas did not exceed 0.2 m^3/m^3 rock.

Hermanowa zone

In the Hermanowa zone, the E cross-section located between Hermanowa 1 and Husów 42 wells was analysed (Fig. 1).

The Ordovician, Silurian and Devonian source rocks in the Hermanowa zone reached a maturity corresponding to the main phase of petroleum generation mainly during the Miocene, although the lower part of the Ordovician source rocks succession reached "oil window" maturity (corresponding to 0.5–0.7% R_o) as early as in the middle Jurassic. Only the lower part of the Devonian–Carboniferous source rocks reached the main phase of petroleum generation, whereas the upper part did not reach 0.7% R_o on the maturity scale.

The transformation ratios ranged from 15% for the Middle Devonian and the Lower Carboniferous, through 30% for the Silurian, to 80% for the Ordovician source rocks.

Petroleum processes in Hermanowa zone

Petroleum generation and expulsion in the Hermanowa zone took place in the late Miocene and the Pliocene. The Ordovician source rock generated about 320 mg/g TOC of oil and 60 mg/g TOC of gas (Figs 7, 8). The Silurian source

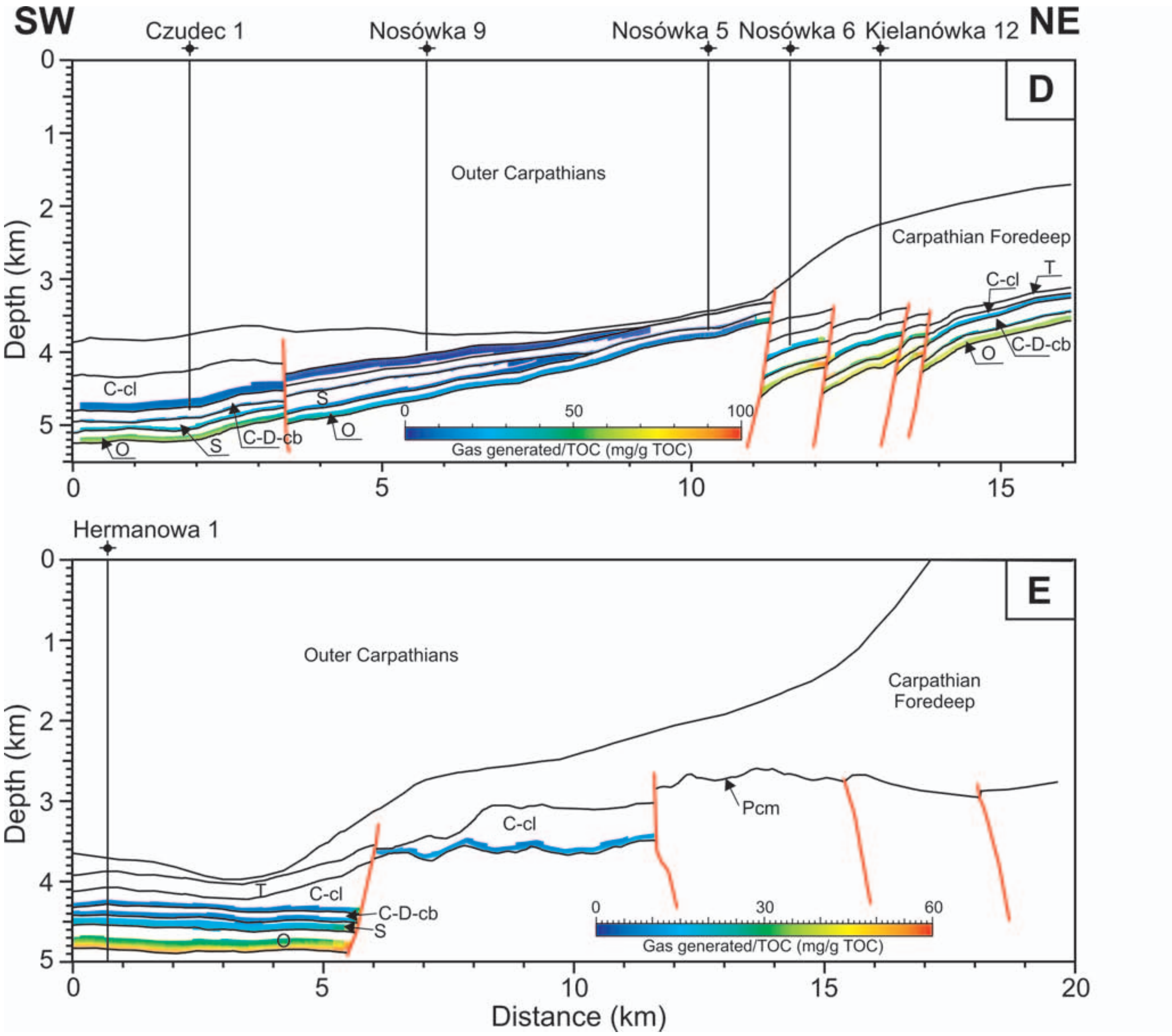

Fig. 8. Amount of generated gas along the **D** and **E** cross-sections. See Fig. 1 for location and Fig. 7 for abbreviations

rocks generated 100 mg/g TOC for oil, and 20 mg/g TOC for gas (Figs 7, 8). The Devonian–Carboniferous source rocks generated almost exclusively gas that amounted to about 10 mg/g TOC, whereas oil generation was negligible (Figs 7, 8).

Expulsion did not take place in the Hermanowa zone; all the generated hydrocarbons stayed *in situ*. The volume of oil accumulation ranged from 0.01 m^3/m^3 rock in the Ordovician to 0.012 m^3/m^3 rock in the Silurian source rocks (Fig. 9). The volume of gas accumulation varied from 0.0005 m^3/m^3 rock in the Upper Palaeozoic strata to 0.002 m^3/m^3 rock in the Lower Palaeozoic source rocks (Fig. 10).

In summation, in the Hermanowa zone the petroleum generation took place in the late Miocene and the Pliocene, but did not result in any significant hydrocarbon accumulation. Although the analysed source rocks achieved maturity from 0.7 to 1% R_o, and oil and gas generation from the Ordovician and Silurian source rocks varied from 120 to 380 mg/g TOC, there was no expulsion. The hydrocarbons were accumulated *in situ*, and saturated the sandstone-part of the Ordovician and Silurian strata.

CONCLUSIONS

Two-dimensional modelling of petroleum generation, expulsion, migration and accumulation in the Tarnów–Rzeszów area indicated that Ordovician and Silurian shales and mudstones proved to be the primary source rocks for accumulations in this area. Depending on the analysed zone, they reached different levels of maturity. The Lower Palaeozoic source rocks usually reached “oil window” maturity and only locally exceeded a maturity corresponding to 1.3% R_o. Under such thermal regime, the Ordovician and Silurian source horizons were totally transformed; only in the Hermanowa zone the transformation ratio ranged from 30 to 80%. Generation of hydrocarbons took place from the end of the middle Jurasssic to the Palaeocene, depending on

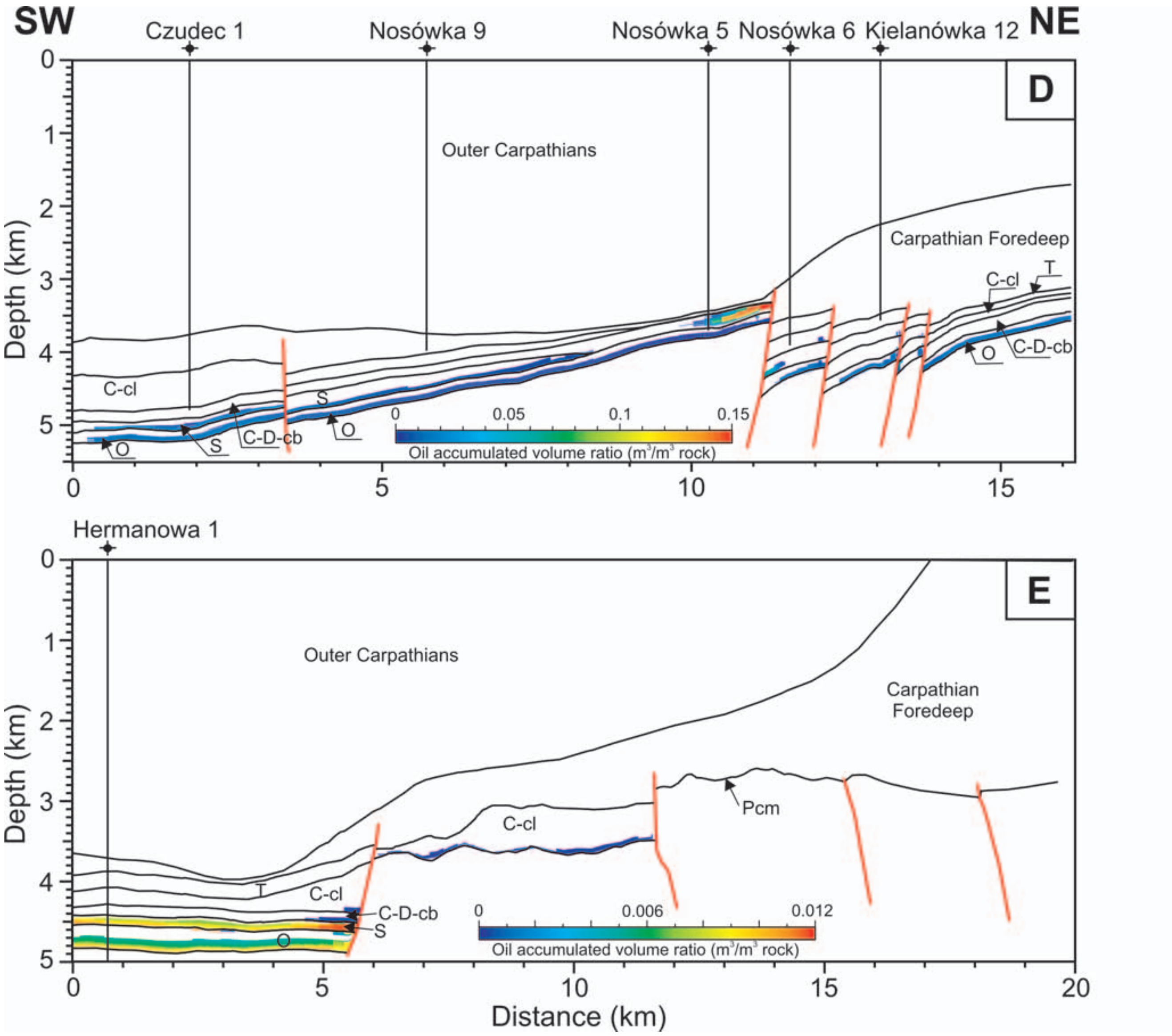

Fig. 9. The volume of the oil accumulation along the **D** and **E** cross-sections. See Fig. 1 for location and Fig. 7 for abbreviations

the local conditions in the study area. In the Tarnów–Ropczyce and Nosówka zones (north-eastern parts of the B, C and D cross-sections), the main phase of petroleum generation took place in the Mesozoic, but generation resumed in the Miocene. More to the south (area covered by the south-western parts of the B, C, D and E cross-sections), the main phase of petroleum generation took place in the Miocene, and have been at least partly associated with the final emplacement of the Carpathian thrust sheets. The amount of oil generation from the Upper Palaeozoic source rocks averaged 400 mg/g TOC. The Hermanowa zone noted the only exception with 300 mg/g TOC of generated oil. Expulsion took place almost exclusively from the Ordovician and Silurian source rocks. The highest volume of expelled hydrocarbons was observed in the central part of the study area (B, C and D cross-sections), where it ranged from 0.0005 to 0.04 m^3/m^3 rock for oil and from 0.004 to 0.01 m^3/m^3 rock for gas. Accumulation of hydrocarbons in the reservoirs took place almost exclusively during emplacement of the Carpathian thrust sheets. In the Tarnów–Ropczyce zone, the Upper Jurassic carbonates and the Upper Cretaceous sandstones show rather variable porosities. Locally, horizons of 10% to 15% porosity occur that form a good reservoir level for the hydrocarbons expelled from the Lower Palaeozoic source rocks. Migration was associated with the Carpathian overthrusting and a significant fault system served as conduits for hydrocarbons migrating to the Upper Jurassic and Upper Cretaceous reservoirs. Accumulation ranged from 0.05 m^3/m^3 rock along the A and B cross-sections (the Jastrząbka Stara and Brzezówka oil fields, respectively) to 0.14 along the C cross-section (the Góra Ropczycka field). The Middle Devonian–Lower Carboniferous carbonates in the Nosówka zone, where the Mesozoic cover and the Lower Carboniferous clastic strata were eroded, serve as secondary reservoirs. The 2-D modelling revealed that in the Nosówka zone, hydrocarbons generated and expelled from the Ordovician and Silurian source rocks migrated through the faults to the Carboniferous carbonates and the

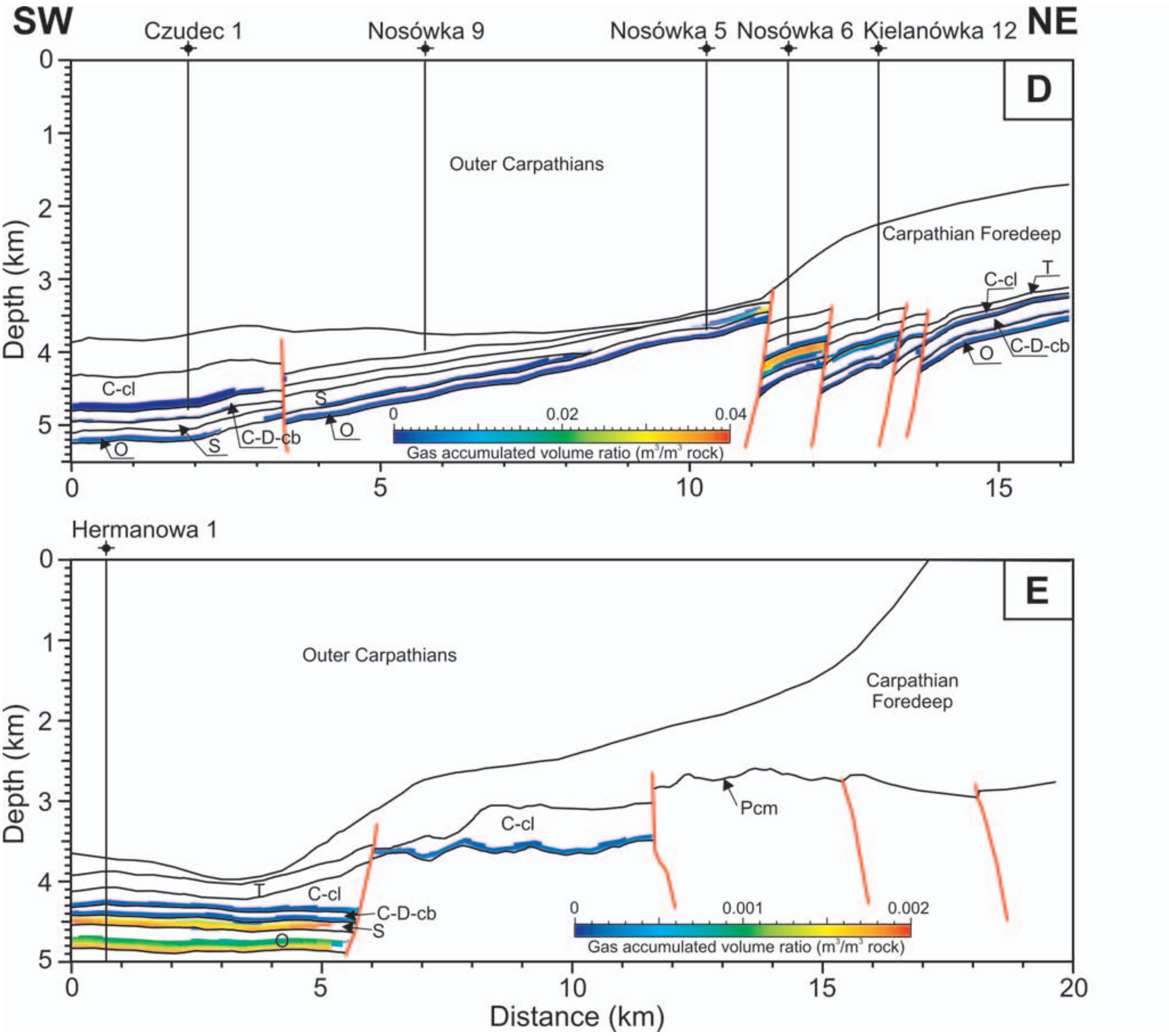

Fig. 10. The volume of the gas accumulation along the **D** and **E** cross-sections. See Fig. 1 for location and Fig. 7 for abbreviations

volume of oil accumulated averaged 0.15 m^3/m^3 rock, while the gas volume did not exceed 0.04 m^3/m^3 rock.

The Middle Devonian–Lower Carboniferous carbonate and the Lower Carboniferous clastic source rocks analysed in the Tarnów–Rzeszów area were not a significant source of hydrocarbons. The amount of oil and gas generated from those horizons did not exceed 130 mg/g TOC. There was hardly any expulsion of hydrocarbons and the volume of mainly gas accumulation was *in situ*, because the hydrocarbons saturation did not exceed the expulsion threshold.

The Middle Jurassic source rocks studied in the Tarnów–Rzeszów area (along the C cross-section) generated only 220 mg/g TOC of hydrocarbons despite a good petroleum potential and maturity in the main and late phases of "oil window". Expulsion was not observed, and most of the generated hydrocarbons stayed *in situ*.

Finally, it should be stressed that one of very important assumptions for the completed 2-D modelling of generation and migration of hydrocarbons was the lack of strike-slip movements and associated lateral displacement of the tectonic blocks. Tectonic wrenching might have significantly modified subsidence pattern and migration paths for oil and gas; a thorough assessment of the role of strike-slip movements would, however, require full 3-D approach.

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