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BURIAL AND THERMAL HISTORY AND HYDROCARBON GENERATION MODELLING OF THE LOWER PALAEOZOIC SOURCE ROCKS IN THE KRAKÓW–RZESZÓW AREA (SE POLAND)

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Abstract: Burial history, thermal maturity and timing of hydrocarbon generation were modelled for the Ordovician and Silurian source rocks in the basement of the Carpathian Foredeep. 1-D modelling was carried out for wells located in the area between Kraków and Rzeszów cities (SE Poland). The following wells were modelled: Będzienica 2, Hermanowa 1, Nawsie 1, Nosówka 2 and 12, Pilzno 40, and Zawada 8K. The Ordovician and Silurian source rocks, containing oil-prone Type-II kerogen, are generally immature showing less than 0.5% reflectance of vitrinite-like macerals (R_o), in most of the Kraków–Rzeszów area and only in the eastern part the organic matter is early mature, reaching 0.7% equivalent R_o. The highest thermal maturity is found in the eastern part of the study area, near Rzeszów city, where the Lower Palaeozoic strata are buried to the greatest depth. Maturity modelling shows that the source rocks reached the initial phase of the “oil window” only in the eastern part of the area, whereas they are immature in the larger, western portion of the area. In addition, modelling indicates that the onset of petroleum generation started in the late Miocene, after the Outer Carpathian overthrust phase. The generation processes in the eastern part of the analysed area reached the main and late generation phase. The generated hydrocarbons were mostly expelled from the source rocks. In the western part of the study area the generation process has not been initialized.

Key words: source rocks, 1-D modelling, generation, expulsion, Lower Palaeozoic, southeastern Poland.

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INTRODUCTION

Hydrocarbon generation and expulsion were studied in the tectonic unit known as the Małopolska Block, constituting the substratum of the Carpathian Foredeep and the Outer Carpathians. The study area extends from the contact zone with the Upper Silesian Block to the west, to the Lower San Horst Structure, a distinct tectonic-morphological structure appearing in the structural picture of the sub-Permian and sub-Tertiary basement to the east (Pożaryski & Tomczyk, 1968). Petroleum generation in the Lower Palaeozoic strata was modelled in seven wells (Fig. 1). The presence of the source rocks was assessed from the results of geochemical analyses of well samples (Więcław *et al.*, 2011), and their total thickness on the basis of interpretation of well logs and lithologic data (Kosakowski *et al.*, in press). Each source rock horizon was assigned an adequate TOC, type of kerogen, maturity and total thickness. Previous studies of petroleum processes in the basement of the Carpathian Foredeep and the Outer Carpathians are restricted to the work of Kotarba *et al.* (2004), which concerns only Carboniferous formations. The lack of interest in the remaining Palaeozoic stratigraphic succession can be explained by the very small number of discoveries of oil and gas accumulations in the area (Karnkowski, P., 1999; Myśliwiec *et al.*, 2006). In the present work, generation and expulsion of hydrocarbons from Lower Palaeozoic source rocks in the area between Kraków and Rzeszów cities were studied.

The modelling includes burial and thermal history reconstructions for the wells, with restoration of the thickness of eroded sediments and heat flow changes over time being of particular importance for the current study. Having burial and thermal history constrained, the basic generation conditions were established for the individual wells by the use of 1-D numerical modelling.

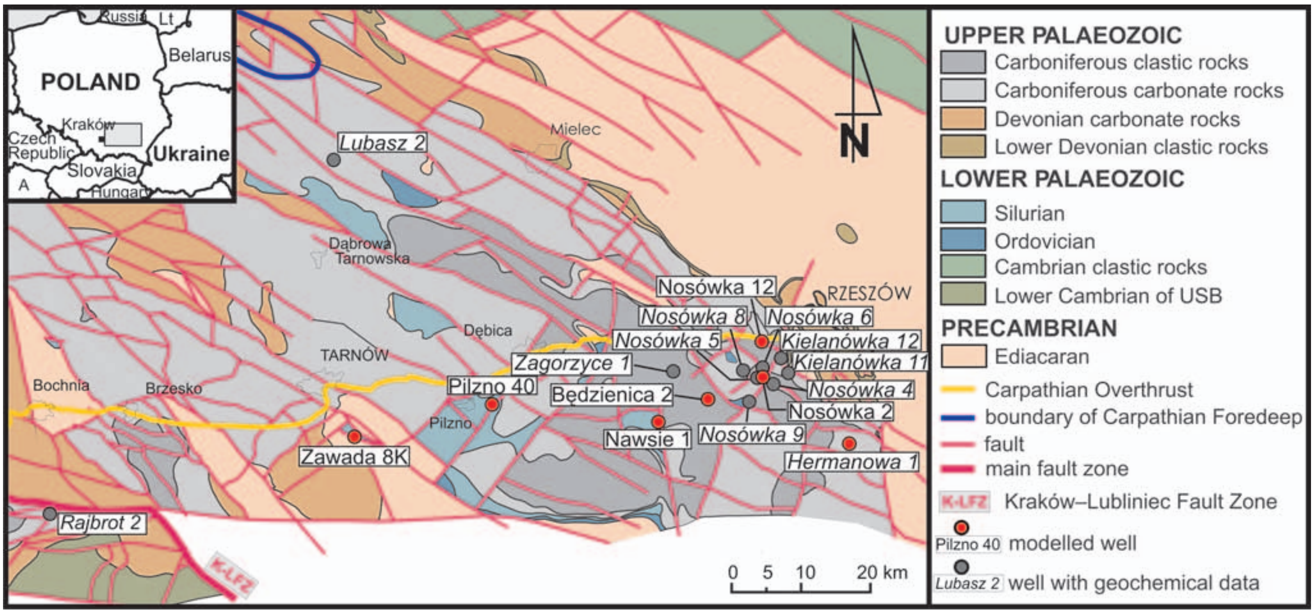

Fig. 1. Tectonic sketch map of the western part of the Polish Carpathian Foredeep (after Buła & Habryn, *eds,* 2008) and location of 1-D modelled wells. USB – Upper Silesian Block, A – Austria, Lt – Lithuania

MODELLING PROCEDURE

The objective of the numerical modelling was to determine the depth and timing of hydrocarbon generation and expulsion for seven wells penetrating the basement of the Carpathian Foredeep and the marginal part of the Outer Carpathians (Fig. 1). Burial history, hydrocarbon generation and expulsion processes were reconstructed using the BasinMod™ 1-D modelling sofware package (BMRM 1-D, 2006). To assess the amount of hydrocarbons generated and expelled from Lower Palaeozoic source rocks, the following data were quantified: definition of events (deposition, erosion, non-deposition), present and original thicknesses, lithology of strata, and present and palaeo-heat flows. Input parameters for the modelling include geochemical data such as the reconstructed TOC and type of kerogen. Maturity was calculated using the EASY% R_o model (Sweeney & Burnham, 1990), whereas for the modelling of hydrocarbon generation and expulsion the LLNL model (BMRM 1-D, 2006) was applied. The maturity modelling was calibrated with Rock-Eval T_{max} temperature and reflectance of vitrinite-like macerals (R_o). The procedure of estimation of the reflectance of vitrinite-like macerals was described in detail by Grotek (2006).

GEOLOGICAL SETTING

The analysed part of the Palaeozoic substratum of the Carpathian Foredeep and the Outer Carpathians, called the Małopolska Block, developed in the foreland of a larger tectonic structure, *i.e*., the East-European Craton. The oldest stages of development of this tectonic unit, which began during Proterozoic to early Cambrian, are unclear or ambiguous (Buła & Habryn, *eds*, 2008; Buła & Habryn, 2011) due to the incompleteness of the Palaeozoic succession or to a simple lack of data. Different views on the basin evolution in this stratigraphic interval were presented by, among others, Nawrocki and Poprawa (2006), Poprawa (2006a, b), Narkiewicz (2007), Nawrocki *et al.* (2007), Buła and Habryn, *eds* (2008), and Żelaźniewicz *et al.* (2009). A description and discussion of those views can be found in Buła and Habryn (2011).

The sedimentary cover of the Małopolska Block comprises three structural stages – the Caledonian, Variscan and Alpine stages (Jawor & Baran, 2004). In the western part, the Caledonian stage affects Ordovician and Silurian formations, whereas Cambrian formations are absent. The Ordovician and Silurian strata rest directly on the anchimetamorphic complex (Buła, 2000; Żelaźniewicz *et al.*, 2004). The absence of Cambrian strata in the western part of the area is probably due to uplift during the Cadomian phase (Buła & Habryn, *eds*, 2008).

The Ordovician formations vary in character from carbonate facies in the western part to graptolitic shale facies in the eastern part. The Silurian strata are more monotonously developed in graptolitic shales facies, although in the southwestern part of the Małopolska Block conglomerates and sandstones occur (Buła & Habryn, *eds*, 2008). Stratal relationships are conformable, and they are perceived as belonging to one single structural complex (Buła & Habyn, 2011). Further to intensive Upper Silurian or Lower Devonian erosion, a hiatus is present in the late Silurian, and deposits of this age are only preserved as thin sheets (Buła & Habryn, *eds*, 2008). Overlying this succession, with a stratigraphic gap in the earliest Lower Devonian, Emsian clastic rocks and/or Middle Devonian–Lower Carboniferous carbonate-clastic successions represent the Variscan structural stage (Jawor & Baran, 2004; Narkiewicz, 2007; Buła & Habryn, *eds*, 2008).

Locally, the Silurian strata are covered by younger strata. The thickness of the Devonian strata is very variable, from tens to more than 1,000 m (Buła & Habryn, *eds*, 2008). Silurian deposits are absent in the Dębica area as well as in the Dąbrowa Tarnowska area. The significant variation in thickness of the Devonian strata is a result of vertical tectonic movements. The late Tournaisian–early Namurian formations occur only in the western part of the Małopolska Block between Kraków and Rzeszów cities, and are represented by three lithological complexes: carbonate-clastic complex A, carbonate complex B, and clastic complex C. The maximum present-day thickness of the Carboniferous formations in the analysed part of the Małopolska Block reaches 1,500 m (Jawor & Baran, 2004; Buła & Habryn, *eds*, 2008).

Permian–Mesozoic strata representing the Alpine structural stage overlie the Devonian–Carboniferous succession. The Permian strata are mainly conglomerates and sandstones with claystones and mudstones in the uppermost part of the interval deposited in depressions, and with thicknesses rarely exceeding a few tens of metres (Jawor & Baran, 2004). The Permian succession is overlain by Lower Triassic formations, represented by the clastics with carbonates in the upper part of the succession (Moryc, 1971). The Middle Triassic consists predominantly of carbonate rocks, whereas the uppermost Triassic consists of claystones and mudstones with sandstones (Maksym *et al.*, 2003; Jawor & Baran, 2004). Following tectonic movements during the Kimmerian orogeny, the Triassic strata were folded, faulted, uplifted and partially eroded, so that presently Triassic formations only occur in the eastern part of the analysed area, to the south of the line Pilzno–Dębica and to the north of the line Dąbrowa Tarnowska–Mielec (Fig. 1) (Buła & Habryn, *ed*s, 2008).

Jurassic formations cover almost the entire western part of the Małopolska Block (Buła & Habryn, *ed*s, 2008). The Middle Jurassic succession consists of clastic rocks with coal (Baran *et al.*, 1997; Dayczak-Calikowska & Moryc, 1988), whereas the Upper Jurassic (Oxfordian and Kimmeridgian) succession consists of carbonates. Locally, in the Dębica region, isolated occurrences of Lower Cretaceous strata are found (Kijakowa & Moryc, 1991; Moryc, 1997). Towards the end of the Lower Cretaceous period, shallowing of the basin and uplifting was accompanied by erosion. Therefore, the Cretaceous succession starts with deposition of Cenomanian-age glauconitic sandstones, however, they occur only in the narrow area between Kazimierza Wielka and Brzesko, delimited by a N–S trending fault zone (Jawor & Jawor, 1989; Jawor & Baran, 2001; Moryc, 2006). The remaining part of the Cretaceous succession consists of carbonates and marls (Jawor & Baran, 2004; Moryc, 2006). The total thickness of the Cretaceous strata does not exceed 800 m (Jawor & Baran, 2004).

Cretaceous sedimentation was interrupted by the Cretaceous/Palaeogene orogeny that caused uplift and deep erosion, in some areas even affecting the Palaeozoic substratum. Erosion prevailed throughout the entire Palaeogene, and only in the Miocene did a marine transgression took place, leading to deposition of thick molasse formations, onto which the Outer Carpathians orogen was overthrust. The thickness of the Miocene cover in the analysed area ranges from tens of metres in the eastern part to 2,500 m in the Rzeszów area (Jawor & Baran, 2004). The thickness of the flysch cover forming the Outer Carpathians grows towards the south and is penetrated to a depth of 7,541 m in the Kuźmina 1 well.

MODELLING OF THE THERMAL AND BURIAL HISTORY

1-D maturity modelling of the thermal and burial history was conducted for seven wells: Będzienica 2, Hermanowa 1, Nawsie 1, Nosówka 2 and 12, Pilzno 40, and Zawada 8K (Fig. 1). The thermal regime was calibrated with either well temperature logs or/and indirectly with data obtained from maps of temperatures at the given depth horizons from the investigated or adjacent area (Jurkiewicz & Szczerba, 1976; Majorowicz & Plewa, 1979; Majorowicz, 1984; Plewa, 1994; Karwasiecka & Bruszewska, 1997). Heat flow values and temperatures differ in the works mentioned above, so average values were used for creating an hydrocarbon generation and expulsion model. Present-day heat flow shows a strict relationship with the extent of the major tectonic structures of the Upper Silesian and Małopolska blocks. A gradual decrease in the value of heat flow can be observed from an average of 70 mW/m^2 in the Silesian Block to *ca*. 50 mW/m^2 in the contact zone of the Upper Silesian and Małopolska blocks, and 30–40 mW/m^2 in the eastern part of the Małopolska Block (Majorowicz & Plewa, 1979; Belka, 1993a,b; Karwasiecka, 2001; Kotarba *et al.*, 2004). That relationship also has impact on the value of the palaeo-heatflow in the Palaeozoic structural stages and in overlying stages.

Geological models by Narkiewicz (2002, 2007), Poprawa *et al.* (1997) and Poprawa (2006a, b) were applied for thermal reconstruction of the area at the Caledonian and Pre-Caledonian stages of development. These models do not include significant thermal events during Cambrian – Lower Devonian time. At the Variscan stage, orogen overheating and later cooling during Permian, Mesozoic and Cenozoic times is generally assumed, in keeping with the work of Majorowicz (1984). In most cases, scarcity of thermal maturity measurements, and particularly their distribution across the section do not allow reliable input data for the modelling to be obtained. Therefore, for some models with weaker geochemical and geological information, a different approach was used, assuming constant heat flow during the Permian, Mesozoic and Cenozoic times (Karnkowski, P. H., 1999; Narkiewicz *et al.,* 2010).

With the above-mentioned limitations of the maturity modelling, several thermal and burial scenarios were analysed. In case of major hiatuses in the sedimentary column and discontinuous maturity profiles, the scenario of constant heat flow through time was applied. The model of constant heat flow, equal to that prevailing today, through time is sufficient to explain the available thermal maturity measurements in most of the analysed wells (Table 1). The reflectance of the vitrinite-like macerals in the Lower Palaeozoic (Ordovician and Silurian) strata ranges from about 0.56% in the Zawada 8K well to 0.80% in the Hermanowa 1 well (Table 1). The vitrinite reflectance values measured in

Table 1

Vitrinite reflectance and reflectance of vitrinite like macerals of the Palaeozoic organic matter

Well	Depth (m)	Stratigraphy	Vitrinite reflectance		
			R_o (%)	Range	Meas.
Będzienica 2	4,364.5	Carboniferous	**0.66**	0.55-0.77	125
	4,367.0		**0.64**	n.m.	3
	4,521.0		**0.77**	n.m.	50
	4,592.5	Silurian	**0.66**	0.48-0.84	61
	4,594.5		**0.64**	0.49-0.73	60
Hermanowa 1	4,581.5	Devonian	**0.63**	0.50-0.70	72
	4,659.5	Silurian	**0.72**	0.57-0.85	103
	4,676.5		**0.65**	0.60-0.78	98
	4,705.5		**0.68**	0.58-0.85	113
	4,798.2	Ordovician	**0.69**	0.58-0.83	42
	4,912.5		**0.80**	0.58-0.95	134
Nawsie 1	3,807.5	Jurassic	**0.60**	0.46-0.67	15
	4,008.5		**0.69**	0.63-0.79	12
	4,818.5	Silurian	**0.67**	0.55-0.88	105
	4,851.5		**0.75**	0.62-0.91	97
	4,857.5		**0.75**	0.62-0.91	97
Nosówka 6	3,698.2	Carboniferous	**0.84**	n.m.	50
	3,699.5		**0.64**	0.51-0.77	91
	3,702.5		**0.65**	0.58-0.73	90
	3,737.5		**0.65**	0.56-0.72	78
	3,762.4		**0.96**	n.m.	50
	3,767.6		**0.66**	0.62-0.76	36
	3,790.5		**0.66**	0.57-0.78	33
	3,831.0		**0.68**	0.58-0.78	89
	3,869.5		**0.71**	0.63-0.77	11
	4,019.6	Ordovician	**0.71**	0.62-0.75	18
Pilzno 40	2,963.5	Jurassic	**0.64**	0.49-0.79	12
	3,149.5		**0.67**	0.58-0.80	13
	3,236.6		**0.67**	0.63-0.79	10
	3,551.0	Silurian	**0.69**	0.57-0.77	63
Zawada 8k	3,327.0	Silurian	**0.56**	0.40-0.71	111
	3,333.5		**0.60**	0.40-0.78	75
	3,335.0		**0.57**	0.36-0.67	67

R_o – vitrinite reflectance; R_{oredep} – redeposited organic matter; Meas. – number of measurements; n.m. – not measured

younger (Devonian, Carboniferous and Jurassic) strata in the analysed well profiles vary in the same range (0.63 to 0.77%) (Table 1). In these models, no significant impact of the Variscan overheating on the maturity of organic matter has been observed (Figs 2B, 3). In all model runs the Outer Carpathian overthrusting played a predominant role in thermal maturation.

The lack of a significant Variscan thermal impact during the Carboniferous can be observed also in other models. Moreover, since the heat flow value used for the Palaeozoic is lower than in the Mesozoic and in the present, the organic matter reaches higher levels of thermal maturity when modelled using a constant heat flow, *e.g*. in the Zawada 8K well (Figs 2B, 3A). The lack of a significant impact of the Variscan overheating on thermal maturity of the organic matter of the Lower Palaeozoic is caused by a fast post-Carboniferous inversion, accompanied by erosion, reaching at times the Lower Palaeozoic substratum.

The deposition of the Mesozoic strata was also interrupted by periods of uplift and erosion. These periods are clearly present, especially in the early Jurassic and in the early Cretaceous and at the turn of the Cretaceous and the Palaeogene (Figs 3–5). Periods of erosion were to some extent quantitatively compensated for by periods of deposition, with the exception of the Upper Jurassic deposition. Therefore, we observe only small changes in the maturity of the organic matter of the Lower Palaeozoic in that stratigraphic range (Fig. 2). The last and the most important thermal – burial event was the Outer Carpathian overthrust on the foreland. It resulted both in an increase in the depth of burial and in temperature and, consequently, towards the end of the stage of the Carpathian thrust belt, also in an increase in organic matter maturity (Fig. 2).

MODELLING OF MATURATION HISTORY OF THE LOWER PALAEOZOIC ORGANIC MATTER

The evolution of the thermal maturity of organic matter was determined for the Ordovician and Silurian complex, because the Cambrian formations are not found in the Kraków–Rzeszów area (Buła & Habryn, *ed*s, 2008). The Lower Palaeozoic formations occur in two separated sheets: south of Tarnów and between Pilzno and Rzeszów towns (Buła & Habryn, 2011); the thermal modelling was carried out in both areas (Figs 1, 6, 7). The geochemical characteristics of the Ordovician and Silurian complexes in the study areas were presented by Więcław *et al.* (2011).

In the area to the south of Tarnów, only a thin sheet of the Silurian formations is present, whereas the Ordovician is absent (Buła & Habryn, *eds.*, 2008). The thermal modelling carried out in the Zawada 8K well, assuming presence of Variscan overheating and with assumed values of erosion, showed that the Silurian source rocks reached the early stage of thermal maturity (0.5–0.7% equivalent R_o) as late as the early Neogene (Figs 2B, 3A). The deposition of the Upper Cretaceous strata caused only an insignificant increase in maturity of the organic matter, but the inversion of the analysed area at the turn of the Cretaceous and the Palaeogene interrupted the process of burial and the increase in temperature and, consequently, the increase in organic matter maturity (Fig. 2B). Another event, which resumed the process of burial of the source rock horizons was the deposition of the Miocene and the process of the Carpathian overthrust. Particularly the latter event caused a significant increase in burial of the Silurian strata from *ca*. 1,800 m at the beginning of the Miocene deposition to over 4,000 m at the end of the episode of Carpathian overthrusting (Fig. 3A). This resulted in an increase in source rock maturity to *ca*. 0.65% equivalent R_o and brought the succession into the main phase of the “oil window” (Fig. 2B).

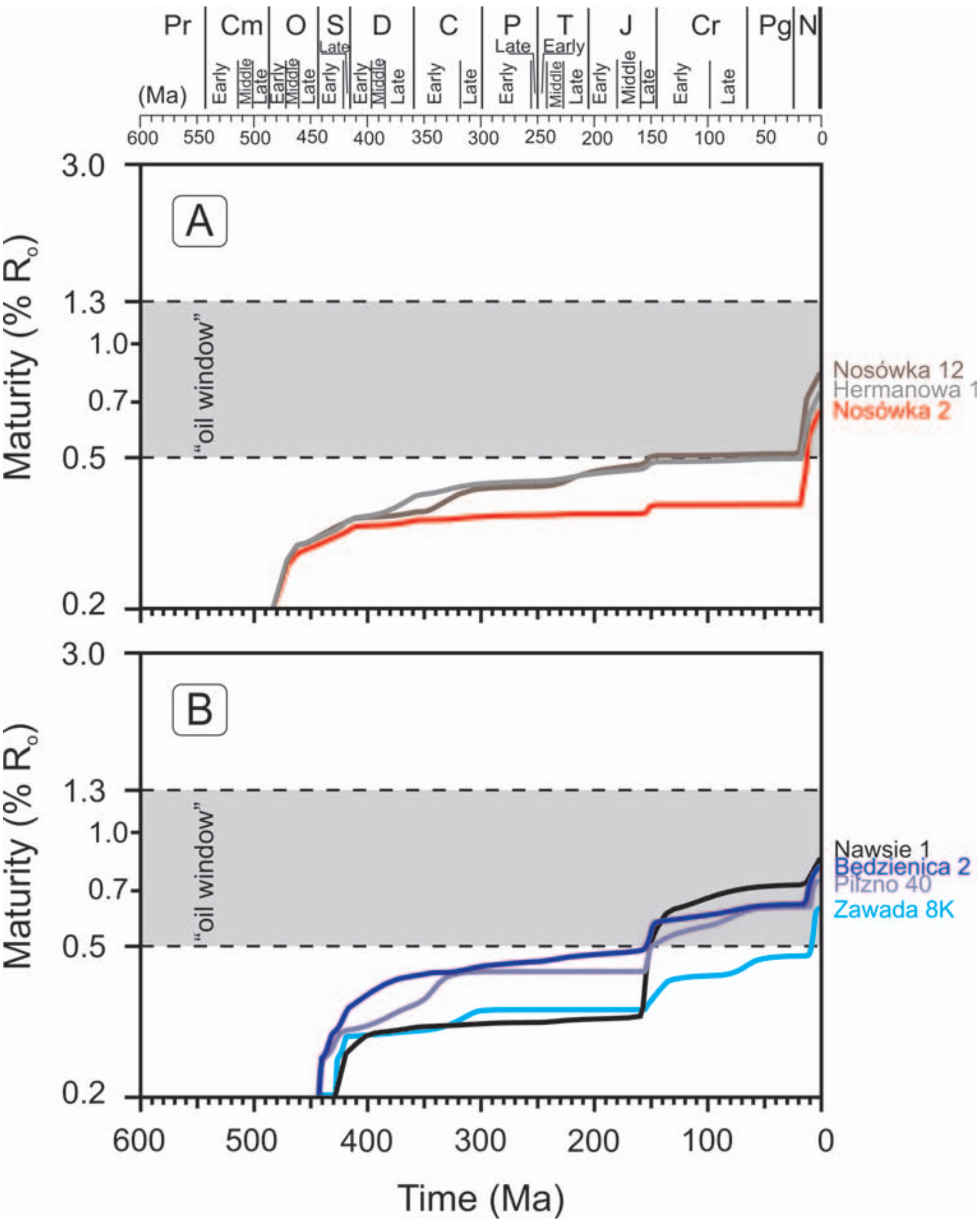

Fig. 2. Maturity evolution curves for the **(A)** Ordovician and **(B)** Silurian source rocks in profiles of analysed wells. Pr – Precambrian, Cm – Cambrian, O – Ordovician, S – Silurian, D – Devonian, C – Carboniferous, P – Permian, T – Triassic, J – Jurassic, Cr – Cretaceous, Pg – Palaeogene, N – Neogene

A thick cover of Ordovician and Silurian formations is present between Pilzno and Rzeszów (Buła & Habryn, *ed*s, 2008; Buła & Habryn, 2011). Here, thermal modelling was carried out in the Pilzno 40 well, representing the eastern portion of the area, and the Będzienica 2, Hermanowa 1, Nawsie 1, Nosówka 2 and 12 wells representing the western part (Fig. 1).

Modelling of the Pilzno 40 well, using similar input parameters as in the Zawada 8K well, shows that the Ordovician and Silurian source rocks reached the initial phase of the "oil window" at the turn of the Jurassic and the Cretaceous, with a burial depth of about 1,800 m and a temperature above 80^{o}C (Figs 2B, 3B). The deposition of the Cretaceous strata caused an increase in organic matter maturity to about 0.65% R_O. The Outer Carpathian overthrusting resulted in a significant increase in burial of the source rock layer to a depth of about 3,900 m, but the increase in thermal maturity was insignificant (Fig. 3B). The resulting level of maturity of 0.75% R_O is higher than that obtained in the Zawada 8K well (Fig. 2B).

Modelling of other wells in the area yield similar results. Just as in the case of the Pilzno 40 well, the initial phase of the "oil window" was reached at the turn of the Jurassic and the Cretaceous (Figs 2, 4, 5). The deposition of Cretaceous formations and, particularly, the Outer Carpathian overthrust, decisively influenced the final organic matter maturity, which, in particular wells, was equal to: Nawsie 1 – 0.85%, Będzienica 2 – 0.80%, Hermanowa 1 –

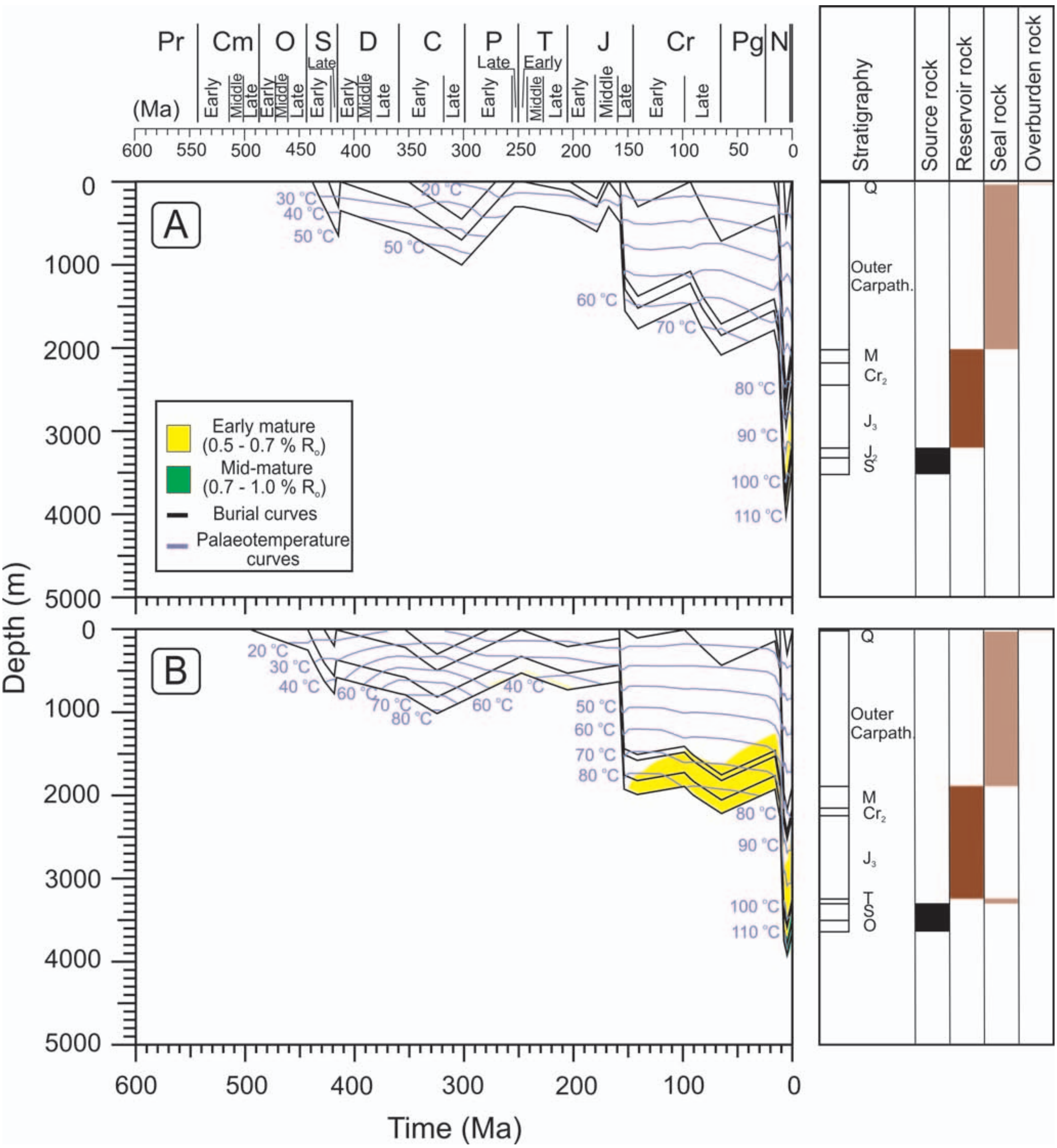

Fig. 3. Burial history curves of **(A)** Zawada 8K and **(B)** Pilzno 40 wells. J_2 – Middle Jurassic, J_3 – Late Jurassic, Cr_2 – Late Cretaceous, M – Miocene, Q – Quaternary, Carpath. – Carpathians. For the remaining abbreviations see Fig. 2

0.78%, Nosówka 2 – 0.65%, and Nosówka 12 – 0.80% R_o (Fig. 2). The maturity values obtained during the thermal modelling are generally compatible with the measured values (Table 1, Fig. 2).

The level of thermal maturity of the Lower Palaeozoic source rocks in all modelled wells is generally sufficient for initiation of petroleum generation. This is encouraging for exploration in areas located to the south of the analysed wells, where the Lower Palaeozoic formations are found at much greater depths (Figs 6, 7).

MODELLING OF HYDROCARBON GENERATION AND EXPULSION

Modelling of hydrocarbon generation and expulsion from the Ordovician and Silurian source rocks reveals that they occur in all stages of thermal maturity, from early to the late mature with respect to petroleum generation. Only in the western part of the study area, in the Zawada 8K well, the source rocks do not reach the early phase of generation (10–25% of generation potential). The maximum degree of

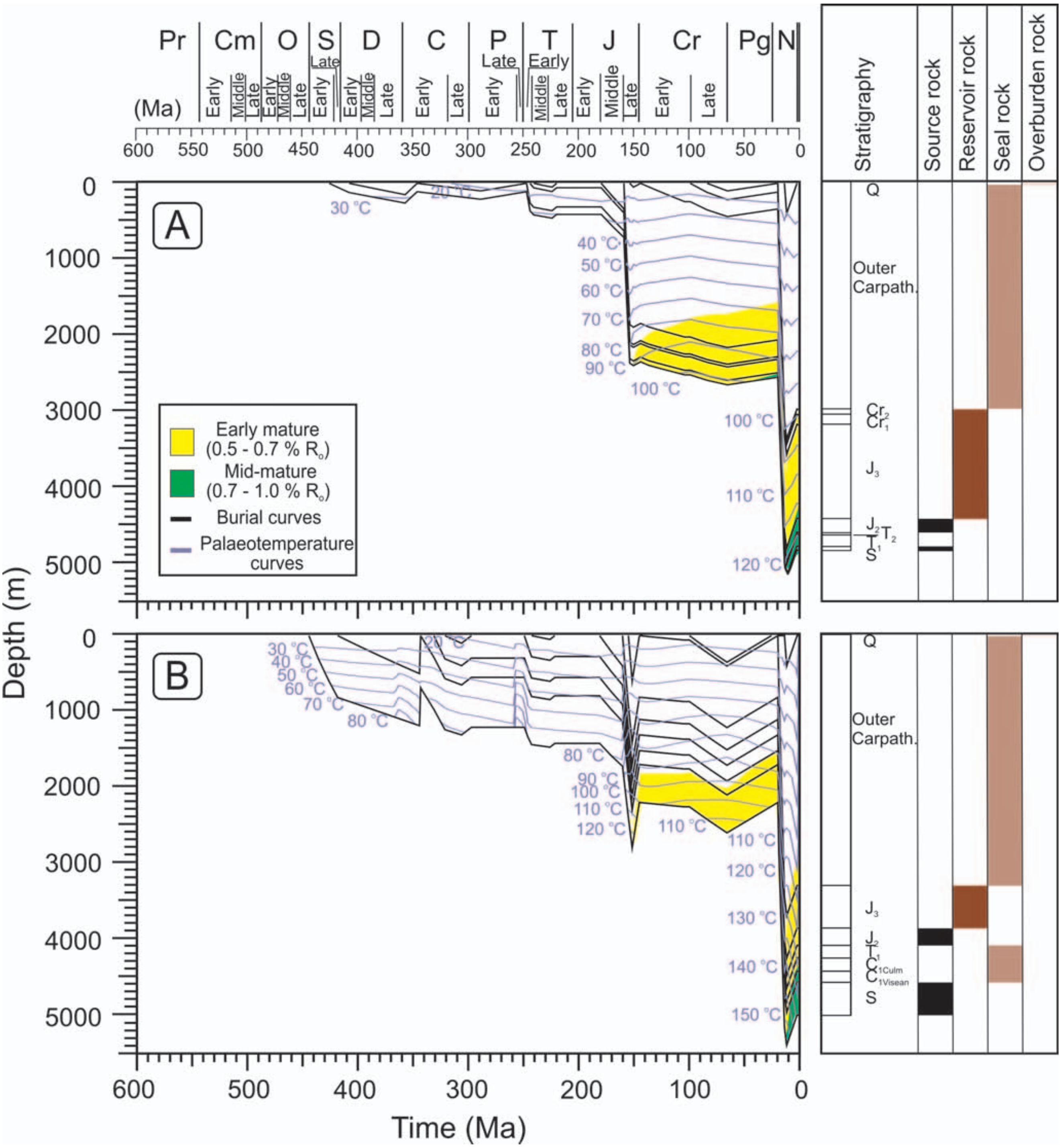

Fig. 4. Burial history curves of **(A)** Nawsie 1 and **(B)** Będzienica 2 wells. $C_{1Visean}$ – Early Carboniferous (Visean), C_{1Culm} – Early Carboniferous (Culm), T_1 – Early Triassic, T_2 – Middle Triassic, Cr_1 – Early Cretaceous. For the remaining abbreviations see Figs 2 and 3

transformation was reached at the stage of the Carpathian overthrust and does not exceed 10% (Fig. 8B). The degree of transformation in the Pilzno 40 well is 35%, suggesting the early phase of generation (Fig. 8B).

Higher thermal maturity and thus degree of transformation is observed in wells located between Pilzno and Rzeszów. In the Nosówka 12 well, the degree of transformation is 60% and was reached, similarly to the Zawada 8K well, at the stage of the Outer Carpathian overthrusting (Fig. 8A). Other wells in the area yield similar results. The highest degree of transformation, 85%, is observed in the Nawsie 1 well, suggesting that the source rocks in this well have passed through the main phase of petroleum generation (25–65% of generation potential) and entered the final phase (65–90% of generation potential) during the short interval of the Outer Carpathian overthrusting (Figs 8A, 9A).

The modelling data indicate that the Ordovician and Silurian strata are effective source rocks, and hydrocarbon generation mainly took place over a brief interval related to the Outer Carpathian overthrusting.

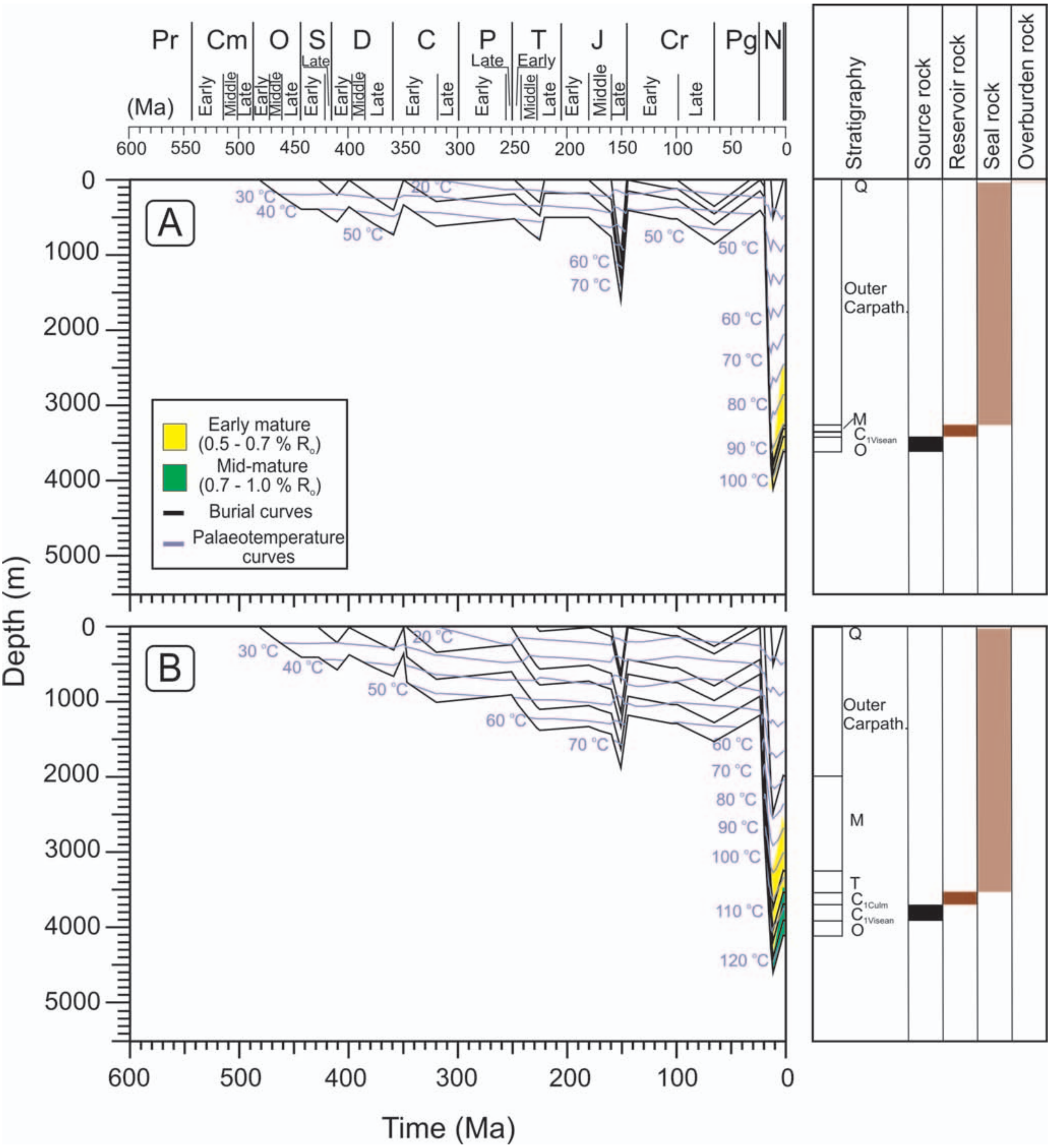

Fig. 5. Burial history curves of **(A)** Nosówka 2 and **(B)** Nosówka 12 wells. For the abbreviations see Figs 2, 3 and 4

AMOUNT OF GENERATED AND EXPELLED HYDROCARBONS

1-D modelling made it possible to calculate the amount of hydrocarbon generation and expulsion potential from the Lower Palaeozoic source rocks. The differences in the degree of transformation of kerogen observed between the modelled wells carry information on the generated masses of hydrocarbons. The resulting hydrocarbon mass varies significantly and depends also on the original content of organic carbon, hydrocarbon potential and the thickness of source rocks, data on which were obtained from geochemical investigations (Więcław *et al.*, 2011) and well logging (Kosakowski *et al.*, in press).

In the Zawada 8K well, which shows the lowest degree of transformation, the amount of hydrocarbons generated per unit of organic carbon mass is the lowest, corresponding to 25 mg HC/g TOC (Fig. 10A). The hydrocarbons were

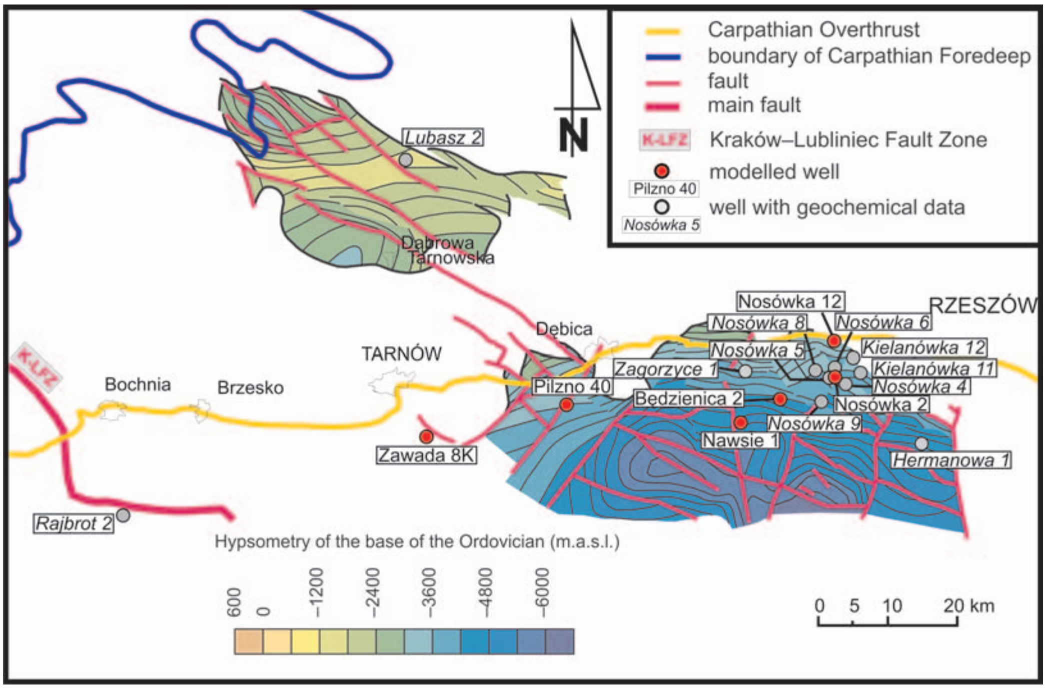

Fig. 6. Map of extent of the Ordovician strata in the Małopolska Block (after Buła & Habryn, *eds*, 2008) and location of 1-D modelled wells

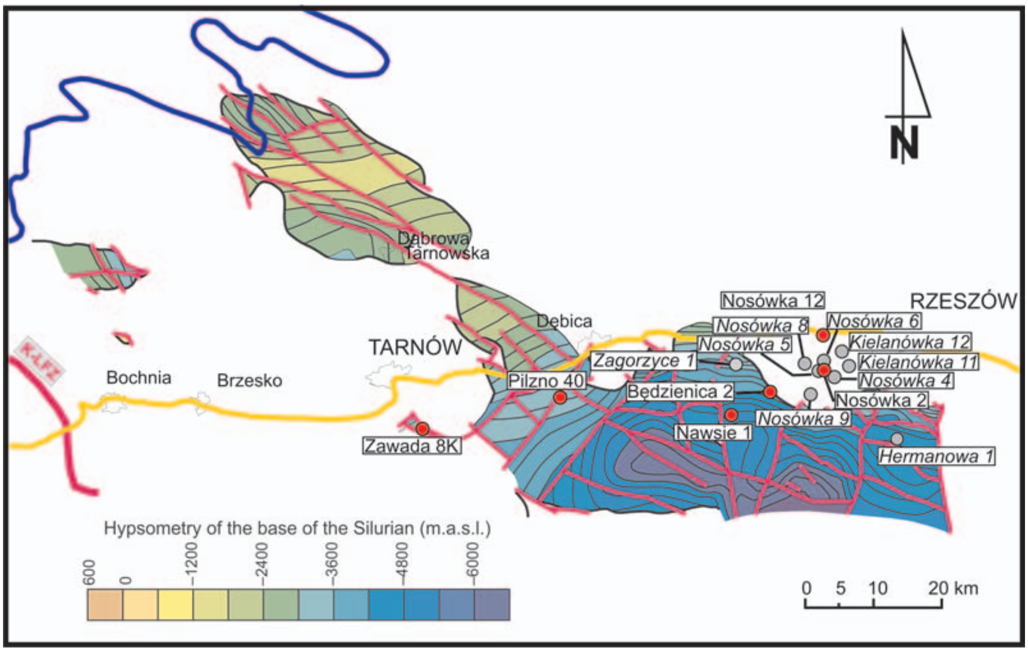

Fig. 7. Map of the extent of Silurian strata in the Małopolska Block (after Buła & Habryn, *eds*, 2008) and location of 1-D modelled wells. Abbreviations – see Fig. 6

generated mainly in the liquid phase. The major part of the hydrocarbon mass was generated at the stage of the Outer Carpathian overthrusting, but expulsion of hydrocarbons was not achieved.

In the Pilzno 40 well, the Silurian source rocks generated 150 mg HC/g TOC (Fig. 10B), and higher amounts were generated in the Będzienica 2 and Nawsie 1 wells (Fig. 10C). In the Hermanowa 1 well, the amount of hydrocarbons generated from the Ordovician source rocks exceeds 280 mg HC/g TOC (Fig. 10D), reaching 380 mg HC/g TOC in the Nosówka 12 well (Fig. 10D). However, the Nosówka 2 well only yielded about 20 mg HC/g TOC because of low organic carbon contents.

A significant portion of the hydrocarbons were expelled. In the Nawsie 1 well approximately 90% of the hydrocarbons were expelled (Fig. 10C). Only in the Zawada 8K and Nosówka 2 wells, expulsion did not take place (Fig. 10A).

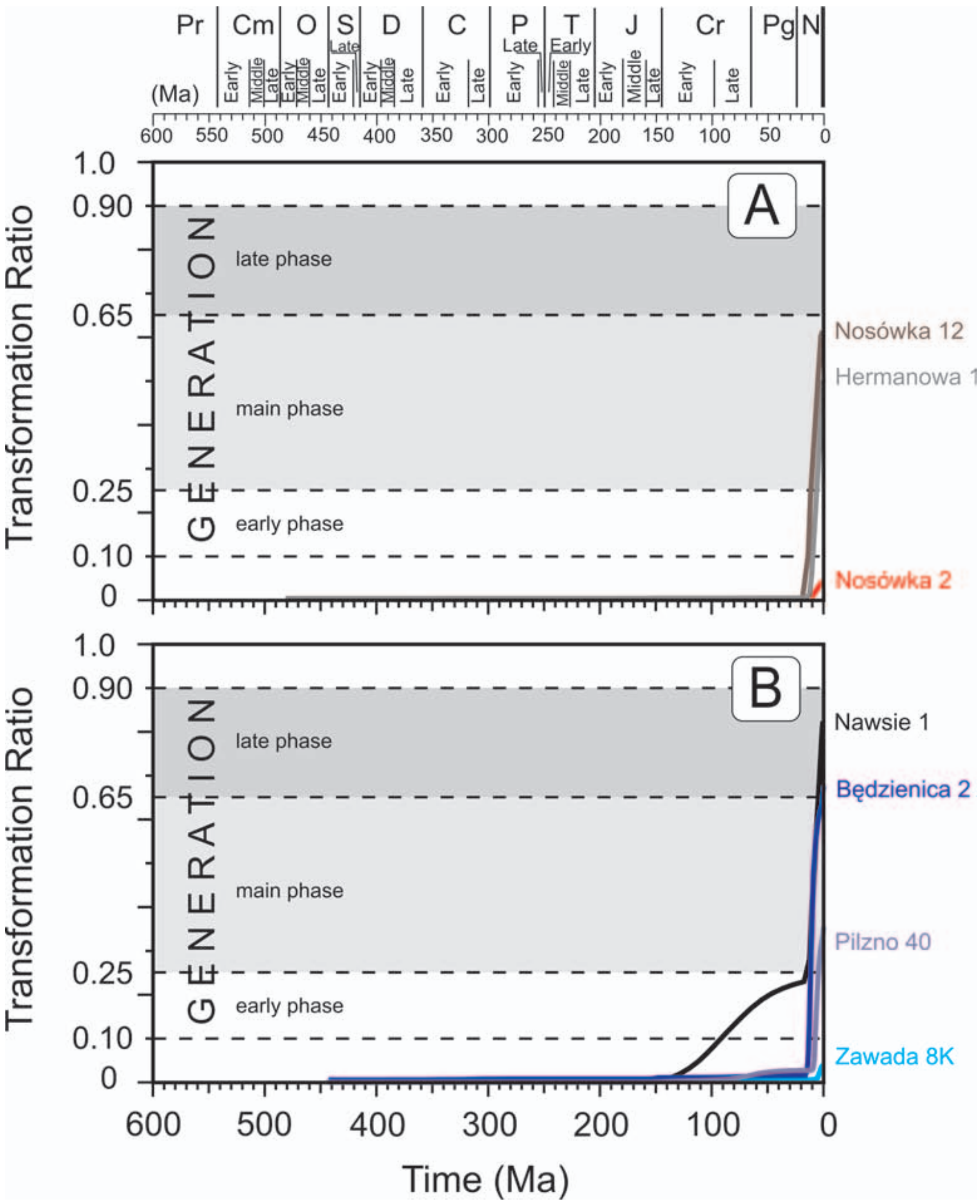

Fig. 8. Transformation ratio of kerogen in the **(A)** Ordovician and **(B)** Silurian source rocks in profiles of analysed wells**.** For abbreviations see Fig. 2

CONCLUSIONS

Modelling of hydrocarbon generation and expulsion from the Lower Palaeozoic complex in the substratum of the Carpathian Foredeep and the Outer Carpathians, in the area between Kraków and Rzeszów cities, revealed that:

(i) Ordovician and Silurian source rocks reached thermal maturity in the initial and main phases of the "oil window". These phases were obtained successively from the turn of the Jurassic and Cretaceous to the Miocene time. The main phase of maturity was connected with overthrusting of the Outer Carpathians;

(ii) over the entire area where the Ordovician and Silurian formations occur, effective source rocks exist. The processes of hydrocarbon generation and expulsion developed, similarly to increasing thermal maturity, mainly at the stage of the overthrusting of the Outer Carpathians. The least transformed source rocks are found in the western part of the study area. The transformation degree grows successively eastwards, where the Lower Palaeozoic formations occur at the greatest depth. The generation processes in that part of the analysed area reached the main and final generation stages, with expulsion of up to 90% of the generated hydrocarbons. The amount of hydrocarbons generated varies significantly, from appr. 20 to appr. 380 mg HC/g TOC.

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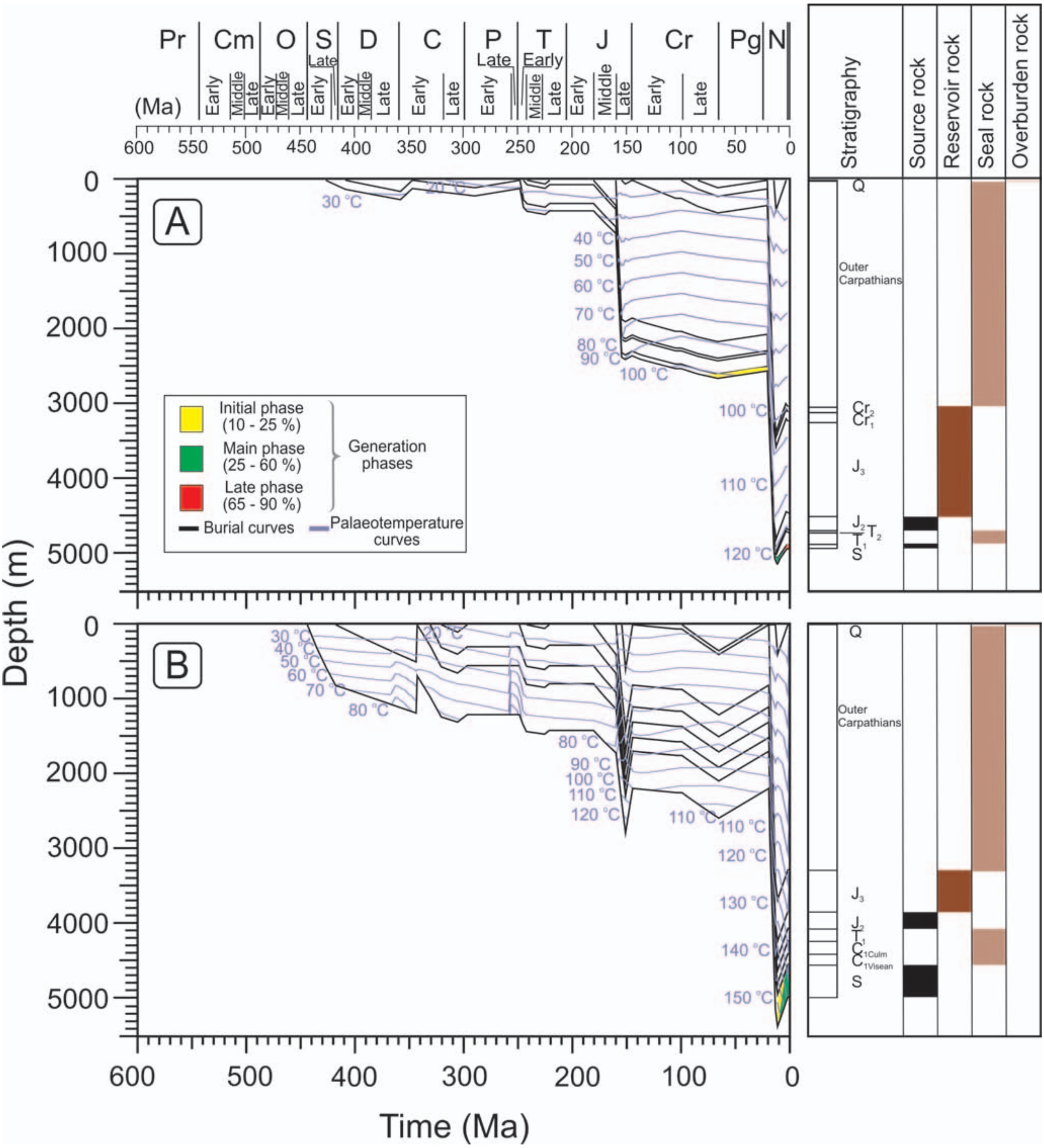

Fig. 9. Burial history curves for the Lower Palaeozoic source rocks with generation stages in the **(A)** Nawsie 1 and **(B)** Będzienica 2 wells. For abbreviations see Figs 2, 3 and 4

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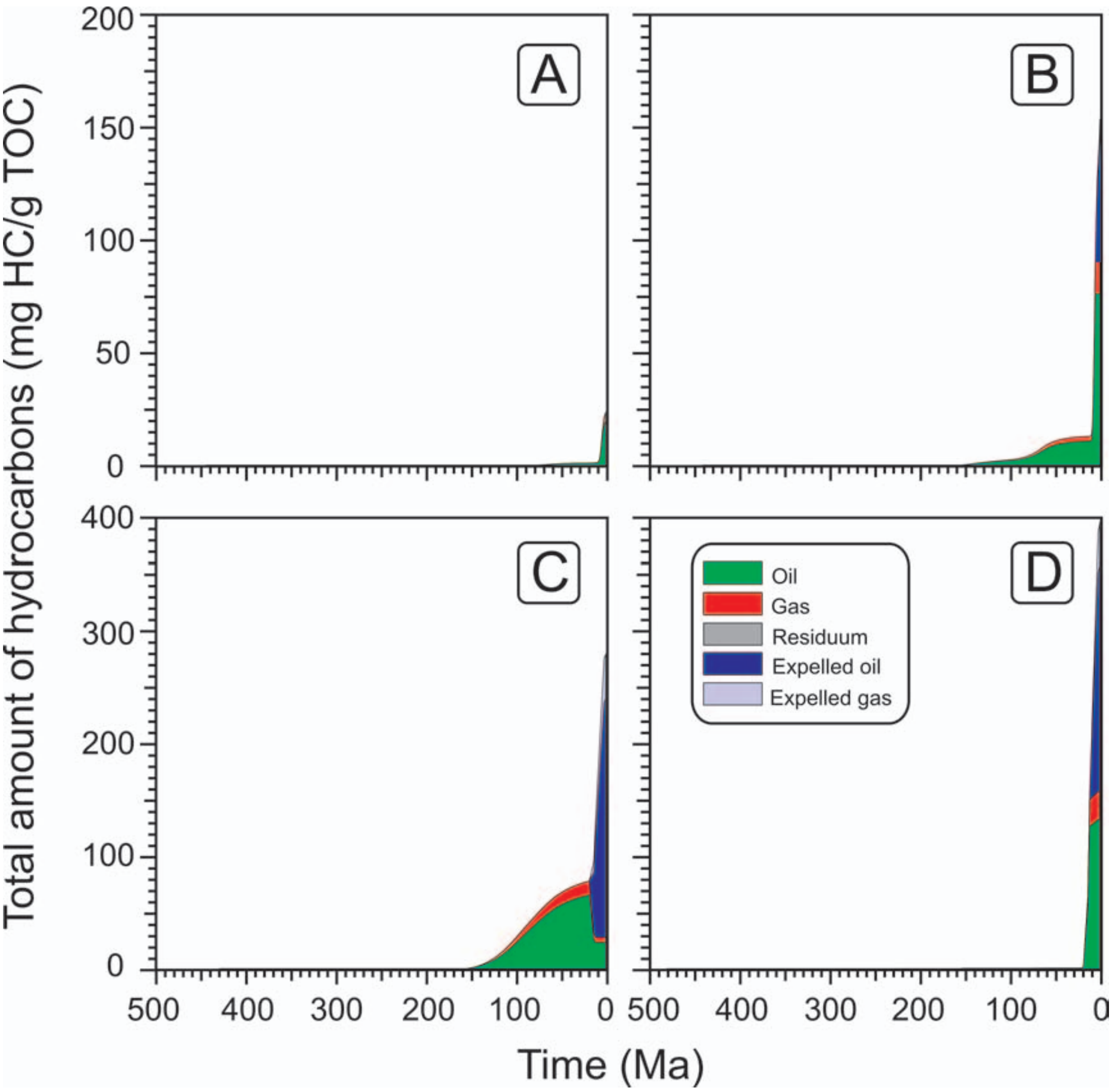

Fig. 10. Total amount of hydrocarbons generated from the Silurian source rocks in the **(A)** Zawada 8K, **(B)** Pilzno 40 and **(C)** Nawsie 1 wells, and the Ordovician source rocks in the **(D)** Nosówka 12 well

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