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Burial history, thermal history and hydrocarbon generation modelling of the Jurassic source rocks in the basement of the Polish Carpathian Foredeep and Outer Carpathians (SE Poland)

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Abstract: Burial history, thermal maturity, and timing of hydrocarbon generation were modelled for the Jurassic source rocks in the basement of the Carpathian Foredeep and marginal part of the Outer Carpathians. The area of investigation was bounded to the west by Kraków, to the east by Rzeszów. The modelling was carried out in profiles of wells: Będzienica 2, Dębica 10K, Góra Ropczycka 1K, Goleszów 5, Nawsie 1, Pławowice E1 and Pilzno 40. The organic matter, containing gas-prone Type III kerogen with an admixture of Type II kerogen, is immature or at most, early mature to 0.7 % in the vitrinite reflectance scale. The highest thermal maturity is recorded in the south-eastern part of the study area, where the Jurassic strata are buried deeper. The thermal modelling showed that the obtained organic matter maturity in the initial phase of the "oil window" is connected with the stage of the Carpathian overthrusting. The numerical modelling indicated that the onset of hydrocarbon generation from the Middle Jurassic source rocks was also connected with the Carpathian thrust belt. The peak of hydrocarbon generation took place in the orogenic stage of the overthrusting. The amount of generated hydrocarbons is generally small, which is a consequence of the low maturity and low transformation degree of kerogen. The generated hydrocarbons were not expelled from their source rock. An analysis of maturity distribution and transformation degree of the Jurassic organic matter shows that the best conditions for hydrocarbon generation occurred most probably in areas deeply buried under the Outer Carpathians. It is most probable that the "generation kitchen" should be searched for there.

Key words: Jurassic, Outer Carpathians, Carpathian Foredeep, SE Poland, 1-D modelling, source rocks, generation.

Introduction

The study area located between Kraków and Rzeszów (Fig. 1) has been subjected to intensive drilling exploration since the 1950s. As a result, many natural gas deposits have been discovered within the Miocene cover (Kotarba & Peryt 2011). The gases accumulated there are microbial, that is formed before the thermogenic processes (Kotarba 2011). Numerous small commercial and uncommercial oil and gas accumulations have also been discovered within the Upper Jurassic–Lower Cretaceous carbonate complex and Upper Cretaceous carbonate and clastic complexes (Karnkowski 1993; Myśliwiec et al. 2006). The Upper Jurassic (–Lower Cretaceous) carbonates were found to contain an oil accumulation in the Partynia-Podborze field, gas accumulations in the Wojsław, Łączki Brzeskie, and Mędrzechów fields, oil and gas accumulation in the Korzeniów-Męciszów, and gas-condensate accumulations in the Góra Ropczycka and Tarnów fields (Myśliwiec et al. 2006; Kotarba et al. 2011). In both the Upper Jurassic and Upper Cretaceous strata the hydrocarbon accumulations were found in the Dąbrowa Tarnowska and Grobla-Pławowice fields (oils and gas), Łapanów (gas), Łąkta (gas and condensate), Smęgorzów (gas), and Żukowice fields (gas). The Upper Cretaceous sandstones were found to contain gas accumulations in the Brzezowiec, Jastrząbka Stara, Rajsko, Rylowa, and Swarzów fields (Karnkowski 1993; Myśliwiec et al. 2006). Gases occurring in the Paleozoic-Mesozoic basement of the Polish Carpathian Foredeep are both microbial and thermogenic (Kotarba 2012).

Due to a significant incompleteness of the sedimentation profile, caused mainly by erosional processes, it is important to define the source of the hydrocarbon mass accumulated later in reservoir rocks and to reconstruct the course of the processes.

In the current work, the generation potential of the Jurassic strata of the basement of the Carpathian Foredeep and the marginal part of the Outer Carpathians was evaluated in the area between Kraków and Rzeszów, with the use of 1-D modelling methods. The analysis was carried out in the Będzienica 2, Dębica 10K, Góra Ropczycka 1K, Goleszów 5, Nawsie 1, Pławowice E1 and Pilzno 40 wells (Fig. 1).

Outline of geology

The study area comprises the Mesozoic cover within the range of the basement of the Carpathian Foredeep and the marginal part of the Outer Carpathians between Kraków and Rzeszów (Fig. 1). Its western boundary reaches the Kraków-Lubliniec Fold Zone and corresponds to the boundary of the

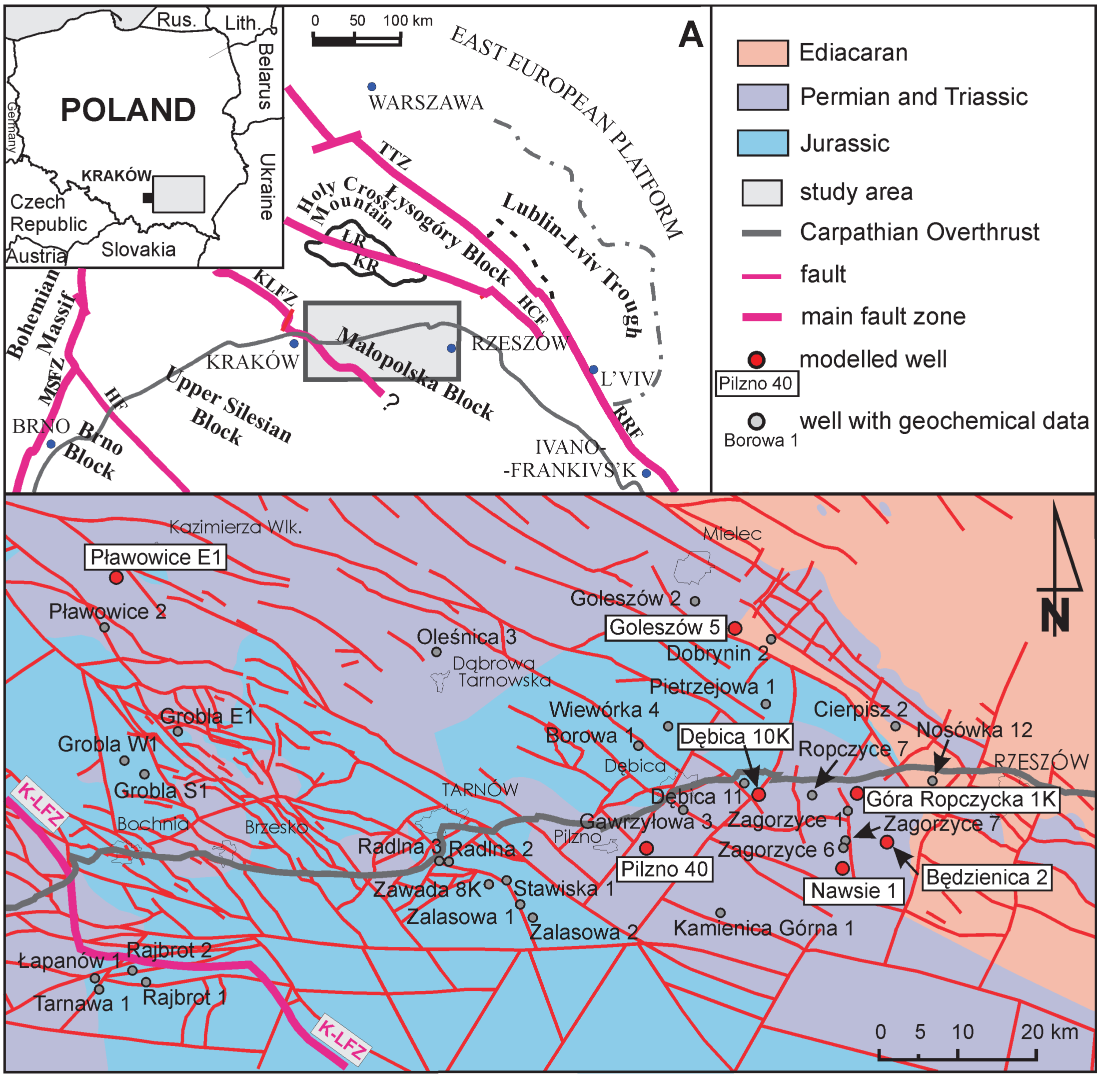

Fig. 1. Extent of the lowermost Mesozoic strata in the study area with location of 1-D modelled wells. **Rus.** — Russia, **Lith.** — Lithuania, **MSFZ** — Moravian-Silesian Fault Zone, **HF** — Hana Fault, **KLFZ** — Kraków-Lubliniec Fault Zone, **HCF** — Holy Cross Fault, **RRF** — Rava Ruska Fault, **TTZ** — Teisseyre-Tornquist Zone, **ŁR** — Łysogóry Region, **KR** — Kielce Region.

Paleozoic structural unit called the Małopolska Block. Its eastern boundary is the Lower San Horst Structure (Fig. 1). The basement of the Carpathian Foredeep and the Outer Carpathians is composed of the Lower Paleozoic strata forming the Caledonian structural stage, the Upper Paleozoic strata forming the Variscan stage, and the Permian and Mesozoic strata forming the Alpine structural stage. A description of the Caledonian and Variscan stages in the study area can be found in Buła & Habryn (2008, 2011) and Kosakowski & Wróbel (2011), and the Alpine stage adopted for the purposes of the modelling of hydrocarbon generation and expulsion processes is given as in Oszczypko et al. (2006), Świdrowska et al. (2008) and Kosakowski et al. (2011).

The Mesozoic strata form three complexes: the Permian–Triassic, Middle Jurassic–Lower Cretaceous and Upper Cretaceous. Their ranges and the interrelationships among them were formed by multi-stage Alpine processes of uplifting of the area and its subsequent erosion (Moryc 2006; Krajewski et al. 2011). Those movements caused reductions in the sedimentation profile of the Mesozoic cover (Gutowski et al. 2007; Matyja 2009; Krajewski et al. 2011; Kosakowski & Wróbel 2011; Kosakowski et al. 2011) and a limitation of the range of occurrence of particular complexes, especially the Permian-Triassic complex (Jawor & Baran 2004). That is a result of erosion that started in the Late Triassic. The next structural complex starts with the Middle Jurassic formations. The complex has the widest extent, and it is formed by the Middle Jurassic, Upper Jurassic as well as the Lower Cretaceous formations. The rocks above, belong to Upper Cretaceous formations with erosional unconformity; the gap is related to the regional deformation of the Austrian phase in the Aptian and Albian time.

The sandy Cenomanian strata begin the Upper Cretaceous section. The remaining part of the profile is composed of carbonate formations. In the Late Cretaceous–Early Paleogene, as a result of the Laramian phase, the study area was uplifted and underwent intensive erosion (Jawor & Baran 2004). The erosion lasted throughout the Paleogene time and resulted in the removal of the Upper Cretaceous strata from a significant part of the study area. The Laramian erosion also affected the formations of the Upper Jurassic–Lower Cretaceous complex. The results included significant differences in thickness between the western part, where the thickness of that complex reaches about 300 m, and the eastern part, where its thickness is even 1300 m (Gutowski et al. 2007; Matyja 2009). The thickness of the terrigenous complex of Miocene age varies and increases from the margin of the Carpathian Foredeep, so that, for example, it amounts to over 1000 m in the region of Tarnów, whereas in the region of Rzeszów it is over 2500 m (Jawor & Baran 2004). From the south, the flysch formations of the Outer Carpathians were overthrusted onto the autochthonous Miocene strata. Their thickness also increases from the margin of overthrusting towards the south. In the study area, the thickness of the flysch strata ranges from a few hundred meters to over 3800 meters (the area of Nosówka).

Modelling procedure

1-D modelling of selected wells was performed using BasinMod™ software (BMRM 1-D 2006). The modelling approach adopted in the software requires input data which describe the present-day geological situation as a result of past events. On this basis, the geological history is simulated from the oldest event to the most recent one (Buła & Habryn 2008, 2011). Rock properties — density, porosity, permeability and thermal conductivity are modelled along with the thermal history. BasinMod software provides an extended database of various lithological types defined by physical properties mentioned above (BMRM 1-D 2006; Kosakowski et al. 2012a). The details on principles of the modelling technique are given in Welte et al. (1997). Thermal evolution is simulated on the basis of boundary assignments applied to certain time steps. The assigned parameters are 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 can only be 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 and reflectance of vitrinite (R_o) data were used (Table 1). For burial history reconstruction was also used: thickness of individual stratigraphic units, numerical ages defining time interval between the upper and lower limit of each stratigraphic unit, and petrophysical parameters for the individual units (compaction coefficient, initial porosity, thermal conductivity, heat capacity). Estimation of eroded thicknesses has to

Table 1: Vitrinite reflectance and maceral composition of the Mesozoic organic matter in the selected wells (Kraków-Rzeszów area).

Well	Depth (m)	Stratigraphy	Pyrite	Macerals			OM (%)	Vitrinite reflectance			$R_{Oredep.}$ (%)
				Vitrinite	Liptinite	Inertinite		R_O (%)	Range	Meas.	
Dębica 10k	2882.4	Upper Jurassic	3.7	tr.	tr.	tr.	tr.	n.m.	n.m.	n.d.	0.90–1.50
Góra Robczycka 1K	3205.4	Middle Jurassic	0.2	3.4	4.5	1.3	9.2	0.63	0.50–0.66	50	n.m.
Góra Robczycka 1K	3212.7	Middle Jurassic	0.2	4.5	3.8	1.0	9.3	0.59	0.48–0.72	108	0.90–1.10
Nawsie 1	3807.5	Upper Jurassic	1.8	0.1	0.3	0.1	0.5	0.60	0.46–0.67	15	1.00–1.35
Nawsie 1	3867.5	Upper Jurassic	1.1	0.6	0.2	0.1	0.9	n.m.	n.m.	n.d.	1.00–1.32
Nawsie 1	4008.5	Upper Jurassic	0.8	0.05	0.1	0.05	0.2	0.69	0.63–0.79	12	0.98–1.16
Nawsie 1	4232.5	Upper Jurassic	0.4	0.05	0.3	0.05	0.4	n.m.	0.60–0.80	8	0.95–1.30
Pilzno 40	2963.5	Upper Jurassic	1.3	0.1	0.4	n.m.	0.5	0.64	0.49–0.79	12	0.90–1.20
Pilzno 40	3149.5	Upper Jurassic	0.8	0.1	0.2	n.m.	0.3	0.67	0.58–0.80	13	0.85–1.30
Pilzno 40	3236.6	Upper Jurassic	0.2	<0.1	0.1	n.m.	0.2	0.67	0.63–0.79	10	0.88–1.10
Tarnawa 1	2985.0	Middle Jurassic	n.m.	n.m.	n.m.	n.m.	n.m.	0.61	n.m.	200	n.m.
Tarnawa 1	2987.0	Middle Jurassic	n.m.	n.m.	n.m.	n.m.	n.m.	0.58	n.m.	200	n.m.
Tarnawa 1	2989.3	Middle Jurassic	n.m.	n.m.	n.m.	n.m.	n.m.	0.59	n.m.	200	n.m.
Tarnawa 1	2990.1	Middle Jurassic	n.m.	n.m.	n.m.	n.m.	n.m.	0.58	n.m.	150	n.m.
Tarnawa 1	2992.8	Middle Jurassic	n.m.	n.m.	n.m.	n.m.	n.m.	0.58	n.m.	200	n.m.
Zagorzyce 6	2817.5	Lower Cretaceous	0.3	0.9	0.4	n.m.	1.3	0.45	0.34–0.60	67	0.75–0.79
Zagorzyce 6	3579.6	Upper Jurassic	0.8	0.1	0.2	tr.	0.3	n.m.	0.41–0.44	11	1.20–1.32
Zagorzyce 6	3681.4	Upper Jurassic	0.9	tr.	0.1	n.m.	0.1	n.m.	n.m.	n.d.	1.25–1.30
Zagorzyce 6	3800.7	Upper Jurassic	3.0	tr.	0.1	n.m.	0.1	n.m.	0.44–0.49	10	1.00–1.10
Zagorzyce 6	3983.5	Middle Jurassic	2.5	3.2	1.1	0.2	3.5	0.75	0.57–0.90	90	1.10–1.50
Zagorzyce 6	4027.5	Middle Jurassic	1.6	5.5	2.0	1.1	8.6	0.78	0.63–0.95	78	1.10–1.30
Zagorzyce 6	4119.5	Lower Triassic	0.2	2.9	1.0	0.3	4.2	0.92	0.84–1.00	65	1.20–1.37

OM — organic matter (sum of macerals); $\mathbf{R_O}$ — vitrinite reflectance; $\mathbf{R_{Oredep}}$ — redeposited organic matter; **Meas.** — number of measurements; **n.m.** — not measured; **n.d.** — no data; **tr.** — traces.

be accompanied by testing various paleoheat flow models. The thermal maturity of organic matter was calculated by the EASY %Ro method (Sweeney & Burnham 1990). Generation and expulsion of hydrocarbons were calculated by the LLNL model (Ungerer et al. 1988; Forbes et al. 1991; BMRM 1-D 2006).

Modelling of maturation and generation history — results and discussion

The 1-D maturity modelling as well as thermal and burial history reconstruction were conducted for 7 wells: Będzienica 2, Dębica 10K, Góra Ropczycka 1K, Goleszów 5, Nawsie 1, Pławowice E1 and Pilzno 40 (Fig. 1). The analysed Middle and Upper Jurassic strata together with Lower Cretaceous strata (Berriasian and Valanginian), form one complex of carbonate sediments separated from the under- and overlying ones by discordances. This complex is represented by Oxfordian marls and marly limestones overlain by a complex of bedded and massive limestones, Kimmeridgian pelitic marly limestones and marls and Tithonian massive carbonates developed in coral-sponge-microbial facies (Krajewski et al. 2011). In the study area the Lower Cretaceous depositional sequence can be divided into two main facies: Berriasian peloidal-microbial-cyanobacterial facies and Valanginian ooidal-bioclastic facies (Zdanowski et al. 2001; Gutowski et al. 2007; Urbaniec et al. 2010).

The model of the recent thermal regime was calibrated with data obtained from maps of temperatures at the given depth horizons (Majorowicz & Plewa 1979; Majorowicz et al. 1984; Karwasiecka & Bruszewska 1997; Kotarba et al. 2004). Moreover, the analysis also takes into account the temperature measurements from adjacent areas, namely the Upper Silesian Block and Lublin Trough. In both areas, the distributions of the thermal field and their reconstruction indicate much lower

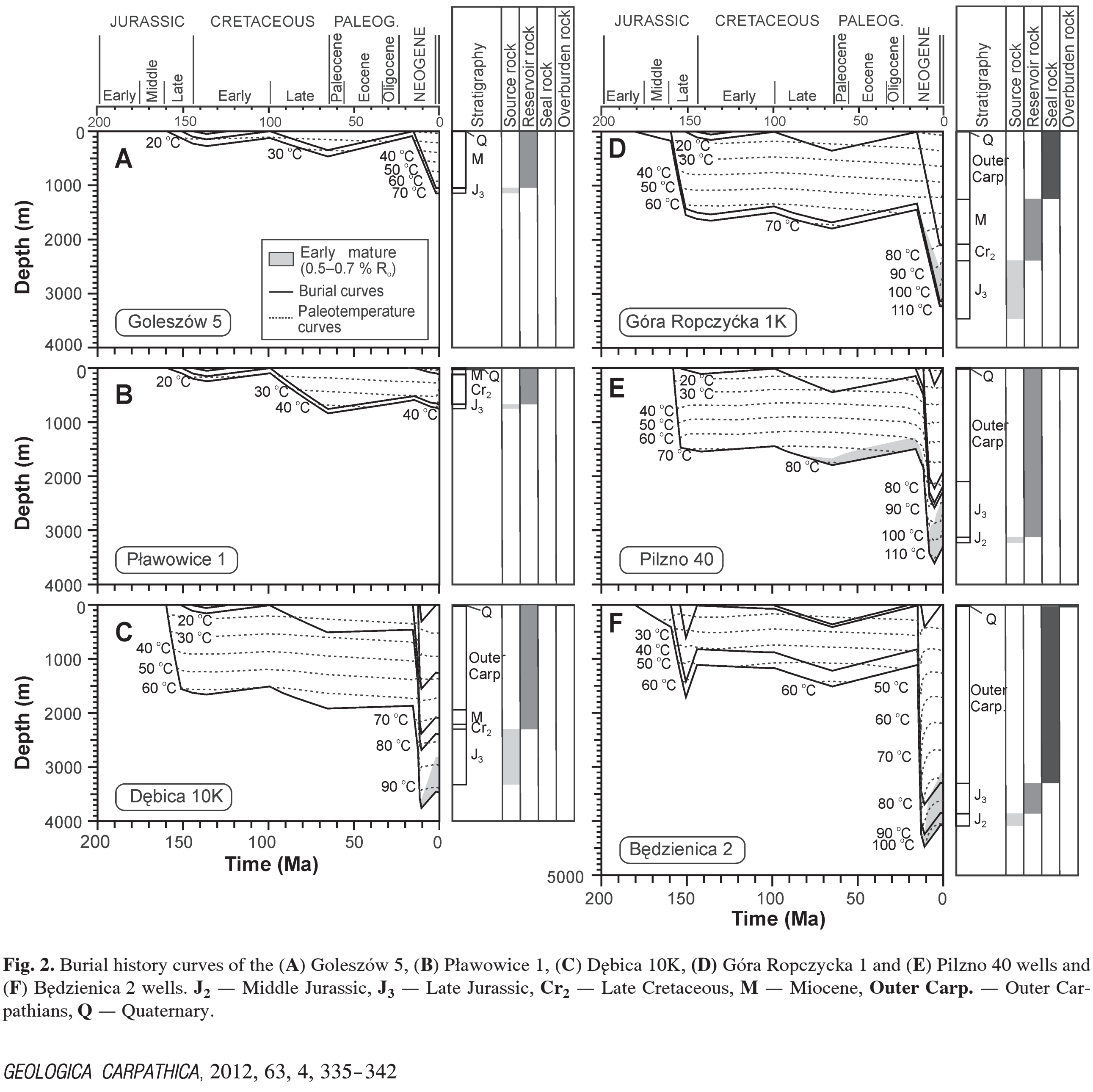

Fig. 2. Burial history curves of the (**A**) Goleszów 5, (**B**) Pławowice 1, (**C**) Dębica 10K, **(D)** Góra Ropczycka 1 and (**E**) Pilzno 40 wells and (**F**) Będzienica 2 wells. $\mathbf{J_2}$ — Middle Jurassic, $\mathbf{J_3}$ — Late Jurassic, $\mathbf{Cr_2}$ — Late Cretaceous, **M** — Miocene, **Outer Carp.** — Outer Carpathians, **Q** — Quaternary.

heat flow values and relative stability of paleothermal conditions in the Mesozoic stage of basin development (Belka 1993; Botor et al. 2002; Kotarba et al. 2004).

The calculated values of recent heat flow across the study area ranged between ca. 50 mW/m^2 in the eastern part and ca. 60 mW/m^2 in its western and central parts.

The maturity modelling was calibrated with thermal maturity measurements, Rock-Eval T_{max} temperature (Kosakowski et al. 2012b) and vitrinite reflectance R_o (Table 1). A significant incompleteness in the stratigraphic section in the study area makes it impossible to create one unique thermal–erosional model. It is worth stressing, that in each of the analysed models there is the possibility to use the alternative model with an other scheme of the thermal and erosion evolution, which in consequence gives a similar recent thermal maturity of organic matter. In view of the above-mentioned points, the selection of a model for analysing hydrocarbon generation and expulsion processes is, to a large extent, subjective and gives an opportunity for a different interpretation of the course of petroleum processes in the study area.

Considerations were based on the model of thermal changes presented by Narkiewicz et al. (2010), who suggested constant heat flow during the Permian, Mesozoic and Cenozoic times.

The pre-Permian stage of basin development, presented by Kosakowski & Wróbel (2011), was ignored in the reconstruction, as one not having a significant impact on the development of organic matter maturity in the Jurassic strata.

The model of constant heat flow over time equal to that of recent times is sufficient to explain the available thermal maturity measurements in the Jurassic strata, because in the Mesozoic the thermal history of the study area is relatively stable.

The key role in the evolution of organic matter maturity was played by the deposition of thicker Upper Jurassic strata, and, above all, by the overthrust of flysch deposits of the Outer Carpathians. The deposition of the Jurassic strata placed the layers of source rocks at the depth with the temperature range of 60–80 °C, which represents the beginning of the early mature phase in the "oil window" (Figs. 2, 3). Only in the wells located farthest north of the Outer Carpathian boundary, namely in the Pławowice E1 and Goleszów 5 wells, the temperatures were much lower and did not exceed 30–40 °C (Fig. 2A,B). The deposition of the Cretaceous strata did not cause a significant increase in temperature, to a maximum of 50 °C. The post-Cretaceous uplift and erosion of the study area stopped the increase in temperature, and consequently, the increase in organic matter maturity (Fig. 3). The deposition of the Miocene strata also did not cause big changes in the Jurassic organic matter maturity. This is the result of both the small thickness of Miocene rocks and low heat flow in the sedimentary basin. Only the Outer Carpathian Overthrust placed the layer of source rocks in the temperature range which determine entering the initial phase of the "oil window" (0.5–0.7 %R_o) (Fig. 3). The maximal values of maturity reached by organic matter in the Jurassic strata range from 0.6–0.65 %R_o in the region of Bochnia-Tarnów-Dębica (Fig. 2C) to about 0.8 %R_o in the south-west of Dębica, under the Carpathian Overthrust (Fig. 2F). The thermal modelling has proven that the extent of

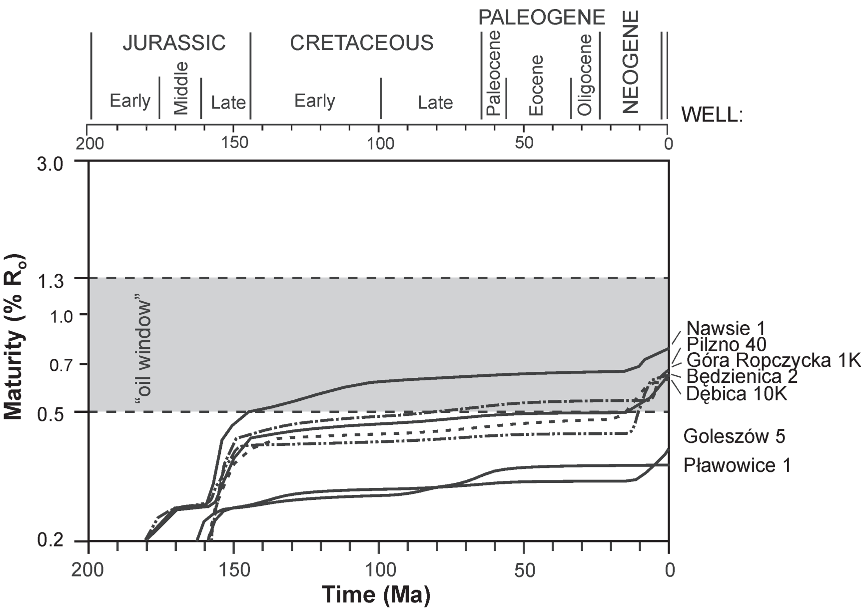

Fig. 3. Maturity evolution curves for the Jurassic source rocks in profiles of analysed wells.

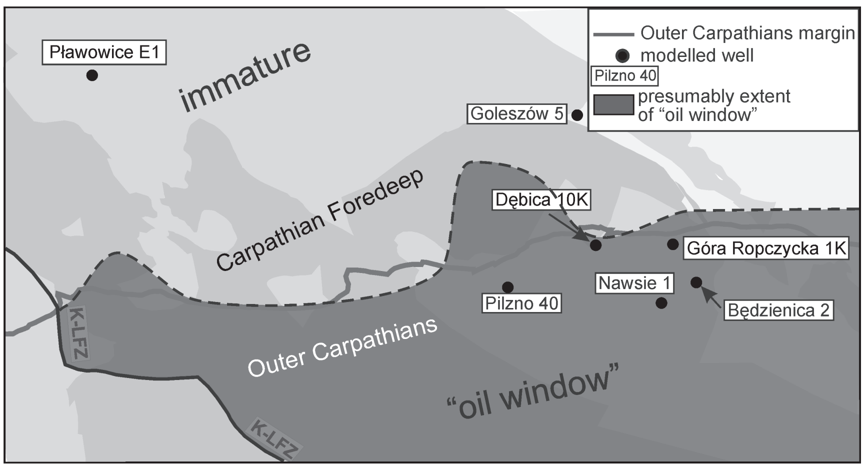

Fig. 4. The presumably extent of the "oil window" in the Jurassic and Cretaceous strata in the Kraków-Rzeszów area.

maturity of the organic matter within the "oil window" is not exactly the same as the extent of the Carpathian Overthrust; for example in the Dębica area, the organic-matter maturity was also influenced by the Miocene deposition (Fig. 4). Nevertheless, it can be stated, in general, that attainment of maturity in the phase of the "oil window" is related to the overthrust of the Outer Carpathians (Fig. 2C,D).

In the Mesozoic profile in the south-eastern part of Poland only the Middle Jurassic strata show rock complexes that meet the quantitative criteria of source rocks (Kosakowski et al. 2012b). The geochemical analysis performed in those strata revealed that the Triassic, Upper Jurassic and Cretaceous strata present generally very low TOC and hydrocarbon (S_1+S_2) contents, and low thermal maturity of organic matter additionally reduced their source rock potential. The Middle Jurassic source rocks show much higher TOC and hydrocarbon contents up to 17.0 wt. % and 53.4 mg HC/g rock, respectively (Kosakowski et al. 2012b). This potential is variable, but the maximum values indicate the presence of good and very good source rocks. Organic matter in the Middle Jurassic strata is of mixed type, dominated by gas-prone Type III kerogen. The organic matter is immature, or mature in the early phase of the "oil window". The maturity of kerogen increases towards to Outer Carpathians (Kosakowski et al. 2012b).

This brief geochemical study of the Mesozoic profile showed that only the Middle Jurassic strata fulfil the criteria for source rocks and the kinetic modelling were carried out only for this strata.

Modelling of hydrocarbon generation from the Middle Jurassic source rocks revealed that they only locally reached the generation stage. In the predominant part of the study area the transformation degree of organic matter is low, below 10 % (Fig. 5). It was only in the eastern part of the study area, where the source rock formations are deeply submerged under the Carpathian Overthrust and reached the highest maturity, that the transformation degree made it possible to initiate the hydrocarbon generation process.

In the Nawsie 1 well, the Middle Jurassic source rocks reached the early

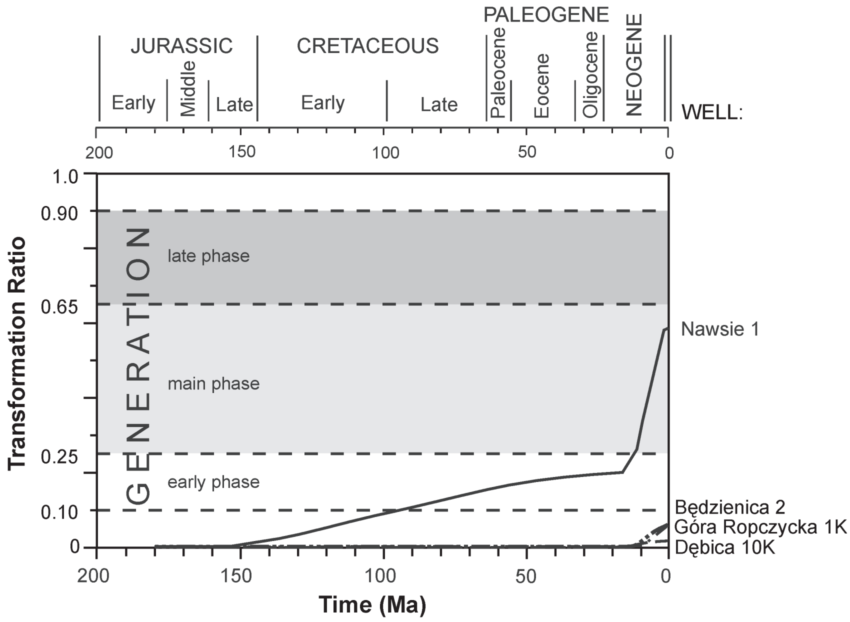

Fig. 5. Transformation ratio of kerogen in the Jurassic source rocks in the profiles of analysed wells.

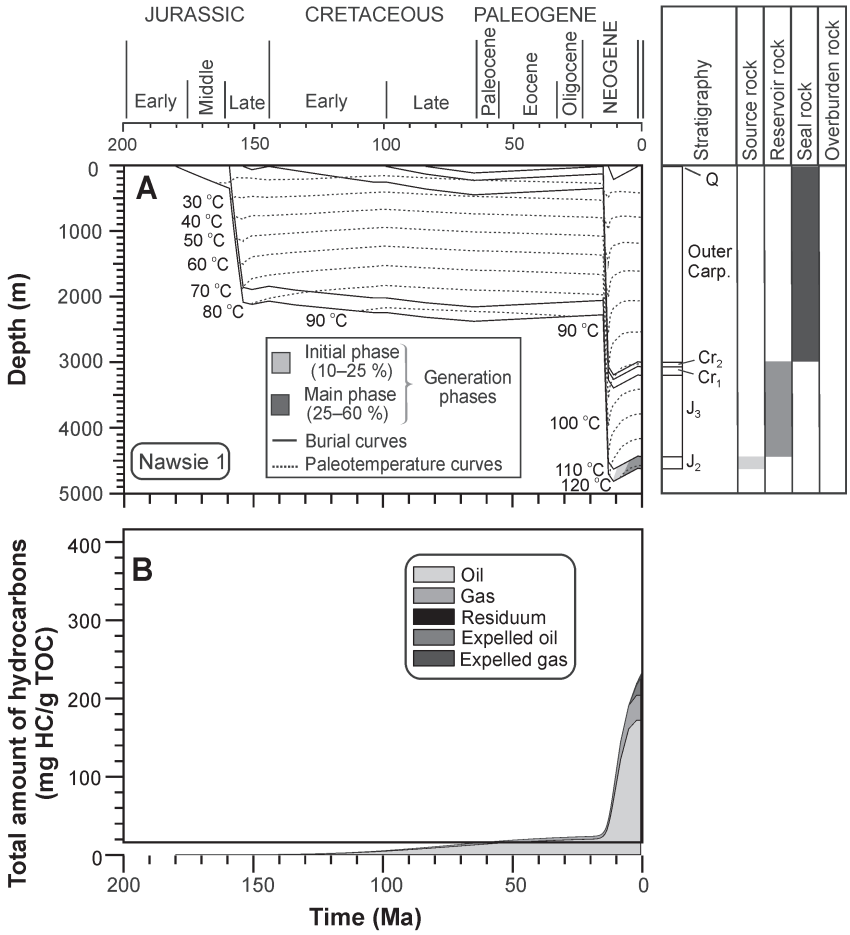

Fig. 6. A — Burial history curves for Jurassic source rocks with generation stages and **B** — total amount of hydrocarbons generated from the Jurassic source rocks in Nawsie 1 well. For the abbreviations see Fig. 2.

phase (10–25 % of generation potential) during the orogenic phase of the Carpathian Overthrust, at a burial depth below 2300 m and at a temperature above 90 °C (Figs. 5, 6A). In that well the source rocks also reached the main phase (25–65 % of generation potential). This phase was reached at the end of the Carpathian thrust belt, with the maximum of 5000 m and the maximum temperature of 120 °C (Fig.6A).

In the remaining wells the initiation of the hydrocarbon generation processes was not obtained, due to maturity being below the threshold of 0.5 $\%R_o$.

The differences in the degree of transformation of kerogen observed in the kinetic modelling also had an impact on the generated hydrocarbon masses. Because the generation process developed only in the Nawsie 1 well, the amount of the obtained hydrocarbon mass was about 220 mg/g TOC (Fig. 6B). In the resulting hydrocarbon mass the liquid phase is dominant. In the remaining wells, the amount of the hydrocarbon mass is minimal, usually below 10 mg HC/g TOC. The expulsion phase is observed only in the Nawsie 1 well (Fig. 6B).

Conclusions

In the Mesozoic profile of the south-eastern part of Poland only the Middle Jurassic strata fulfill the quantitative criteria for source rocks. The hydrocarbon potential of the Middle Jurassic strata is variable, but the maximum values indicate the presence of good and very good source rocks.

The burial and thermal history and generation modelling with a determination of the amount of generated of hydrocarbons revealed that source rocks in the Middle Jurassic strata of the basement of the Carpathian Foredeep were effective only in a part of the study area. The analysis of the distribution of organic matter maturity and its evolution showed that only in the eastern part of this area favourable conditions occurred for mass generation of hydrocarbons. In this part of the study area the source rocks reached the generation process in the early and the main phase of the "oil window". The initial phase of generation was generally reached at the stage of the Outer Carpathian overthrusting on the foreland. Only in the Nawsie 1 well the source rock reached the initial phase of the "oil window" during the deposition of the Upper Cretaceous strata. The main phase of the "oil window" was reached at the orogenic stage of the Carpathian Overthrust. The maximum transformation degree was 60 %. The amount of hydrocarbons generated from source rocks was proportional to the transformation of the organic matter and it reached 220 mg HC/g TOC.

The obtained modelling results clearly indicate that the Middle Jurassic strata, with the heat flow constant over time and equal to that found in recent times, can reach the transformation of organic matter necessary for the initiation of the hydrocarbon generation process only at depths below 5000 m.

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