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1-D MODELLING OF THE HYDROCARBON GENERATION HISTORY OF THE JURASSIC SOURCE ROCKS IN THE TARNOGRÓD–STRYI AREA (SE POLAND – WESTERN UKRAINE)

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Abstract: Reconstruction of burial and thermal history was modelled for the Mesozoic strata in the basement of the Polish and Ukrainian parts of the Carpathian Foredeep and in the marginal part of the Outer Carpathians. The 1-D modelling was carried out in profiles of the wells located in the area between Tarnogród and Stryi towns. In the Polish part, the modelling were performed in the profiles of the Księżpol 15, Lubliniec 9, Markowice 2 and Opaka 1 wells, and in the Ukrainian part in the profiles of the Chornokuntsi 1, Korolyn 6, Mosty 2, Podiltsi 1 and Voloshcha 1 wells. The geochemical characteristics of the Mesozoic stratigraphical horizons revealed that the best features of source rocks were present in the Middle Jurassic strata in the Polish part of the study area and in the Middle and Upper Jurassic strata in the Ukrainian part. Within these strata, the horizons of source rocks were distinguished and their quantitative evaluations were characterized. For these horizons, reconstruction of processes for hydrocarbon generation and expulsion were performed. The source rocks in the Polish part reached maturity only in the initial phase of "oil window". However, the maturity achieved towards the end of the Upper Jurassic was insufficient to exceed the 10% threshold of the transformation degree for hydrocarbon generation. Therefore, the amount of generated hydrocarbons was minimal. Slightly higher maturity of organic matter in the Ukrainian part resulted in exceeding the thresholds of kerogen transformation and the initiation of hydrocarbon generation and expulsion processes. The process began after the deposition of thicker Miocene formations and developed even up to the main phase of the "oil window". The amount of the generated hydrocarbons reached *ca.* 150 mg/g TOC with an insignificant volume of expulsion.

Key words: source rocks, 1-D modelling, hydrocarbon generation, hydrocarbon expulsion, Jurassic, SW Poland, western Ukraine.

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INTRODUCTION

The processes of hydrocarbon generation were characterized in the area between Tarnogód and Stryi towns. The Polish part of this area is located in the eastern part of the Małopolska Block, constituting the basement of the Carpathian Foredeep and the Outer Carpathians, east of the Lower San Horst Structure. The Małopolska Block continues in the Ukrainian part, where it is termed the Kokhanivka Zone. Numerical modelling was also performed in the marginal, western part of the Łysogóry–Radom Block. Petroleum processes in the Jurassic strata were modelled in nine wells (Fig. 1). For 1-D modelling stratigraphic and lithologic data from the wells were used, together with interpreted geophysical data (Kosakowski *et al.*, in press, a). The presence of the source rocks in the analysed stratigraphic profiles of wells was assessed on the basis of the results of geochemical studies (Kosakowski *et al.*, in press, b; Kotarba *et al.*, 2011). The results of these studies confirmed the regional source maturity of the Jurassic strata (Golonka *et al.*, 2009). The modelling incorporated results of burial and thermal history reconstructions for the wells, with restoration of initial thickness of sediments and heat flow changes through time (*e.g.*, Narkiewicz *et al.*, 2010). Having burial and thermal histories constrained, the basic generation conditions were established for the individual wells by the use of 1-D numerical modelling.

Fig. 1. Sketch map of the occurrence of rocks at the bottom of Cenozoic strata in the study area with location of 1-D modelled wells, modified after Buła and Habryn, *eds* (2008). Lt. – Lithuania

MODELLING PROCEDURE

1-D modelling of selected wells was performed using BasinMod™ software (BMRM 1-D, 2006). The modelling approach adopted in the software required input data, which described the present-day geological situation as a result of past events. Rock properties – density, porosity, permeability and thermal conductivity were modelled along with the thermal history. BasinMod software provided an extended database of various lithological types defined by physical properties mentioned above (BMRM 1-D, 2006). The details on the principles of the modelling technique are given in Welte *et al.* (1997). Thermal evolution was simulated on the basis of boundary assignments applied to certain time steps. The assigned parameters were heat flow densities in mW/m^2 and surface temperatures in °C. Heat flow and surface temperatures assignment for the past stages of basin history could be only estimated based on the general tectonic setting and evolution of the investigated region (Besse & Courtillot, 1991; Van der Voo, 1993; Yalcin *et al.*, 1997; Allen & Allen, 2005). To determine the magnitude of burial and erosion, Rock-Eval T_{max} temperature (Kosakowski *et al.*, in press, b) and vitrinite reflectance (R_o) (Table 1) data were used. Estimation of eroded thicknesses had to be ac-

Table 1

Vitrinite reflectance of the Mesozoic organic matter

Well	Depth (m)	Stratigraphy	Vitrinite reflectance		
			R_o (%)	Range	Meas.
Polish part					
Lubieniec 4	730.4	Middle Jurassic	0.54	0.46-0.76	97
	796.5		0.57	0.51-0.78	97
	837.5		0.65	0.52-0.90	115
Lubliniec 9	858.6		0.4	0.34-0.45	75
	930.1		0.42	0.31-0.52	117
Markowice 2	753.0		0.51	0.43-0.65	102
	800.0		0.52	0.40-0.66	60
	899.2		0.66	0.50-0.81	71
	902.8		0.66	0.53-0.79	89
Opaka 1	1,135.2		0.45	0.37-0.56	50
Tymce 1	550.4	Lower Cretaceous	0.42	0.43-0.52	77
	1,091.3	Upper Jurassic	0.44	0.33-0.60	92
Ukrainian part					
Bortyatyn 1	1,820.0-1,830.0	Upper Jurassic	0.47	0.37-0.59	63
	2,522.0-2,529.0		0.57	0.53-0.68	17
	2,846.0-2,857.0	Middle Jurassic	0.61	0.53-0.77	62
Dieduszicy 2	1,100.0-1,108.0	Upper Cretaceous	0.45	0.34-0.60	67
	1,706.0-1,712.0		0.43	0.35-0.49	52
Korolyn 6	2,144.0-2,146.7	Upper Jurassic	0.48	0.35-0.72	60
	2,243.5-2,261.0		0.45	0.34-0.62	67
	2,589.0-2,594.0		n.m.	0.33-0.48	5
	2,751.0-2,760.0		n.m.	0.68-1.1	6
	3,132.0-3,140.0		0.58	0.49-0.65	43
	3,421.8-3,429.7		0.70	0.62-0.78	62
	3,495.4-3,500.4	Middle Jurassic	0.76	0.62-0.89	74
Korolyn 2	3,642.2-3,652.1		0.84	0.72-0.90	86
	4,157.0-4,164.0		0.99	0.88-1.25	71
Moryanti 1	2,576.0-2,582.0	Upper Jurassic	0.78	0.71-0.88	13
	3,055.0-3,063.0		0.90	0.68-1.10	37
Podiltsi 1	3,303.0-3,306.1	Middle Jurassic	0.65	0.57-0.73	61
	3,475.0-3,482.0		0.61	0.50-0.77	91
Rudki 300	3,241.0-3,246.0	Lower Jurassic	1.74	1.44-2.00	14
	3,491.9-3,495.5		1.84	1.59-2.20	12
	3,902.0-3,905.0		1.99	1.74-2.30	17
Voloshcha 1	2,255.0-2,265.0	Upper Jurassic	0.54	0.42-0.67	68
	2,500.0-2,508.0		0.57	0.45-0.69	78
	2,651.0-2,659.0		0.58	0.46-0.73	74
	2,850.5-2,860.5		0.65	0.52-0.77	93
	2,903.7-2,912.0		0.65	0.57-0.83	114
	3,089.0-3,093.0		0.62	0.48-0.80	139
	3,126.0-3,134.0		0.67	0.54-0.83	140
	3,296.0-3,305.0		0.67	0.55-0.87	87
	3,547.0-3,557.0		1.41	1.10-1.50	23

R_o – vitrinite reflectance; Meas. – number of measurements; n.m. – not measured

companied by testing various palaeo-heat flow models. The thermal maturity of organic matter was calculated by the EASY %R_O method (Sweeney & Burnham, 1990). Generation and expulsion of hydrocarbons were calculated with the use of the LLNL model (Ungerer *et al.*, 1988; Forbes *et al.*, 1991; BMRM 1-D, 2006).

Measurements of mean random vitrinite reflectance (R_O) were done at 546 nm in oil with Zeiss-Opton microphotometer. In the measurements applied the following standards: 0.496%, 0.921%, 1.141% and 1.662% reflectance (R_O). Sample preparation and point counts were used in accordance with the ICCP procedure (Taylor *et al.*, 1998).

OUTLINE OF GEOLOGY

In the analysed part of the basement of the Carpathian Foredeep, in the area between Tarnogród and Stryi towns, the Mesozoic strata form three structural complexes. The first and the oldest complex are built up of the terrigenous Lower(?)–Middle Jurassic strata (Krajewski *et al.*, 2011a). The carbonate rocks of the Upper Jurassic–Lower Cretaceous (Valanginian) overlay them. The most recent is the carbonate Upper Cretaceous complex. The complexes occur directly on the Palaeozoic formations, which represent mainly different horizons of the Cambrian strata (Buła & Habryn, *eds*, 2008; Buła & Habryn, 2011).

The analysed Mesozoic formations constitute the sedimentary cover of two Palaeozoic tectonic units – the Kielce Fold Zone (in the Ukrainian part named the Kokhanivka Zone) and the Łysogóry–Radom Block (the Rava Rus'ka Zone) (Buła & Habryn, 2011). The tectonic boundary between these units is the Holy Cross Fault, which, in the Ukrainian part, continues as the Krakovets Fault. The Mesozoic strata, covering above-mentioned tectonic units, clearly emphasize their separate character. In the Kielce Fold Zone (the Kokhanivka Zone) the Jurassic and Cretaceous strata occupy only a small area in the Lubaczów area and continue in Ukraine, where their range is also limited (Krajewski & Olszewska, 2007; Krajewski *et al.*, 2011a) (Fig. 1). A fundamental difference can be observed in the extent of the Mesozoic strata, especially Jurassic, ones in the Łysogóry–Radom Block (the Rava Rus'ka Zone), where hydrocarbon generation and expulsion processes were also modelled. The Mesozoic formations occupy almost the entire area of the unit. The sedimentary section is also more complete than that of the Kielce Fold Zone.

The Mesozoic sedimentary section begins with the Lower(?) Jurassic formations (Krajewski *et al.*, 2011a). However, their stratigraphic position in the Polish part is poorly constrained and called into question (Moryc, 2004; Świdrowska *et al.*, 2008). In the Ukrainian part, the Lower Jurassic formations with thicknesses of 100–200 m were also identified, *e.g.* in the Bortyatyn 1, Yuriyiv 1, Podiltsi 1 and 2 wells (Krajewski *et al.*, 2011a). Nevertheless, like in the Polish part, this stratigraphical horizon was isolated only on the basis of lithological criteria; palaeontological evidence has not been provided so far.

The overlying horizon of the Middle Jurassic strata has a similar range of occurrence. In the Kielce Fold Zone, it is

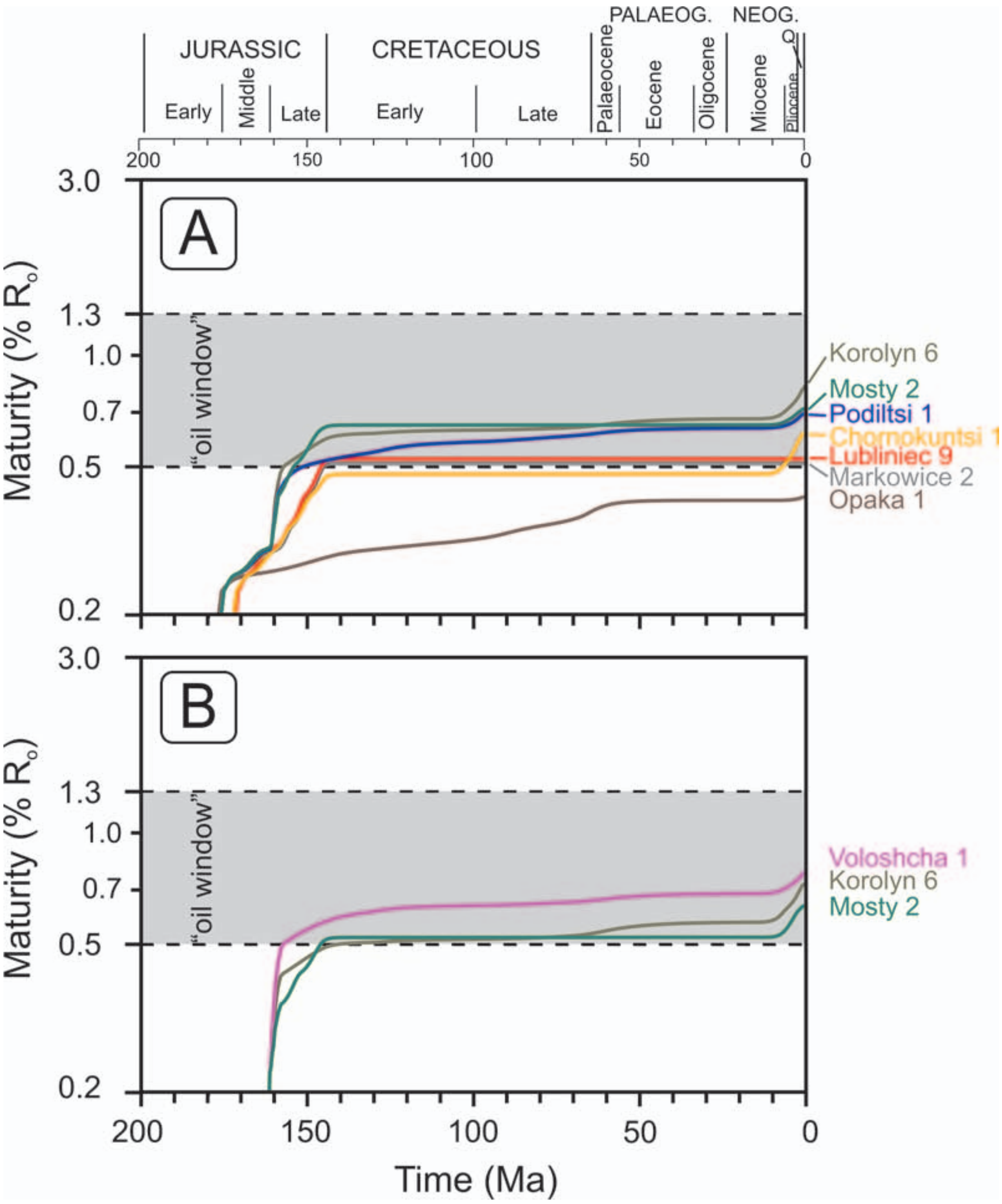

Fig. 2. Maturity evolution curves for the (**A**) Middle Jurassic and (**B**) Upper Jurassic source rocks. Palaeog. – Palaeogene, Neog. – Neogene, Q – Quaternary; R_o – vitrinite reflectance scale

limited to the south-eastern border part and extends from the Lubaczów area to Gorodok area in the Ukrainian part. Due to significant tectonic complexity, the range and thickness of the Middle Jurassic strata are strictly connected with the orientation of fault zones and illustrate well the block character of the structure of this unit (Moryc, 2004). Similar to the Lower Jurassic strata, in the Ukrainian part, the range and thicknesses are greater and the section is stratigraphically more complete. The recorded thickness of these formations reaches even 1,000 m (Dulub *et al.*, 2003). However, it is probably a result of tectonic multiplication and the true thickness is smaller and does not exceed a few hundred metres (Dulub *et al.*, 2003; Moryc, 2004). In the Łysogóry – Radom Block and its Ukrainian counterpart, the Rava Rus'ka Zone, the occurrence range of the Middle Jurassic formations corresponds almost completely with the boundaries of these units.

The Upper Jurassic–Lower Cretaceous carbonate complex extends over a significantly larger area. Although in the Polish part the range of occurrence of this complex is smaller than that of the Middle Jurassic terrigenous rocks, in the Ukrainian part its range comprises the entire area of the Carpathian Foredeep (Gutowski *et al.*, 2005; Anikeyeva & Zhabina, 2002; Krajewski & Olszewska, 2007; Krajewski *et al.*, 2011b).

The marine Miocene strata completely overlay the terrigenous – carbonate Mesosoic cover. The thickness of this cover varies. In the analysed Tarnogród–Stryi area it ranges

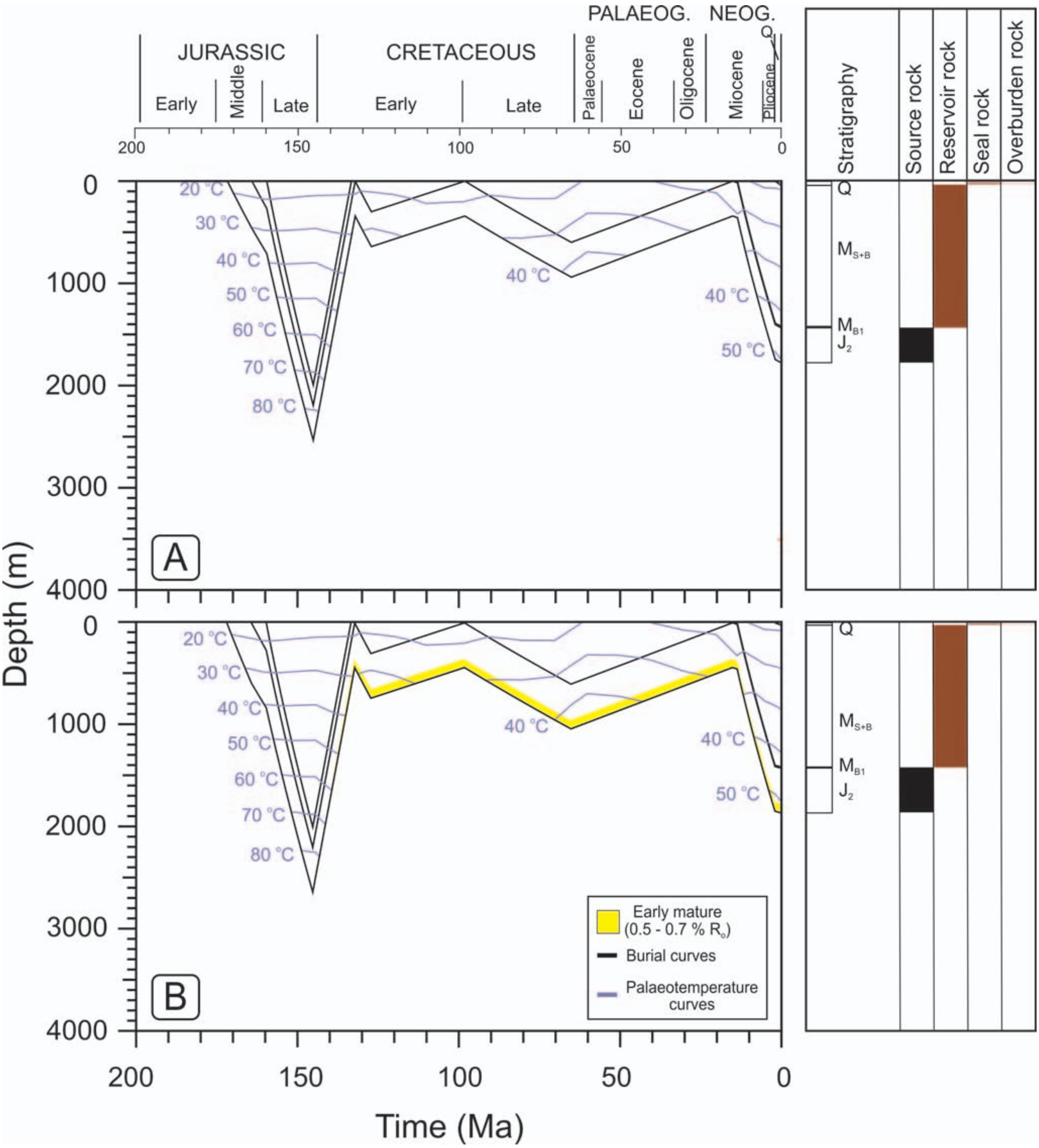

Fig. 3. Burial history curves of (**A**) Księżpol 15 and (**B**) Markowice 2 wells. J_2 – Middle Jurassic, M_{B1} – Miocene (Lower Badenian), M_{S+B} – Miocene (Sarmatian and Badenian). For the remaining abbreviations see Fig. 2

rom about a few hundred metres up to 3,500 m in the Wielkie Oczy Depression, and to more than 5,000 m in the Krukenychy Depression (Ney *et al.*, 1974; Kurovets *et al.*, 2004; Oszczypko *et al.*, 2006). In the Ukrainian part, in the vicinity of Stryi, the section is additionally supplemented by the flysch strata of the Carpathian Overthrust.

THERMAL MATURITY AND GENERATION MODELLING OF THE JURASSIC SOURCE ROCKS

The 1-D maturity modelling as well as thermal and burial history reconstruction were conducted for nine wells located in the Polish and Ukrainian parts of the study area. In

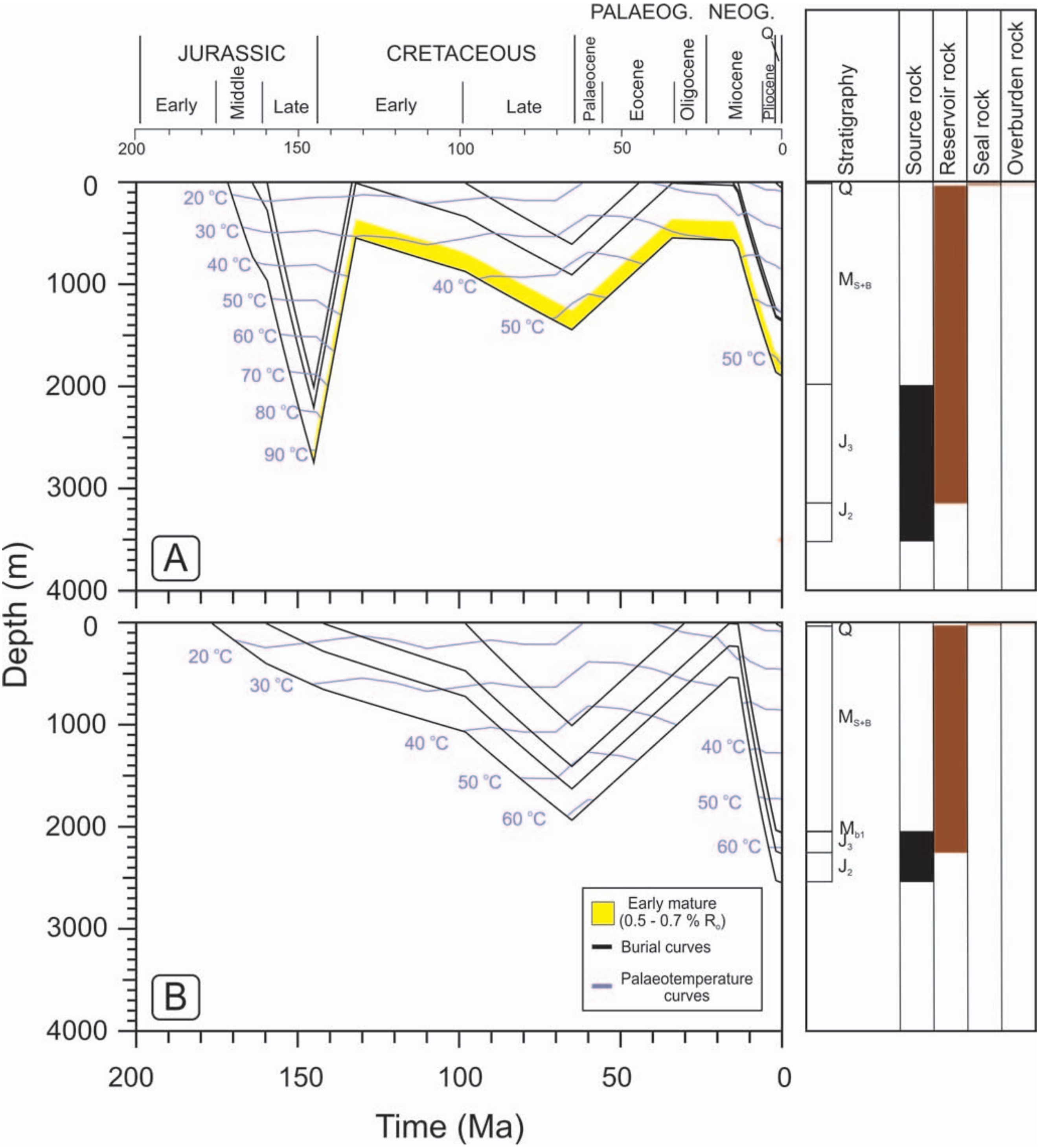

Fig. 4. Burial history curves of (**A**) Lubliniec 9 and (**B**) Opaka 1 wells. J_3 – Upper Jurassic. For the remaining abbreviations see Figs 2 and 3

the Polish part, the numerical modelling was performed in the Księżpol 15, Lubliniec 9, Markowice 2 and Opaka 1 wells (Fig. 1). In the Ukrainian part, the analysis was carried out in the Chornokuntsi 1, Korolyn 6, Mosty 2, Podiltsi 1 and Voloshcha 1 wells (Fig. 1).

The model of recent thermal regime was calibrated with data obtained from maps of temperatures at the given depth horizons from the analysed area and interpolated from the adjacent areas (Majorowicz & Plewa, 1979; Karwasiecka & Bruszewska, 1997). The thermal model for the Ukrainian part was assumed per analogy to the Polish part. The values of recent heat flow across the study area were from *ca*. 48–55 mW/m^2 in its western part to *ca*. 55–65 mW/m^2 in the eastern part.

The maturity modelling was calibrated with thermal maturity measurements: Rock-Eval T_{max} temperature (Kosakowski *et al.*, in press, b) and vitrinite reflectance R_o (Table 1). As in western part of the Małopolska Block, here

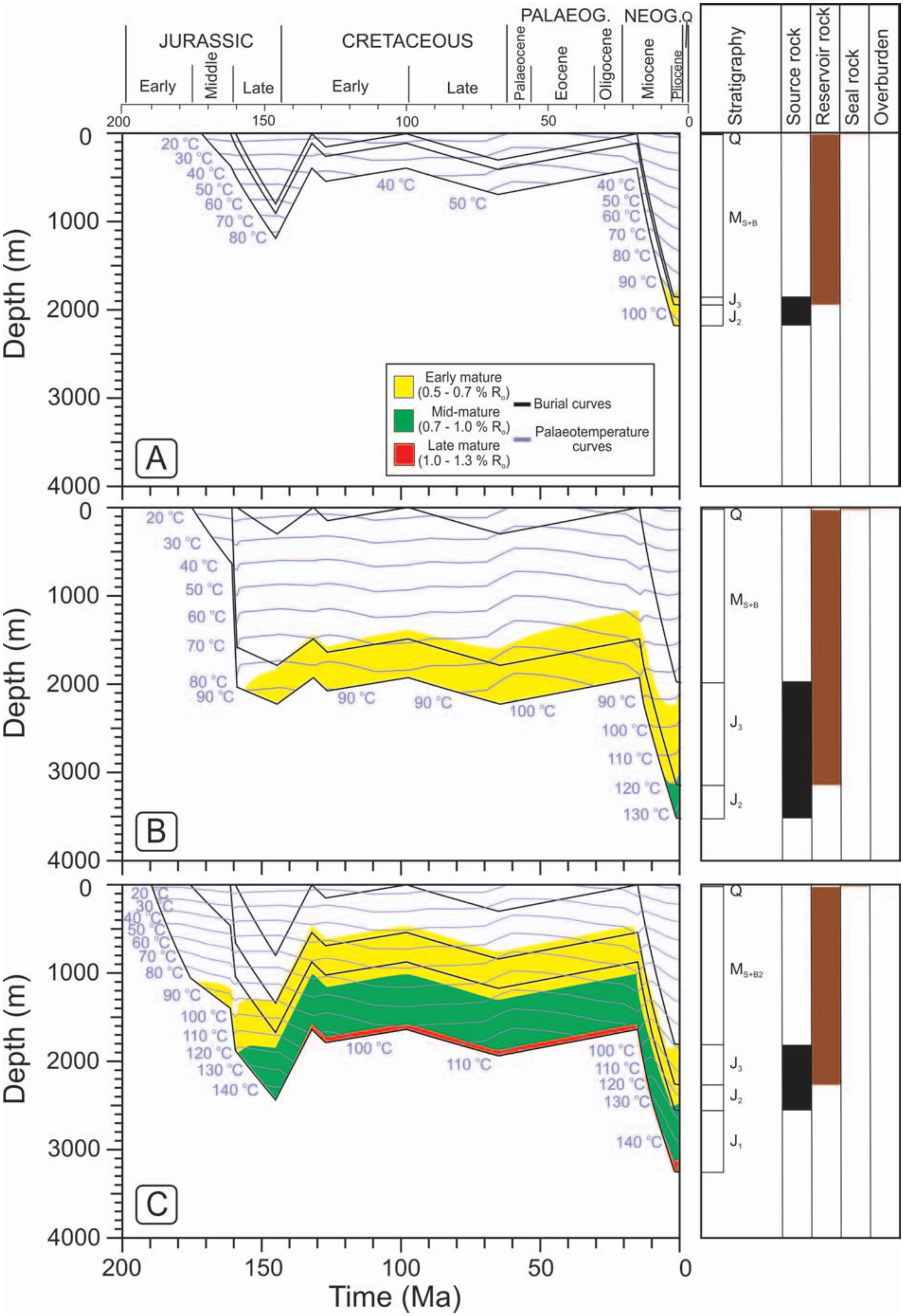

Fig. 5. Burial history curves of (**A**) Chornokuntsi 1, (**B**) Korolyn 6, and **(C)** Mosty 2 wells. J_1 – Lower Jurassic, M_{S+B} – Miocene (Sarmatian and Badenian). For the remaining abbreviations see Figs 2 and 3

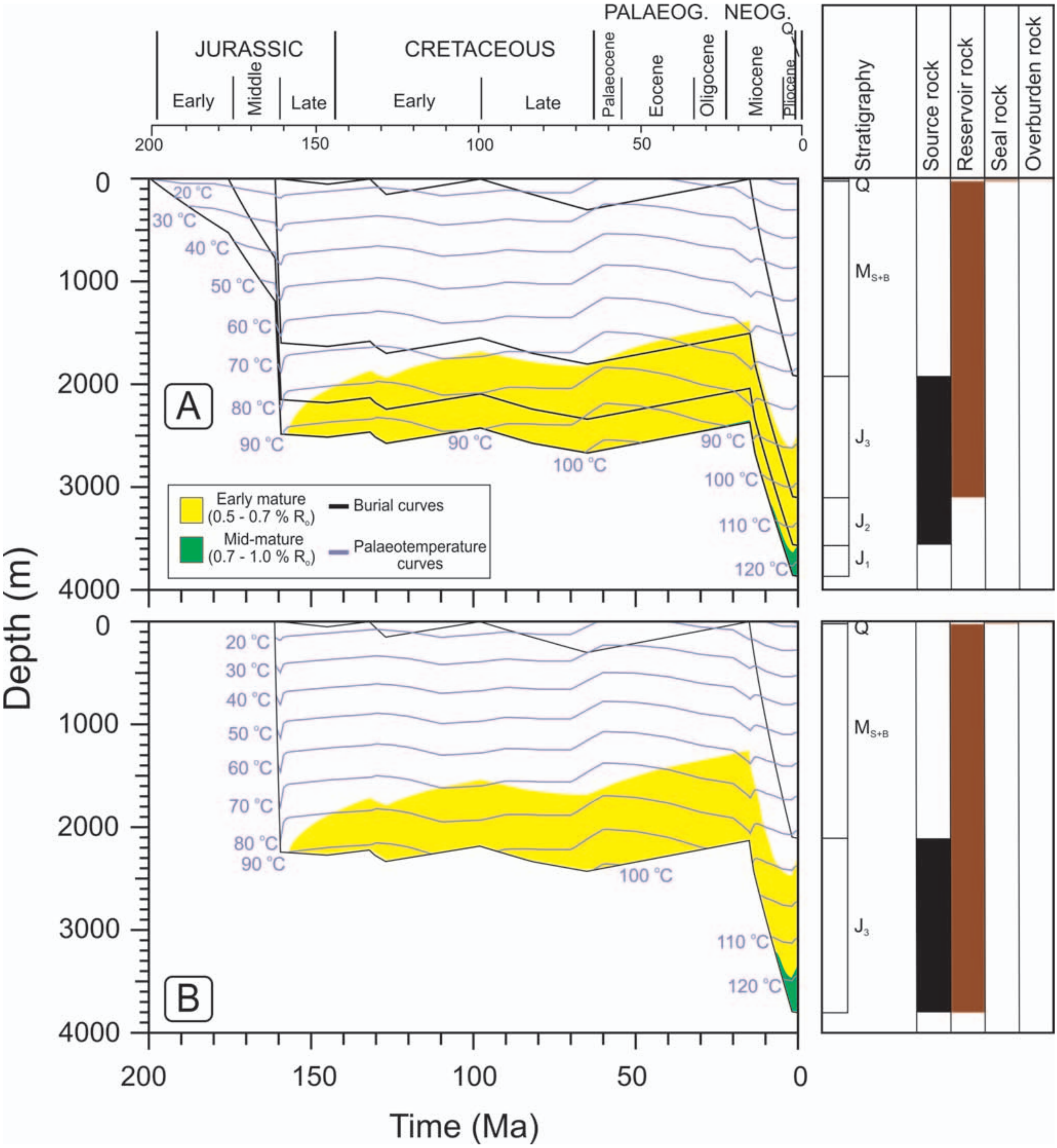

Fig. 6. Burial history curves of (**A**) Podiltsi 1 and (**B**) Voloshcha 1 wells. For abbreviations see Figs 2, 3 and 4

are also significant lacks in the section. These gaps in the geological section did not allow for full calibration or creation of a fully acceptable thermal-erosion model. Accordingly, a simple thermal evolution model was assumed with constant heat flow in the Mesozoic time of basin development equal to the present heat flow. The pre-Permian stage of basin development was ignored in the reconstruction, as not having a significant impact on the development of organic matter maturity in the Jurassic strata.

The existence of alternative ways of reconstructing thermal evolution of the basin and its magnitude means that the presented reconstruction of hydrocarbon generation conditions could have alternate solutions. For constant heat flow value, the primary thickness of the Jurassic horizon, and partly also flysch Carpathian overthrust, played a fundamental role in the calibration of the thermal – erosion model.

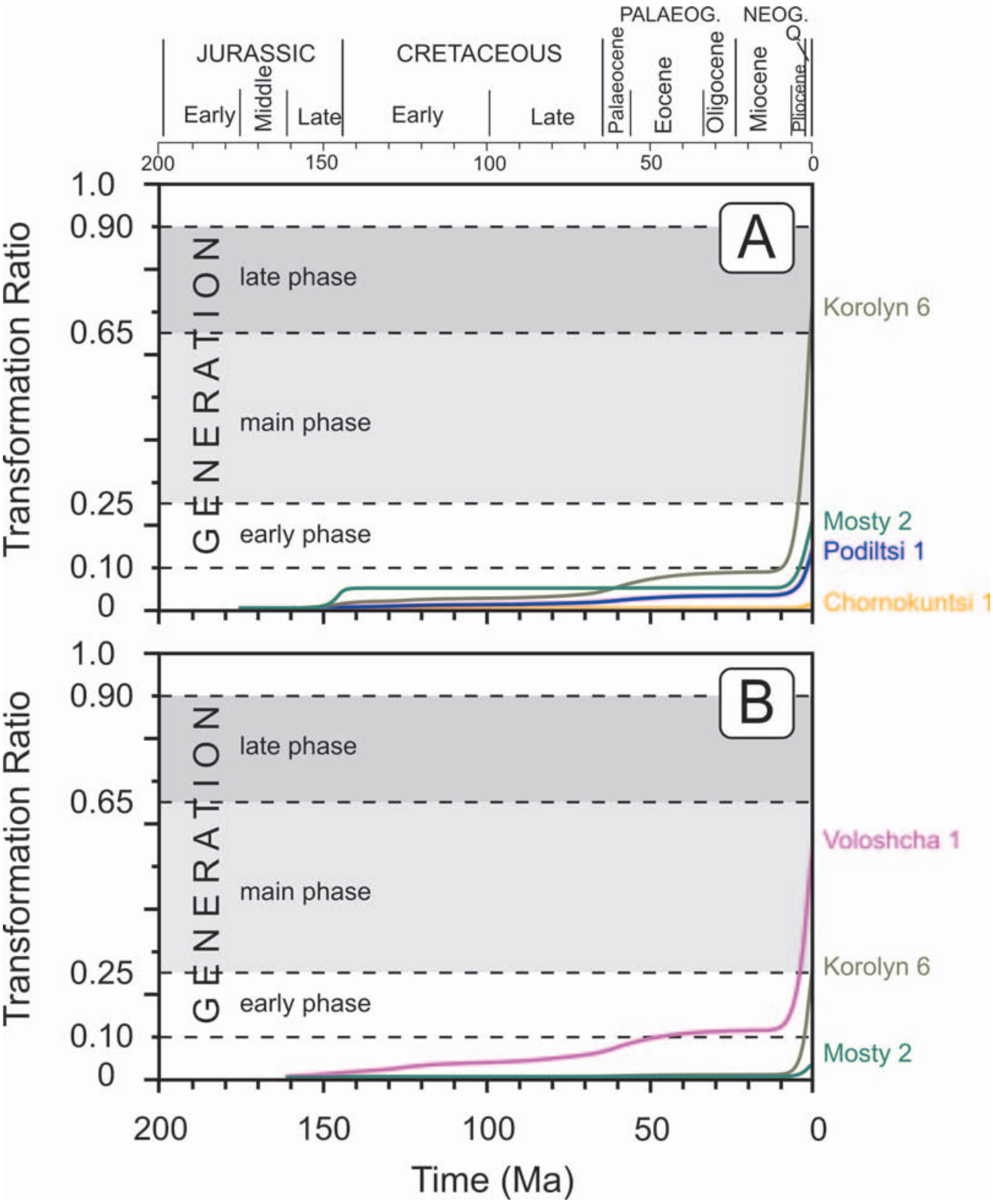

Fig. 7. Transformation ratio of kerogen in the (**A**) Middle Jurassic and (**B**) Upper Jurassic source rocks in logs of analysed wells**.** For the abbreviations see Fig. 2

The measured values of maturity (Rock-Eval T_{max} temperature – Kosakowski *et al.* (in press), and vitrinite reflectance R_o – Table 1) in the Jurassic strata revealed that the maturity of organic matter varies in a wide range, from immature to overmature. The vitrinite reflectance values of the Lower Jurassic strata, measured only in the Rudki 300 well, varies from 1.74 to 1.99% R_o (Table 1). The vitrinite reflectance of Middle Jurassic organic matter in Poland ranges from 0.40 to 0.66% R_o, while in Ukraine from 0.61 to 0.99% R_o (Table 1). The maturity of the Upper Jurassic source rocks, analysed mainly in the Ukrainian part, varies from about 0.45% R_o in the Korolyn 6 well to 0.90% in the Moryanti 1 well and even 1.41% in the Voloshcha 1 well (Table 1).

Thermal modelling indicated that maturity in the Middle Jurassic source rocks was reached in two stages. The first stage was related to deposition of thick Jurassic strata, resulting in maturity close to the present day situation (Fig. 2A). The depth of this initial phase was relatively small, *i.e.* 1,500 m and the attained temperature was 70–90 °C (Figs 3B, 4A). The Lower Cretaceous erosion was interrupted by the increase of the depth of burial and increased maturation of organic matter. The deposition of the Upper Cretaceous strata did not cause a significant increase in temperature, and the post-Cretaceous erosion uplifted the study area. The second stage of maturity growth was related to the deposition of Miocene sediments. The increase did not exceed 20% of maturity before their deposition (Fig. 2A). Despite

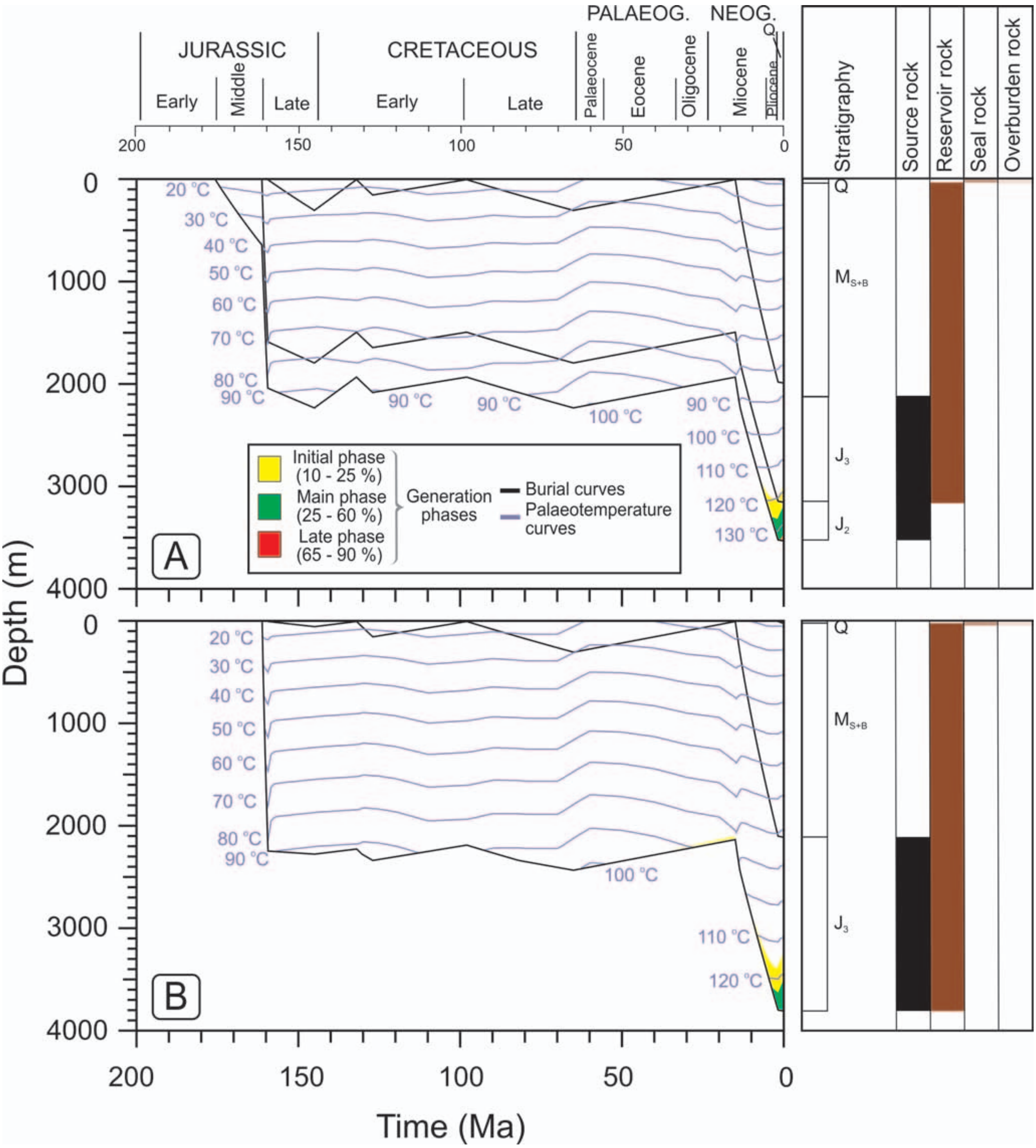

Fig. 8. Burial history curves for the Jurassic source rocks with generation stage in the (**A**) Korolyn 6 and (**B**) Voloshcha 1 wells. Pal. – Palaeogene, Eoc. – Eocene, O. – Oligocene. For the remaining abbreviations see Fig. 2, 3 and 4

this, in some wells in the Ukrainian part of the study area, *e.g.*, Korolyn 6, Mosty 2 and Podiltsi 1 wells, the source rock entered the main phase of the "oil window" (Figs 2A, 5B, C). This increase of maturity was influenced by the Outer Carpathian overthrusting. However, the range of this influence cannot be evaluated due to lack of wells in this zone.

In the Ukrainian part, the geochemical analyses (Kosakowski *et al.*, in press, b, and Table 1) revealed that the Upper Jurassic strata also meet the criteria for source rocks. The source rock horizons were found in, *e.g.*, the Korolyn 6, Mosty 2 and Voloshcha 1 wells (Fig. 1). The results of thermal modelling revealed that the evolution of the source rock in this stratigraphic horizon very much resembled the Mid-

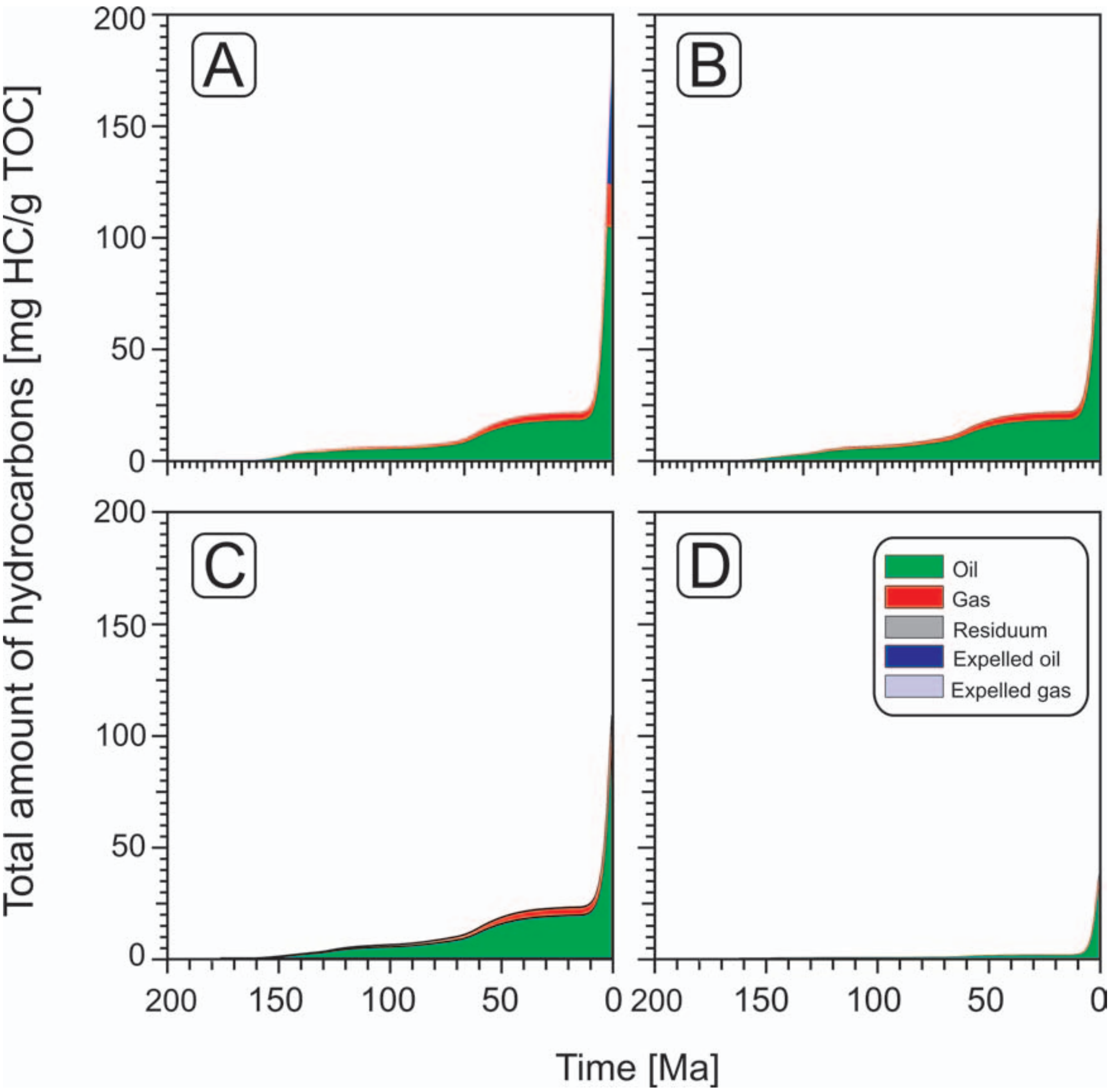

Fig. 9. Total amount of hydrocarbons generated from the (**A**) Middle Jurassic source rocks (Korolyn 6 well) and Upper Jurassic source rocks in the (**B**) Korolyn 6, (**C**) Chornokuntsi 1, and (**D**) Podiltsi 1 wells

dle Jurassic. The growth of organic matter maturity took place in two stages: (i) deposition of the Jurassic and partly Cretaceous strata, and (ii) deposition of Miocene strata (Figs 2B, 5B, C, 6B). The maximum maturity of organic matter in the Upper Jurassic strata is similar to that in the Middle Jurassic horizon (Fig. 2B).

Modelling of hydrocarbon generation from the Middle Jurassic source rocks in the Polish part of the study area revealed that they did not reach the generation stage. The transformation degree of organic matter was low, considerably below the 10% threshold of the transformation ratio (TR). In the Ukrainian part, the thermal maturity of organic matter was higher, and therefore the achieved transformation degree exceeded 10%, except Chornokuntsi 1 well (Fig. 7A). In the Mosty 2 and Podiltsi 1 wells, the transformation of organic matter reached the final 20% at the end of the Neogene. A much higher TR, up to 70%, was obtained in the Korolyn 6 well (Fig. 7A).

The transformation degree of organic matter in the Upper Jurassic source rocks was slightly lower. In the Korolyn 6 well, the TR of organic matter exceeded 20% and in the Voloshcha 1 well 50% (Fig. 7B). In the Mosty 2 well, the organic matter in this source rock horizon did not obtain 10% of TR (Fig. 7B).

The above values of transformation degree controlled the generation and expulsion of hydrocarbons in the analysed area. The Middle Jurassic source rocks in the Korolyn 6 well reached the early phase of generation (10–25% of generation potential) during the late Miocene deposition, at a burial depth below 3,000 m and temperature above 110 °C (Fig. 8A). In this well, the source rocks also reached the main phase (25–65% of generation potential) and even the late phase of generation (65–90% of generation potential) in the bottom of strata. These phases were reached at the end of the Miocene and the beginning of the Pliocene (Fig. 8A). In the Mosty 2 and Podilts 1 wells, the source rocks reached the early phase of generation also at the end of the Miocene and the beginning of Pliocene (Fig. 7A), at a burial depth below 2,450 m and temperature above 110 °C.

The Upper Jurassic source rocks, analysed in the Korolyn 6 and Voloshcha 1 wells, reached similar generation levels as in the Middle Jurassic strata. The initial phase of generation was reached in the late Miocene (Voloshcha 1 well) or in the early Pliocene (Korolyn 6 well), below 3,000 m of burial and temperature above 110 °C (Fig. 8A). The main generation phase was reached only in that part of analysed area. The main phase, reconstructed in the Voloshcha 1 well, was obtained in the early Pliocene, below 3,600 m depth and at temperature above 120 °C (Fig. 8B).

In the Mosty 2 well, the transformation degree was insufficient to initiate the generation process (Fig. 7B).

The amount of hydrocarbons generated from the Jurassic source rocks was strongly diversified. It depended on the transformation of organic matter. In the Korolyn 6 well, where the TR was the highest, during the petroleum process from the Middle and Upper Jurassic there were generated 175 mg HC/g TOC with 30% of expulsion and 100 mg HC/g TOC without expulsion, respectively (Fig. 9A). In the Voloshcha 1 well, 110 mg HC/g TOC without expulsion was generated from the Upper Jurassic source rocks (Fig. 9B).

CONCLUSIONS

The burial and thermal history and generation modelling with a determination of the amount of the generated hydrocarbons showed that the organic matter in the Middle Jurassic strata of the substratum of the Carpathian Foredeep is generally immature. Only in the Ukrainian part of the study area the maturity of organic matter is higher, qualifying source rocks to initial and partly main phase of the "oil window". This maturity also controlled the transformation level of kerogen. The degree of TR, needed to initiate processes of hydrocarbon generation and expulsion, was obtained in the Ukrainian part of the study area, and it was only there where these processes took place. Hydrocarbon generation and expulsion took place during the late Miocene–early Pliocene time. The amount of hydrocarbons generated from the Jurassic source rocks depended on transformation degree of organic matter and amounted to 175 mg HC/g TOC with 30% of expulsion, at maximum.

The obtained results of 1-D modelling clearly indicate that the Jurassic source rocks, with the heat flow constant in time and equal to the recent one, could reach the transformation of organic matter necessary for the initiation of the hydrocarbon generation process only in the Ukrainian part of the analysed area. In the Polish part, the organic matter is immature.

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