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RESERVOIR PROPERTIES OF THE PALAEOZOIC–MESOZOIC SEDIMENTARY COVER IN THE KRAKÓW–LUBACZÓW AREA (SE POLAND)

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Abstract: During the 50-year-long intense petroleum exploration of the Palaeozoic–Mesozoic basement of the Carpathian Foredeep, more than 20 oil and gas accumulations have been discovered. The basic and most important oil-bearing levels in the Mesozoic section are Oxfordian carbonates and Cenomanian sandstones. The Nosówka, Zalesie, Trzebownisko–Krasne, Cetynia, Uszkowce and Lachowice hydrocarbon accumulations and numerous hydrocarbon shows have been found in the Palaeozoic horizons. This paper is focused on evaluation of reservoir properties of the entire Palaeozoic–Mesozoic basement of the Carpathian Foredeep and marginal part of the Outer Carpathians for finding new reservoir horizons. 558 rock samples from 51 wells in the Kraków–Lubaczów area were analysed. The well log results from 20 wells were additionally used for the assessment of petrophysical properties. The results of porosimetry measurements and well logs varied in all discussed Palaeozoic and Mesozoic basement horizons of the Carpathian Foredeep. The best reservoir properties were estimated within the Jurassic–Lower Cretaceous carbonate complex. Despite great variability, the carbonate rocks display highest average porosity and good permeability values. The variability of reservoir properties is mostly a result of the character of the reservoir-porous-fracture space. Good reservoir properties were also estimated for the Upper Cretaceous carbonate rocks. However, in most of the analysed wells the potential reservoirs were watered. The Palaeozoic complex displays weaker reservoir properties and they mainly refer only to the Devonian–Lower Carboniferous horizon. The Lower Palaeozoic rocks display weak reservoir properties. Their potential is additionally lowered by negligible range of occurrence and a small thickness. Generally, the gas- and oil-bearing properties of the analysed zone can be attributed only to the Jurassic–Cretaceous reservoir horizons. The remaining horizons, especially the Upper Palaeozoic complex, are only supplement to the reservoir potential of the area.

Key words: reservoir rocks, petrophysical properties, well logging, Palaeozoic, Mesozoic, SE Poland.

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INTRODUCTION

In the Carpathian Foredeep and marginal zone of the Outer Carpathians, between Kraków and Lubaczów, there are over one hundred and twenty hydrocarbon accumulations (Karnkowski, 1999; Myśliwiec *et al.*, 2005; Kotarba *et al.*, 2011a). Most of them are gas fields localized within the Miocene strata (Kotarba & Peryt, 2011; Kotarba *et al.*, 2011a). Oil accumulations and some gas accumulations are mainly connected with the Oxfordian carbonates and Cenomanian sandstones, *i.e.* the two most oil-bearing horizons in the basement of the Carpathian Foredeep and marginal zone of the Outer Carpathians (Maksym *et al.*, 2000; Jawor & Baran, 2001; Myśliwiec *et al.*, 2005; Kotarba, *et al.*, 2011b; Więcław, 2011). Less significant as reservoir rocks are the Upper Cretaceous carbonates and older Palaeozoic complex. The accumulations in these stratigraphic horizons assume the form of various traps, and display different reservoir properties.

The paper is focused on the characteristics of reservoir rocks on the ground of their petrophysical properties, mainly porosity and permeability. These characteristics are based on the results of laboratory analyses and interpretation of well logs. The porosimetric measurements were performed to determine critical parameters of reservoir rock, *i.e.* porosity, permeability and genetic types of reservoirs, and also as paradigms for geophysical interpretation. The well logs interpretation was used for establishing petrophysical parameters in the entire Palaeozoic and Mesozoic sections, as well as depth intervals of best reservoir properties.

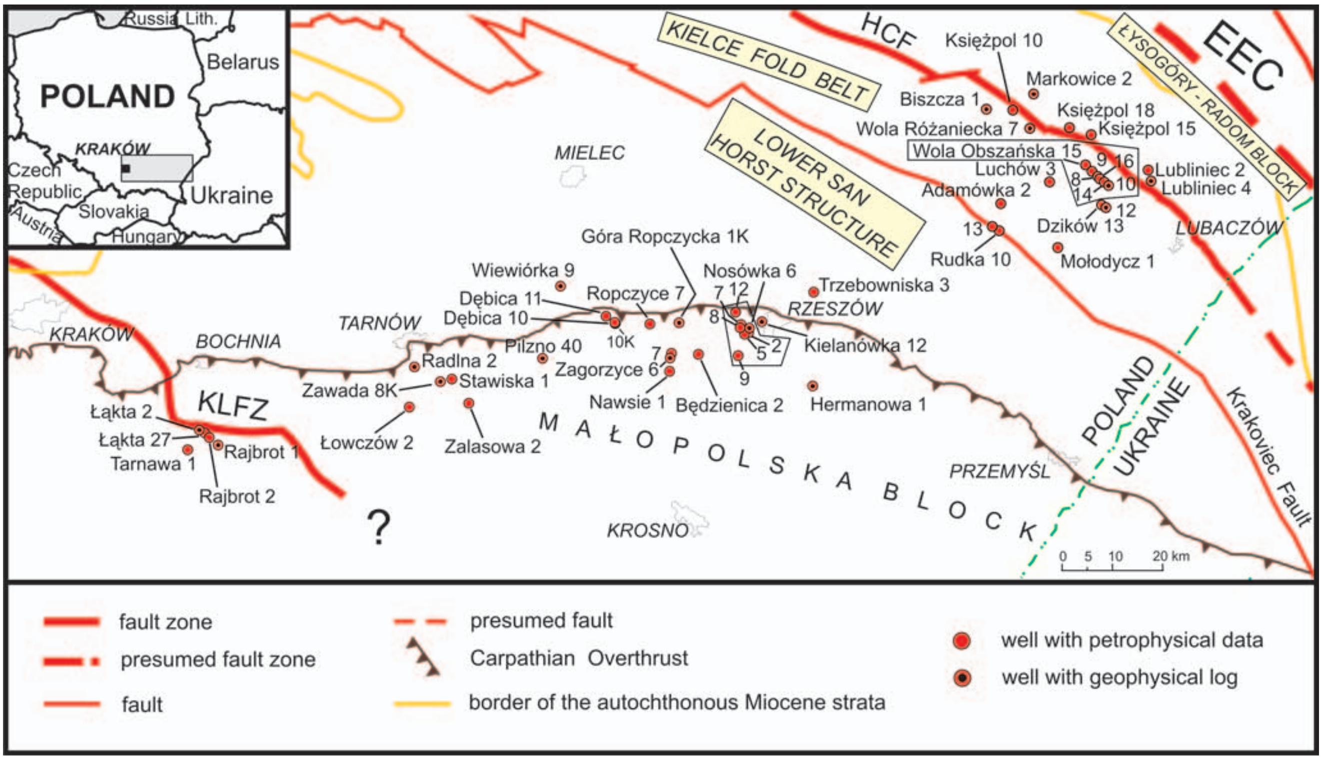

Fig. 1. Sketch tectonic map of the study area with location of main tectonic units and analysed wells. KLFZ – Kraków–Lubliniec Fault Zone, HCF – Holy Cross Fault, EEC – East European Platform, Lith. – Lithuania

The study area covers the Palaeozoic and Mesozoic basement of the Carpathian Foredeep and marginal part of the Outer Carpathians, between Kraków and Lubaczów (Fig. 1).

GEOLOGICAL SETTING

The Palaeozoic, Mesozoic, autochthonous Miocene and Carpathian flysch complex form several structural stages. The Caledonian structural stage consists of the Cambrian, Ordovician and Silurian strata and is incomplete. As a result of multiphase erosion, mainly at the turn of the Silurian and Devonian, and also at the turn of the Devonian and Carboniferous and after the Carboniferous time, those strata were strongly reduced both in their thickness and range of occurrence (Buła & Habryn, *eds*, 2008; Buła & Habryn, 2011). The Cambrian strata are not present in the western part of the Małopolska Block, west of the Lower San River Horst, probably because the analysed area was uplifted at that time (Buła & Habryn, 2011). The Ordovician strata occur in the area between Pilzno and Rzeszów, between Dąbrowa Tarnowska–Szczucin–Busko Zdrój and locally near Lubaczów (Buła & Habryn, *eds*, 2008). The range of the Silurian strata is slightly broader as they are present along the western margin of the Małopolska Block and in the form of sheets south of Proszowice, north of Dąbrowa Tarnowska, between Pilzno–Rzeszów and near Lubaczów (Buła & Habryn, *eds*, 2008).

The Cambrian is represented by black, grey or grey-green claystones and usually sandy mudstones, as well as fine or rarely medium sorted light gray quartzitic sandstones, frequently interbedded or laminated with mudstones and claystones (Buła & Habryn, *eds*, 2008). Fragmentary recognition of the Cambrian sections and its tectonic involvement often renders difficult the determining of its total thickness, which probably exceeds 1,000 m (Buła & Habryn, *eds*, 2008; Buła & Habryn, 2011).

The Ordovician strata in the lower part of the section are represented by quartzitic sandstones, black graptolitic shales and limestones. The Silurian strata formed the black graptolitic shales and siltstones (Moryc & Nehring-Lefeld, 1997; Buła & Habryn, 2011). The thickness of the Ordovician and Silurian complex ranges from tens to over 300 m (Jawor & Baran, 2004; Buła & Habryn, 2011).

The next Variscan structural stage was represented by the Lower Devonian terrigenous rocks, Middle and Upper Devonian carbonates and Lower Carboniferous carbonate-clastic complex (Jawor & Baran, 2004). The thickness of the above stratigraphic horizons was variable: from several dozen to about 150 m in the Lower Devonian strata, and from several hundred metres in the eastern part of the study area to over 1,000 m in the western part in the Middle and Upper Devonian strata. Similar thickness and variability can be found for the Lower Carboniferous clastic and carbonate rocks (Jawor & Baran, 2004). The Upper Palaeozoic strata do not occur in the eastern part of the Małopolska Block (Buła & Habryn, 2011).

In the western part of the Małopolska Block, the Kimmerian structural stage is composed of Permian–Triassic terrigenous-carbonate complex, Middle Jurassic clastic rocks, Upper Jurassic–Lower Cretaceous and Upper Cretaceous carbonates (Dayczak-Calikowska & Moryc, 1988;

Jawor & Baran, 2004; Moryc, 2006; Krajewski *et al.*, 2011). These rock complexes were distinguished as separate units because of structural-tectonic system of the Kimmerian structural stage.

The Permian conglomerates and sandstones, and the Triassic clastic-carbonate complex are separated by an erosional discontinuity from the clastic Middle Jurassic rocks. As a result of early Jurassic erosion, the Permian–Triassic formations occur in the eastern part of the analysed area, towards the south of the Pilzno–Dębica line and towards the north of the Dąbrowa Tarnowska–Mielec line (Buła & Habryn, *eds*, 2008).

The overlying Middle Jurassic formations occur in the almost entire area of the western part of the Małopolska Block (Buła & Habryn, *eds*, 2008). The Upper Jurassic–Lower Cretaceous carbonates are more widespread. Towards the end of the Early Cretaceous period, a shallowing of the basin and uplift and erosion of the area took place. The Upper Cretaceous complex begins with Cenomanian sandstones, but the remaining part of the Cretaceous section consists of carbonates and marls (Jawor & Baran, 2001; Moryc, 2006; Krajewski *et al.*, 2011). The total thickness of the Cretaceous strata does not exceed 800 m (Jawor & Baran, 2004).

The Mesozoic strata in the Kielce Fold Zone are incomplete. Only in the SE part, south of Lubaczów, fragments of the Middle and Upper Jurassic and Cretaceous complex, tens of metres thick, were drilled (Dayczak-Calikowska & Moryc, 1988; Buła & Habryn, *eds*, 2008; Krajewski *et al.*, 2011; Kosakowski *et al.*, in press).

The final structural layout of the Kimmerian stage was a result of the Laramian orogeny. The entire area was covered by marine Miocene sediments, and in the southern part also by the Outer Carpathians flysch.

ANALYTICAL PROCEDURE

Examination of density, porosity and capillary pressure analysis

The coefficient of porosity is the basic index of storage volume of the porous layer. The measurement of the porosity coefficient depends on the measured density and volume, but does not take into account the morphology of pore space. The parametrization of pore space is obtained through the measurement of capillary pressure curves. Capillary pressure curves presented in this work have been obtained with the use of mercury porosimetry. Porosimetric examinations, being independent of technical solutions, are based on the cylindrical model of pore space, in which the pore space is simulated as a bunch of cylindrical capillaries transporting reservoir fluids. The distribution of the equivalent pore diameters and their distribution in the examined pore space are obtained from Washburn's (1921) equation (1):

$$d \quad \frac{\cos(\ )}{4 \quad P} \tag{1}$$

where: d – pore diameter, P – applied pressure, φ – contact angle between the rock and the reservoir fluid, τ – surface tension.

The proportional distribution of pores of a given diameter in the pore space is determined by counting partial volumes of mercury injected to a sample. The measurement consists in injecting mercury to the examined sample under a given pressure, measurement of this pressure and the volume of mercury that has migrated into the sample under this pressure.

Having measured the partial volumes we can calculate the specific surface of the rock using the formula (2):

$$A \quad \frac{(\quad P \quad V)}{(\quad \cos(\ )\ )} \tag{2}$$

where: A – specific surface, ΔV – partial volumes corresponding with the pressure P.

Two cumulative curves: imbibitions and drainage are obtained.

Methodology of measurements

Measurement of density

The density was measured using a helium pycnometer. This apparatus makes use of the perfect ability of helium to penetrate even into smallest sub-micropores. Consequently, a precise value of skeleton density is obtained by this measurement. Having calculated the volumes of the rock skeleton of the sample and its external volume, we can compute the coefficient of open porosity, using the formula (3):

$$por \quad \frac{V_b \quad V_{sk}}{V_b} \quad 100(\%) \tag{3}$$

where: V_b – external volume (cm^3), V_{sk} – volume of rock skeleton (cm^3).

Porosimetric examinations

AutoPore IV mercury porosimeter applied in the examination of pressure enables one to obtain two cumulative curves drawn for the increasing pressures imbibitions curve and drainage curve. Porosimetric measurements allow for the calculation of the following values:

– porosity counted by means of the porosimeter (dynamic porosity). It differs from open porosity since we count the volume of non-wetting fluid that has migrated into the sample. This volume does not include all those sub-micropores whose diameter is too small to allow the penetration of mercury;

– capillary size, which is a standard quantity for evaluation of the quality of reservoir rock. The mean capillary size is calculated as weighted mean average, taking into account weight of the number of pores, not the percentage of pore space;

– specific surface, which represents the overall surface of pores per volume unit of the examined rock, and constitutes the measure of resistance of the porous centre against the transported fluid.

Analysis of the shapes of cumulative curves

In the shape of each capillary pressure curve we may distinguish several characteristic points. The point at which mercury starts migrating into the sample we define as entry pressure, and the corresponding diameter is described as entry diameter. This point determines the largest size of pores occurring in the sample.

The next distinguished point is of great physical importance. In the mathematical criteria it is the inflexion point of the cumulative curve, which, from the point of view of physics, represents a specific value of pressure (or diameter). When it is exceeded, saturation with mercury starts growing very fast at slight changes of pressure. In literature, this point is called threshold pressure or threshold diameter (Webb, 2001; Such *et al.*, 2007).

Examination of effective permeability

Permeability is a property of reservoir rock, based on the ability to transport reservoir fluids. It is numerically characterized by the coefficient of absolute permeability, defined by Darcy's law (4):

$$q \quad \frac{c \quad k \quad A}{} \quad \frac{P}{x} \tag{4}$$

where: A – size of the cross-section, x – length counted in accordance with flow direction, q – quantity of flow, μ – dynamic flow viscosity, $\Delta P/\Delta x$ – gradient of pressure fall along the flow direction, c – numerical constant dependent on units, k – coefficient of permeability.

The necessary conditions of the correct measurement depends on the laminar flow of reservoir fluids and 100% saturation of the examined sample with a given reservoir fluid during the analysis.

WELL LOGGING INTERPRETATION

Reservoir properties, *i.e.* total porosity and permeability and shaliness, were reconstructed with the software GeoWin and application of the INTERLOG (Jarzyna *et al.*, 1999). All applied logs have been established at depth conditions by Geofizyka Kraków Ltd. On such prepared logs a comprehensive interpretation was performed. In the first step of this process the volumetric mineralogical model used for interpretation was assumed on the basis of NPHI-RHOB cross-plots (when logs were performed). Moreover, the descriptions of cores in the output documentation of wells and preliminary evaluation of well logs were used at this stage. Comprehensive interpretation of well logging was made with the use of resistivity logs, gamma ray logs, NPHI logs and acoustic logs. During the interpretation, standard models were selected on the basis of relevant log data. On the ground of the above interpretation, the porosity, permeability, water and hydrocarbon saturations were evaluated. The calculations were made separately for every lithostratigraphic horizon. Reservoir parameters were interpreted using the INTERLOG (Jarzyna *et al.*, 1999) by selecting appropriate models and parameters connected with them. The porosity was estimated on the basis of acoustic logs using Wyllie's equation. The next parameter, *i.e.* shaliness, was defined as the volume content of clay minerals in the layer. To determine the water saturation the Archie or/and Simandoux equation was used. The permeability was estimated on the basis of the Zawisza model. As a result the output logs were obtained, giving information about the mineral composition of the rock matrix, porosity, permeability and value of saturation in flushed zone and virgin zone. On the basis of these results the suitable plots were graphically worked out.

EVALUATION OF PETROPHYSICAL PARAMETERS IN THE PALAEOZOIC STRATA

The evaluation of petrophysical properties of the Palaeozoic strata were performed in two areas – in the western part of the Małopolska Block and in the Kielce Fold Zone (Fig. 1). In the first area petrophysical analyses were made in the wells: Dębica 10, 10K and 11, Łąkta 27, Łowczów 2, Nawsie 1, Nosówka 2, 5, 6, 7, 8, 9 and 12, Radlna 2, Rajbrot 1 and 2, Ropczyce 7, Tarnawa 1, Trzebownisko 3, Zagorzyce 6 and 7, Zalasowa 2, Zawada 8K, and Żegocina 1 (Fig. 1). The total of 306 of core samples were used for evaluating reservoir properties, *i.e.* porosity, permeability and threshold diameter (Table 1). In the Kielce Fold Zone, the total of 103 lab measurements of porosity and 34 measurements of permeability were used for evaluating reservoir properties in the wells: Adamówka 2, Biszcza 1 and 3, Dzików 12 and 13, Luchów 3, Lubliniec 4, Księżpol 10, 15 nad 18, Markowice 2, Mołodycz 1, Rudka 10 and 13, and Wola Obszańska 8, 9, 10, 13, 14, 15 and 16 (Table 1, Fig. 1).

The reservoir rocks were evaluated separately for specific stratigraphic horizons of the Carpathian Foredeep basement. The evaluation was performed using the porosity, threshold diameter and percentage of pores with diameter greater than 1 μm. These diameters and the percent of macropores showed to a potential transport of reservoir fluids through the pore space. The analysed strata were grouped in classes showing similar reservoir and filtration properties. The class of similarity is a group of rocks within analysed geological object that have characteristic common features. The proper assignment to classes of similarity for particular region makes it easy to quickly estimate storing and transportation abilities of reservoir fluids and to determine the trends in changes of reservoir properties. The clustering of analysed rocks into similarity groups enables one to extrapolate the results onto samples, for which no complete database of results exists. The description of these classes is presented in Tables 2 and 3.

Cambrian strata

The Cambrian strata were found only in the marginal zone of the Upper Silesian and Małopolska blocks. In the Cambrian rocks occurring in the Rajbrot 1 (6 samples) and Rajbrot 2 (11 samples) wells the petrophysical properties varied (Table 1). The porosity ranged from 2.81 to 13.6%,

Table 1

Petrophysical characteristics of the Palaeozoic strata in the western part of the Małpolska Block and Kielce Fold Zone

Stratigraphy / Parameters	MAŁOPOLSKA BLOCK Cambrian	MAŁOPOLSKA BLOCK Ordovician	MAŁOPOLSKA BLOCK Silurian	MAŁOPOLSKA BLOCK Devonian	MAŁOPOLSKA BLOCK Carboniferous	KIELCE FOLD ZONE Cambrian	KIELCE FOLD ZONE Silurian
Porosity (%)	2.81 to 13.6 (17) / 7.9 (2)	1.13 and 11.6 (2) / 10.9 (1)	0.51 to 11.0 (6) / 2.2 (1)	0.00 to 16.6 (36) / 3.5 (4)	0.00 to 17.4 (146) / 0.6 (12)	0.53 to 17.1 (87) / 5.4 (21)	1.4 to 12.0 (8) / 6.8 (3)
Permeability (mD)	0.001 to 0.52 (7) / 0.001 (2)	0.001* (2) / 0.001 (1)	0.00 to 63.9 (5) / 0.001 (1)	0.001 to 55.2 (4) / 0.001 (2)	0.001 to 11.6 (53) / 0.01 (6)	0.001 to 54.9 (33) / 0.001 (21)	0.001 (1) / - (1)
Threshold diameter (μm)	1.03 to 10.0 (17) / 2.0 (2)	0.03 to 2.01 (2) / 1.0 (1)	0.13 to 0.42 (6) / 0.3 (1)	0.00 to 30.0 (36) / 0.6 (4)	0.01 to 10.0 (42) / 0.2 (6)	0.001 to 30.0 (85) / 0.2 (21)	0.10* (5) / 0.1 (2)

* – all results have the same value. Range of petrophysical parameters is given as numerator; median values in denominator, in parentheses: number of samples from wells (numerator) and number of sampled wells (denominator)

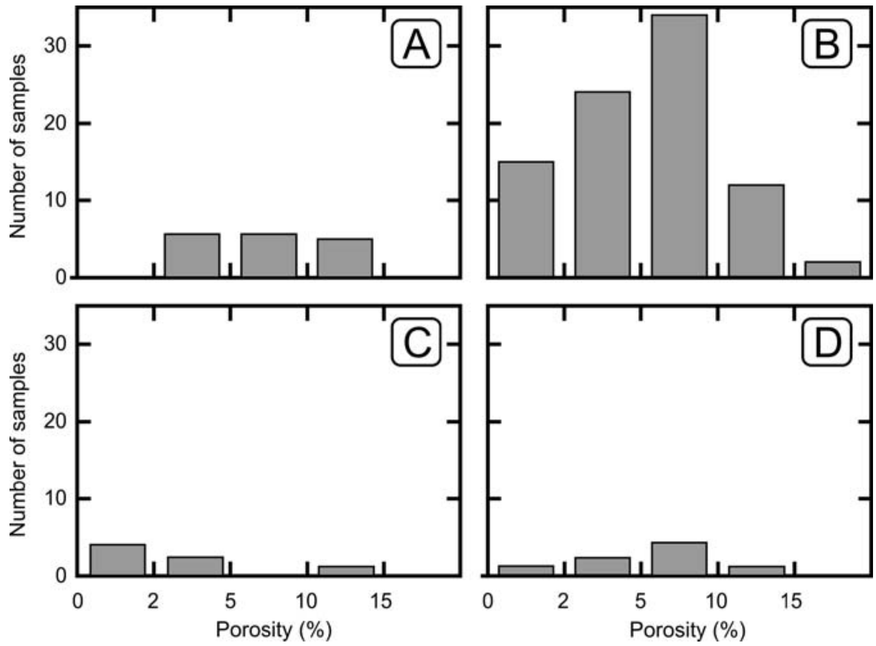

Fig. 2. Frequency histograms of porosity range of the Cambrian strata in (**A**) the western part of the Małopolska Block and (**B**) Kielce Fold Zone, and Silurian strata in (**C**) the western part of the Małopolska Block and (**D**) Kielce Fold Zone

with median equal to 7.9% (Table 1, Fig. 2A). Better porosity was observed in the Rajbrot 2 well. The threshold diameters varied from 1 to 3 μm, though in the bottom part of the strata (4,148.3–4,181.1 m) this parameter increased to 6–10 μm (Table 1, Figs 3A, 4A). Such values caused non-zero values of permeability, which was confirmed by plug samples investigations. The Cambrian rocks in these two wells represented the porous–fracture type of resorvoir.

In the Kielce Fold Zone almost all of the analysed samples (87 samples) come from the Cambrian strata (Table 1, Fig. 2B) and for all of the the density, porosity, as well as the results of the mercury porosimetry were analysed. Permeability analyses were performed for 33 samples only (Table 1). Generally, the analysed rocks were porous. The frequency diagram of porosity is shown in Fig. 2B. The modal value of porosity was found to be between 5 and 10% and the filtration properties appeared to be poor. Cross-plot permeability–porosity shows that only 30% of analysed samples display a measurable permeability (Fig. 5). For these samples the permeability equal to 0.001 mD means no permeable sample. Measured permeability value equal to 55 mD also represents a pure fracture permeability (Fig. 5). These rocks are single porosity (intergranular), single permeability (fracture) rocks. The analysis of threshold diame-

Table 2

Classes of similarity for the Palaeozoic clastic rocks

Type	Porosity (%)	Threshold diameter (µm)	Type description
I	>10	0.01–12	Very good porosity, double or fracture permeability
II	5–10	0.01–12	Medium porosity, double or fracture permeability
III	2–5	0.01–12	Low porosity, double or fracture permeability
IV	<2	<0.2	Sealing rocks

ters frequency diagram indicates that the values are very low, the median is 0.15 µm, and only 25% of the measurements are above 1 µm (Table 1, Fig. 3A). The filtration properties of the Cambrian sediments are limited to fractures.

Generally, the petrophysical properties of the examined strata assessed on the basis of the results from two wells from the western part of the Małopolska Block and 21 wells from the Kielce Fold Zone, show that the Cambrian clastic rocks can be classified as the II class of similarity (Table 1).

Ordovician strata

The Ordovician strata were represented only by two samples from the Nosówka 9 well (western part of the Małopolska Block) (Fig. 1). The measured porosity was high, *i.e.* 1.13 and 13.6% (Table 1). The threshold diameters were found to be 0.03 and 2 µm. The permeability is very low, to 0.001 mD in both samples. The results are not representative for the assessment of the Ordovician strata characteristics.

Silurian strata

The Silurian strata were characterized by 6 samples from the Zawada 8k well in the western part of the Małopolska Block and 8 samples from Markowice 2, Wola Obszańska 10 and Wola Obszańska 13 wells in the Kielce Fold Zone (Table 1, Fig. 1). The rocks have low porosities and microporous character of pore space (Fig. 2C, D). The measured values vary widely, from 0.51 to 11.0% in the Małopolska Block and from 0.53 to 17.1% in the Kielce Fold Zone, respectively (Table 1). The threshold diameters also vary widely, especially in the Kielce Fold Zone (Table 1). The cross-plot of threshold diameter– porosity indicated good sealing properties (Fig. 4B). The permeability was non-zero, which was attributed to the presence of microfractures. Measured permeability value equal to 63.9 mD represents the pure fracture permeability (Table 1).

The Silurian rocks can be classified as the III class of similarity – low porous rocks playing subordinate role as reservoir rocks (Table 2).

Devonian strata

In the study area, the Devonian strata occurred only in the western part of the Małopolska Block. The Middle and Upper Devonian carbonate complex was investigated in the Hermanowa 1 (4 samples from depth interval 4,545.6–4,584.7 m), Nosówka 6 (12 samples from depth interval 3,980.1–4,019.7 m), Nosówka 9 (4 samples from 4,061.5–4,062.5 m) and Trzebownisko 3 (16 samples from 2,010.1–2,068.5 m) wells. The carbonates in the entire area were low- porous and non-permeable. The porosity widely ranged from *ca.* 0.0 to 16.6%, with median equal to 3.33% (Table 1). The measured threshold diameters were usually equal to or lower than 2 µm (Figs 3C, 4C, 6A). Only in the Trzebownisko 3 well the rocks did demonstrate higher porosity, up to 16.6% (Fig. 6) and higher threshold diameters, up to 30 µm (Table 1, Fig. 3C). These parameters indicate good filtration properties in classes I –III (Table 2). The permeability in the Devonian carbonates was measured only for four samples, equalling to 0.001 mD, and 55 mD in the one case (Table 1).

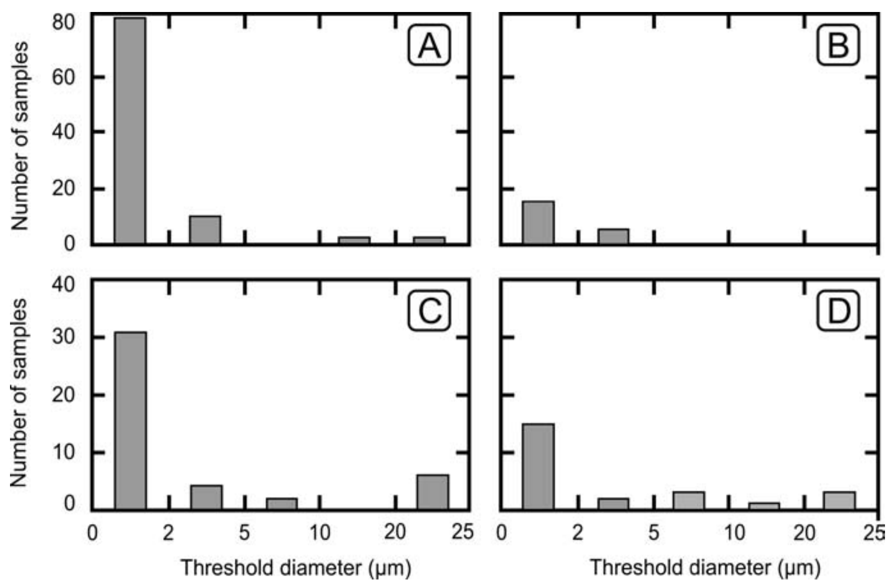

Fig. 3. Threshold diameter frequency histograms in the (**A**) Cambrian, (**B**) Silurian, (**C**) Devonian, and (**D**) Carboniferous strata

Table 3

Classes of similarity for the Carboniferous carbonate rocks

Type	Porosity (%)	Threshold diameter (μm)	% of pores (diameter >1 μm)	Type description
I	>15	>20	>80	Very good reservoir and filtration rocks
II	>15	>3	30–60	Very good reservoir, moderate filtration rocks
III	5 - 10	>4	>50	Good reservoir, poor filtration rocks
IV	5 - 10	3–4	30–60	Good reservoir, very poor filtration rocks
V	>5	2–3	<50	Moderate reservoir, very poor filtration rocks
VI	5 - 10	<2	<30	Porous, non permeable rocks
VII	<5	<1	<30	Low porosity, zero permeability rocks

Table 4

Classes of similarity for the Mesozoic carbonate rocks

Type	Porosity (%)	Threshold diameter (μm)	% of pores (diameter >1 μm)	Type description
I	>15	>20	>80	Very good reservoir and filtration rocks
II	>15	>3	30–60	Very good reservoir, moderate filtration rocks
III	5–10	>4	>50	Good reservoir, poor filtration rocks
IV	5–10	3 - 4	30–60	Good reservoir, very poor filtration rocks
V	>5	2 - 3	<50	Moderate reservoir, very poor filtration rocks
VI	5–10	<2	<30	Porous, non permeable rocks
VII	<5	<1	<30	Low porosity, zero permeability rocks

Carboniferous strata

Like in the Devonian strata, the Carboniferous carbonates occur only in the western part of the Małopolska Block. The petrophysical properties of these carbonates were represented by the largest population of samples collected from the Palaeozoic complex. The investigations were performed for 146 core samples from wells: Dębica 10 (3 samples, 3,513.3–3,587.05 m), Dębica 10K (3 samples, 3,513.2–3,587.05 m), Łowczów 2 (68 samples, 3,470.7–4,066.9 m), Nosówka 2 (4 samples, 3,418.3–3,422.6 m), Nosówka 5 (2 samples, 3,582.0–3,582.7 m), Nosówka 6 (22 samples, 3,735.8–3,978.5 m), Nosówka 7 (12 samples, 3,525.5–3,573.9 m), Nosówka 8 (2 samples, 3,809.4–3,809.9 m), Nosówka 9 (6 samples, 4,061.5–4,062.5 m), Nosówka 12 (4 samples, 3,914.4–3,932.3 m), Rajbrot 1 (1 sample, 3,504.2 m), Rajbrot 2 (5 samples, 2,796.2–3,680.8 m), Zagorzyce 6 (4 samples, 4,520.0–4,591.0 m) and Żegocina 1 (19 samples, 3,252.5–3,507.6 m) (Fig. 1).

The analysed rocks show very poor reservoir properties. The porosity was lower than 1% for the major part of investigated rocks (Fig. 6B). Only 5% of analysed population of samples do show a porosity higher than 5%. The threshold diameter widely ranged from *ca.* 0.01 to 10.0 μm (Fig. 4D). Despite such variability, poor samples prevailed. The median

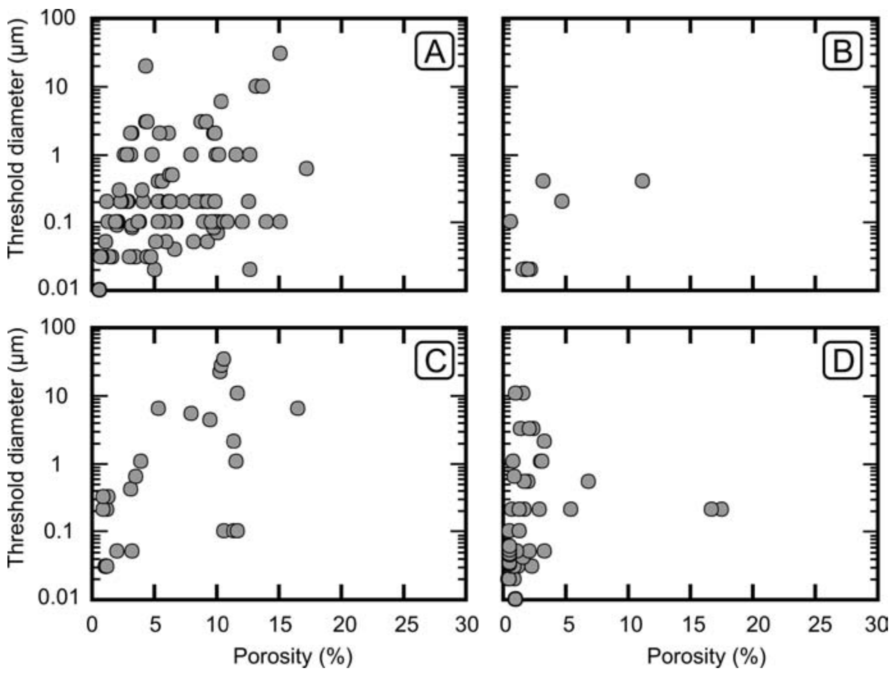

Fig. 4. Threshold diameter versus porosity in the (**A**) Cambrian, (**B**) Silurian, (**C**) Devonian, and (**D**) Carboniferous strata

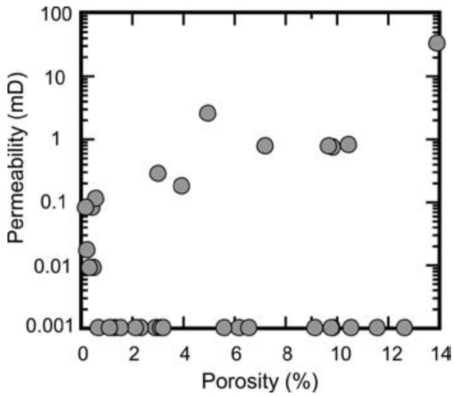

Fig. 5. Permeability versus porosity in Cambrian strata in the Kielce Fold Zone

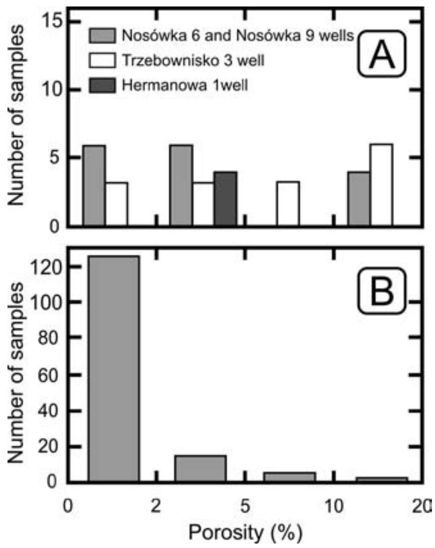

Fig. 6. Frequency histograms of porosity range in the (**A**) Devonian (Trzebownisko 3, Nosówka 6 and Nosówka 9 wells) and (**B**) Carboniferous strata

of the entire population was only 0.2 μm and was the lowest among the Palaeozoic strata (Table 1). The cross-plot of porosity – threshold diameter indicated good sealing properties (Fig. 4D). Only a small part of the measured samples does display good reservoir properties. Permeability analyses were performed for 53 samples. Only for 2 samples permeabilities were greater than 1 mD and fracture permeability was observed. For other samples permeabilities ranged from 0.001 to 0.2 mD (Table 1). The analysis of obtained threshold diameters (Fig. 3D) and measured values of specific surfaces allow us to qualify the Carboniferous samples as non-porous rocks (Table 3).

EVALUATION OF PETROPHYSICAL PARAMETERS IN THE MESOZOIC STRATA

The petrophysical properties of the Mesozoic strata were assessed on the basis of results of 292 core samples

Table 5

Petrophysical characteristics of the Mesozoic strata in the western part of the Małopolska Block

Parameters \ Stratigraphy	U. Jurassic-L. Cretaceous	Upper Cretaceous
Porosity (%)	0.00 to 18.3 (281) / 1.3 (12)	0.38 to 9.62 (9) / 1.5 (2)
Permeability (mD)	0.00 to 436.0 (61) / 0.001 (8)	n.m.
Threshold diameter (μm)	0.00 to 100.0 (182) / 0.3 (12)	0.02 to 3.00 (7) / 0.03 (2)

U. – Upper; L. – Lower; n.m. – not measured. Range of petrophysical parameters is given as numerator; median values in denominator, in parentheses: number of samples from wells (numerator) and number of sampled wells

from 12 wells: Dębica 10K and 11, Góra Ropczycka 1K, Lubliniec 2 and 4, Łąkta 27, Nawsie 1, Radlna 2, Rajbrot 2, Ropczyce 7, Tarnawa 1, Zagorzyce 6 and 7, and Zawada 8K (Tables 1, 2, Fig. 1). The petrophysical properties were determined on the basis of a class of similarity presented in Table 4.

Upper Jurassic–Lower Cretaceous strata

The Upper Jurassic and Lower Cretaceous carbonates create one reservoir horizon and therefore their reservoir properties will be discussed together. These horizons were the best represented, *i.e.* 210 core samples of Upper Jurassic carbonates from 12 wells, and 71 core samples of Lower Cretaceous carbonates from Zagorzyce 7 well were examined (Table 5, Fig. 7A, B). The research material is derived from the western part of the Małopolska Block only. These stratigraphic horizons had the best petrophysical properties in the entire Mesozoic section (Darłak *et al.*, 2004; Gliniak *et al.*, 2004, 2005). The Upper Jurassic–Lower Cretaceous carbonates in the whole of the area were low-porous and non-permeable (Fig. 8). The measured values of porosity varied greatly from 0.0 to 18.3%, with median equal to 1.3% (Table 5). In samples from the Upper Jurassic 50% of values were below 2% (Fig. 7A), whereas in the Lower Createaceous samples 85% was below 2wt% (Fig. 7B). Likewise, in the Upper Jurassic carbonates the low values of threshold diameter, *i.e.* below 2 μm, were about 65% of the analysed population, and in the Lower Cretaceous they constituted 95% of the population (Table 5, Fig 9A, 9B). The major part of the Upper Jurrasic (–Lower Cretaceous) strata was composed of non-permeable rock (Figs 7A, 7B, 8). The measured values ranged from 0 up to 436 mD (Table 5, Fig. 8). Despite such variability, poor samples prevailed and the median for the entire population was only 0.01 mD (Table 5). These permeability properties were often upgraded by a system of fractures. The authors' investigations have shown that filtration properties resulting in microporous structure of pore space was critical for the Jurassic and Cretaceous rocks. Only the samples grouped in class I did represent good reservoir and filtration parameters. However, it should be noted that the entire database consisted of only 13 samples (and only 1 in the Cretaceous rocks).

The analysed rocks belonged to all classes of similarity. Types I and II were found in the Lubliniec 4 and 9, Radlna 2, Rajbrot 2, Tarnawa 1 and Zawada 8k wells (Table 4). Additionally, type III was found in the Nawsie 1, Ropczyce 7 and Zagorzyce 7 wells. They could store reservoir fluids but the whole transport must have been realized by the fractures. In other words, they were porous-fracture reservoir rocks. Possible accumulations of hydrocarbons in such type of rocks were connected only with fractures.

Upper Cretaceous strata

The Upper Cretaceous carbonates were represented only by 9 core samples from Dębica 11 and Zagorzyce 7 wells (Table 5, Fig. 7C). The carbonates show low porosity, which usually does not exceed 2% (Table 5). The maximum value of porosity – 9.66%, was measured in the Zagorzyce 7 well (Table 5, Fig. 1). Very low values are also observed in the threshold diameter. The measured values did not exceed 2 μm and the median was only 0.03 μm (Table 5, Fig. 9C).

Generally, the results show that the Upper Cretaceous carbonates made up the VI and VII classes of similarity rocks (Table 5).

According to the obtained results the basic type of reservoir in the Mesozoic sediment was a porous–fracture reservoir. Hydrocarbons were stored in pore space, and the transport was realized by a system of fractures.

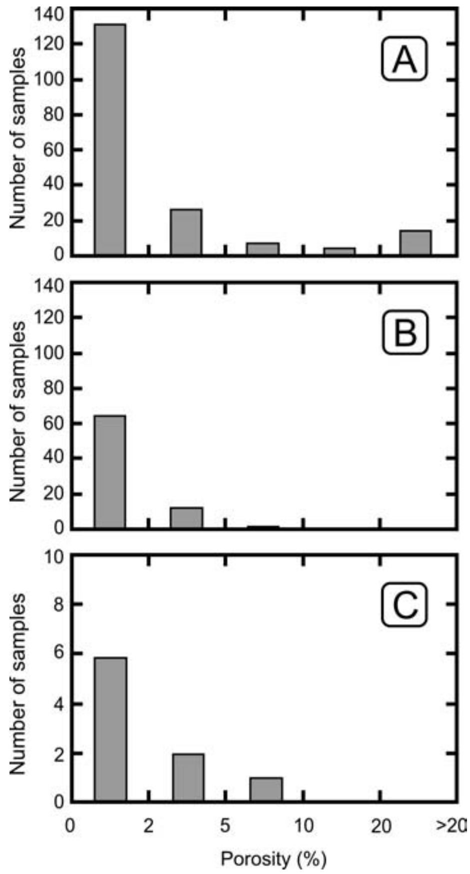

Fig. 7. Frequency histograms of porosity range of the (**A**) Upper Jurassic, (**B**) Lower Cretaceous, and (**C**) Upper Cretaceous strata

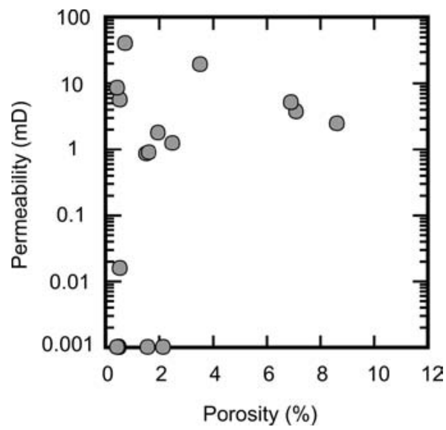

Fig. 8. Permeability versus porosity in the Upper Jurassic strata

RESULTS OF WELL LOGS INTERPRETATION FOR THE ASSESSMENT OF RESERVOIR PROPERTIES

The analysis of reservoir properties of Palaeozoic and Mesozoic strata interpreted on the basis of well logs was performed for 20 wells in the Kraków–Lubaczów area (Fig 1). The wells were localized in the western part of the Carpathian Foredeep, covering its Palaeozoic and Mesozoic basement. The uneven distribution of analysed wells reflects the incompleteness of sedimentary sections and ranges of specific stratigraphic horizons in the Palaeozoic and Mesozoic strata. Moreover, such a distribution hinders correlation of specific stratigraphic horizons.

The analysis of petrophysical properties was carried out for the Palaeozoic strata, and for Mesozoic strata, separately.

Cambrian strata

The Cambrian strata were analysed in 4 wells located in the Kielce Fold Zone – Dzików 12, Wola Różaniecka 7, Biszcza 1 and Wola Obszańska 10 wells, and two wells – Lubliniec 2 and Markowice 2, located in the marginal part of the Kielce–Radom Block (Fig. 1).

In the Wola Różaniecka 7 and Biszcza 1 wells, located in the north-western part of the Kielce Fold Zone, drillings were performed in the Cambrian strata represented by quartzite sandstones and shales (also dated for the Middle Cambrian). They turned out to be practically non-porous and impermeable (1–1.5 mD). In the Dzików 12 and Wola Obszańska 10 wells, located south-east of Tarnogród (Fig. 1), the Cambrian claystones and quartz-sandstones also display poor porosity and permeability. The obtained porosity values oscillated between 3 to 4%. In the Lubliniec 2 and Markowice 2 wells, the Cambrian strata taking the form of quartzite sandstones and shales, do not reveal reservoir

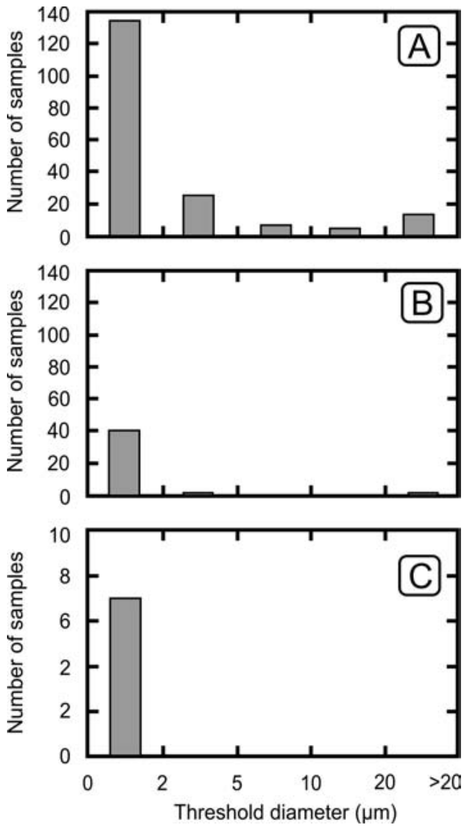

Fig. 9. Threshold diameter histograms in the (**A**) Upper Jurassic, (**B**) Lower Cretaceous, and (**C**) Upper Cretaceous strata

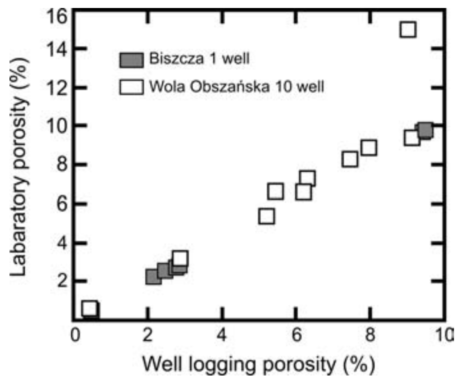

Fig. 10. Well logs and results of comprehensive interpretation in the Hermanowa 1 well, depth interval 4,050–5,080 m

qualities. Both measurements made on cores, and the values obtained during the interpretation of well log curves support this conclusion (Fig. 9).

Ordovician–Silurian strata

The Ordovician and Silurian clastic and carbonate rocks were analysed mainly in the western part of the Małopolska Block. The Palaeozoic strata were also represented by Devonian and Carboniferous beds in this area. In the Kielce Fold Zone, only the Silurian strata were analysed in one well, *i.e.* Wola Obszańska 10 well (Fig. 1).

The Lower Palaeozoic in the Małopolska Block shows very low porosity and permeability values (Figs 2–4). The Ordovician siltstones and sandstones were recognised in the Hermanowa 1 and Kielanówka 12 wells only. They display weak reservoir parameters, low porosity and high silting. The clayey Silurian beds measured in the Zagorzyce 6 well also showed porosity below some percent and were impermeable. Very limited range of occurrence of Ordovician and Silurian strata in the analysed area, basically reduced to the Pilzno–Rzeszów area and north of Dąbrowa Tarnowska (Buła & Habryn, 2011), caused that the Lower Palaeozoic horizons were interesting as potential reservoir rocks. Mainly the Silurian siltstones had the best sealing properties, which in the view of lack of the Cambrian strata and the observed weak source character of Lower Palaeozoic rocks (Więcław *et al.*, 2011; Kosakowski & Wróbel, in press), also resulted in low evaluation of these stratigraphic horizons.

Devonian–Carboniferous strata

The Upper Palaeozoic strata covered nearly the entire analysed area of the Carpathian Foredeep basement (Jawor & Baran, 2004), and thus were represented by a more numerous population of wells. The well logging was performed for a relatively more numerous population of wells representing zones of most intense petroleum exploration. In the Tarnów region there is Radlna 2 well, where Carboniferous carbonates containing mobile hydrocarbons reveal good petrophysical properties. The lack of correlation with other wells in that zone made the evaluation of petrophysical properties of the Carboniferous strata impossible. The Rzeszów zone was better represented. The petrophysical properties were obtained on the basis of well logs performed in the Kielanówka 12, Nosówka 6, Hermanowa 1, and Zagorzyce 6 wells (Figs 1, 11, 12). The results obtained in wells Zagorzyce 6 and Hermanowa 1 for each layer are shown in Fig. 13. The Carboniferous beds in this zone had weak reservoir properties. Slightly better reservoir parameters were found only in the near-top parts of the carbonaceous complex in the Góra Ropczycka 1K well.

The Devonian beds were analysed in the Kielanówka 12 and Hermanowa 1 wells. Like in Carboniferous rocks, the Devonian carbonaceous beds are weakly permeable and weakly porous (Florek & Zacharski, 2008). In the Hermanowa 1 well, a slightly increased porosity and hydrocarbon saturation were locally observed in the Lower Devonian strata (Fig. 11).

Upper Jurassic–Lower Cretaceous and Upper Cretaceous strata

Similar to the Palaeozoic horizons, the Mesozoic rocks also reveal high variability of their reservoir properties. The Triassic strata, analysed in the Hermanowa 1, Nosówka 6, Zagorzyce 6 and Łąkta 2 wells, show weak reservoir properties, *i.e.* low porosity and weak permeability (Figs 7, 8, 12). The clastic Triassic beds locally revealed good petrophysical properties in the Pilzno 40 well. Unfortunately, this horizon was watered.

The obtained geophysical results show that the Upper Jurassic–Lower Cretaceous and Upper Cretaceous strata display the best reservoir properties among the Palaeozoic–Mesozoic basement in the Kraków–Rzeszów area. The car-

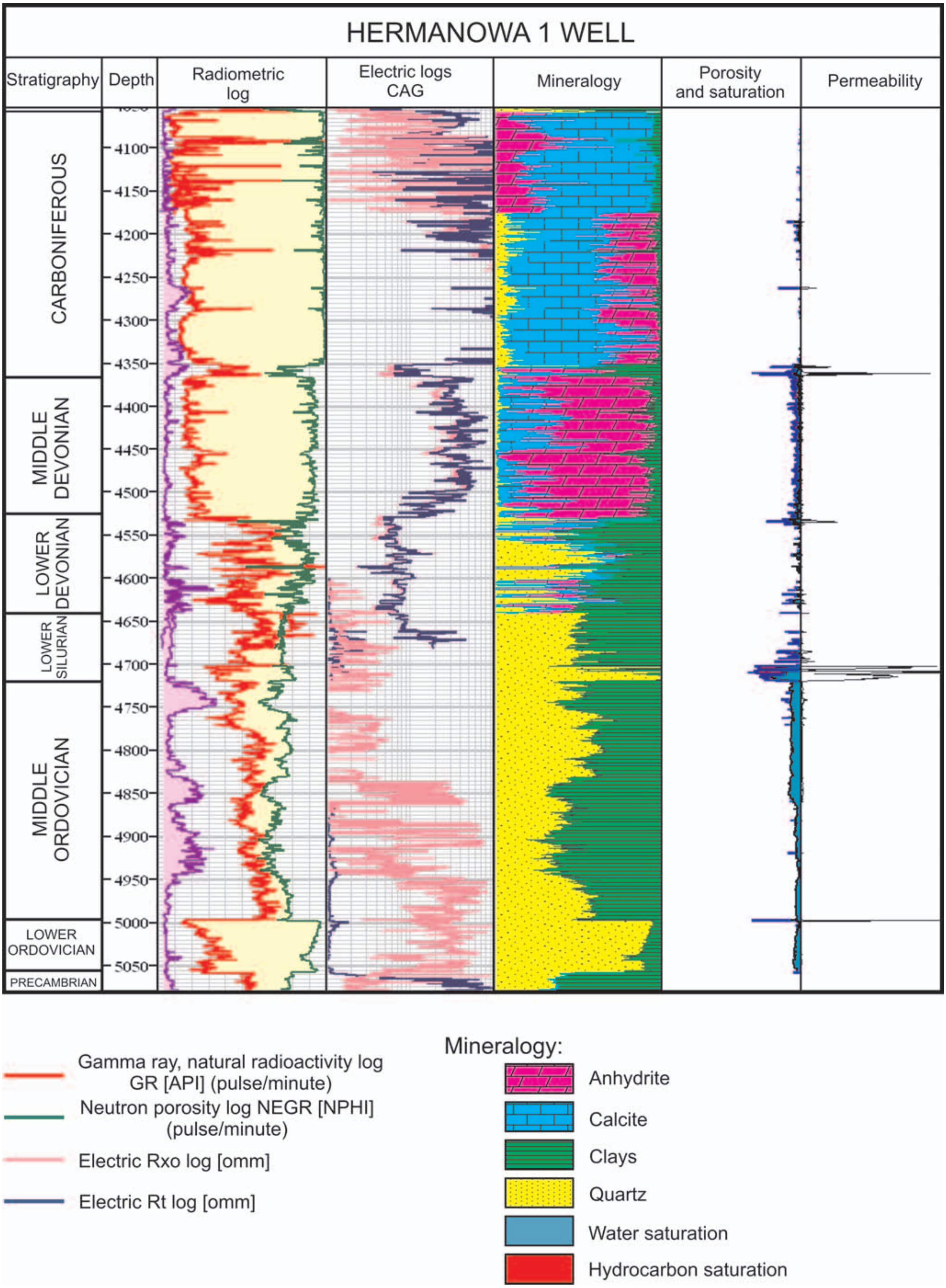

Fig. 11. Well logs and results of comprehensive interpretation in the Zagorzyce 6 well, depth interval 2,700–4,180 m

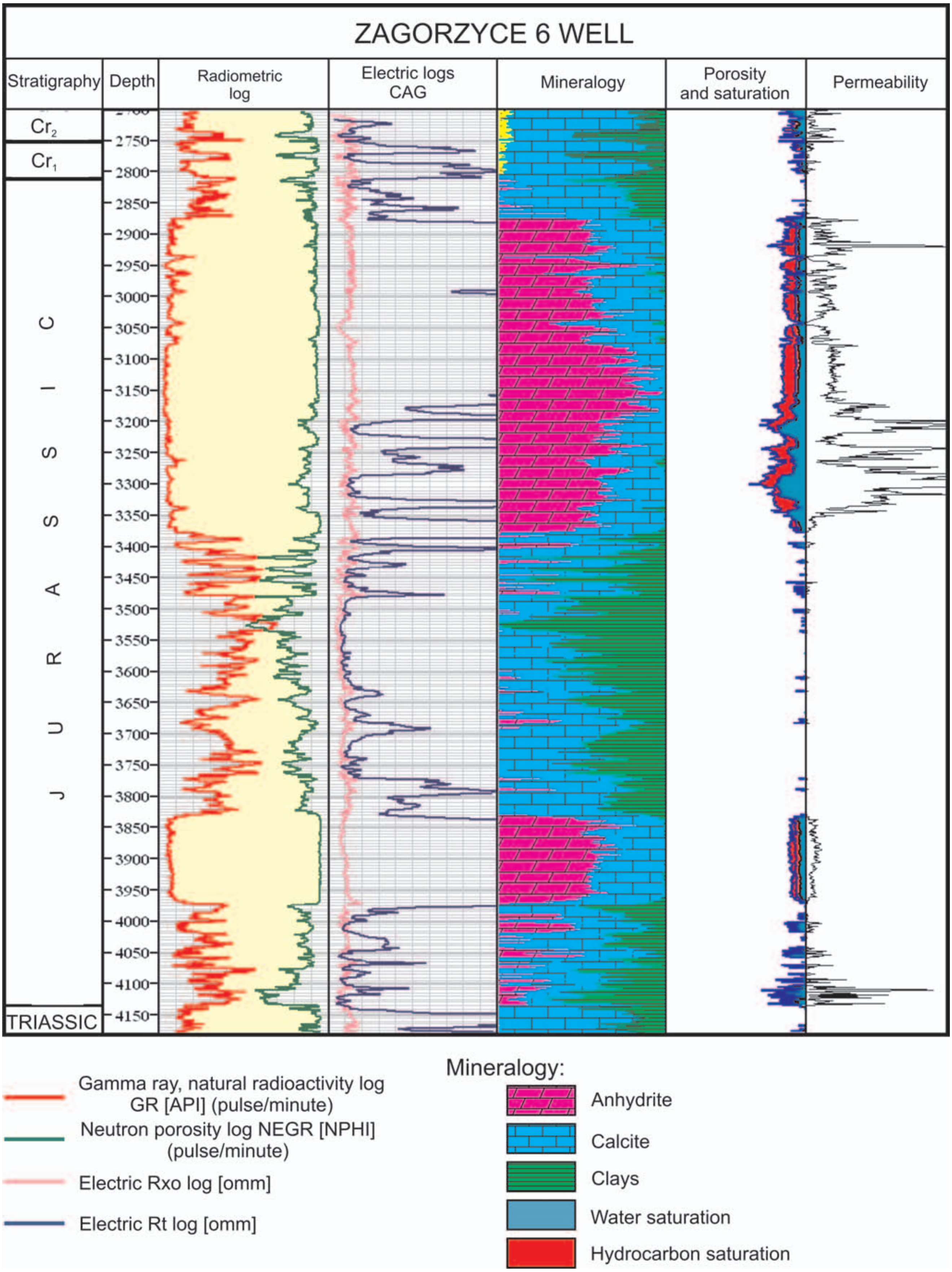

Fig. 12. Laboratory porosity *versus* well logging porosity in Cambrian strata in the Wola Obszańska 10 and Biszcza 1 wells. Explanation of geophysical curves and mineralogy see Fig. 1

bonate complex of the Upper Jurassic–Lower Cretaceous shows variable reservoir properties. In the southernmost wells, *i.e.* in the contact area with the Upper Silesian Block in the Rajbrot 1 and Łąkta 2 wells, the carbonate rocks exhibit very low porosity and practically no permeability. Slightly better properties could be observed in the Tarnów area, where in the Upper Jurassic carbonates complex, analysed through the Zawada 8K and Radlna 2 wells, the porosity was even 10–15%, and the permeability was good. The observed porosities varied from some to ten or so percent in the Dębica 10K, Ropczyce 7 and Góra Ropczycka 1K wells in the Dębica area and farther to the east, as well as in the Wiewiórka 9 well (north of Dębica). The porosity of the Lower Cretaceous beds in the Zagorzyce 6 well was even 20% (Fig. 12). Generally, the Upper Jurassic (–Lower Cretaceous) complex was well permeable. Unfortunately, no samples were available from the Zagorzyce 6 well cores of this interval. Therefore, it is impossible to correlate the results of the geophysical interpretation of laboratory data.

The Upper Cretaceous beds drilled in the Zawada 8K, Radlna 2, Wiewiórka 9, Zagorzyce 6 (Fig. 12) and Pilzno 40 wells also display variable reservoir properties. Maximum porosity of 10–12% was noted in the Pilzno 40 well, though these reservoirs were watered. Similarly, in the Radlna 2 well the good reservoir conditions were accompanied by watering. In the remaining wells the Upper Cretaceous beds reveal weak reservoir qualities.

CONCLUSIONS

The porosimetry measurements and well log results revealed high variability of reservoir properties in all the analysed horizons of the Palaeozoic and Mesozoic strata of the Carpathian Foredeep basement. Well logs interpretation supplements the laboratory tests performed to determine the properties of reservoir rocks. Therefore, it was impossible to correlate the obtained results. The analysis of data and the well cores from adjacent wells reveals that the values obtained in the course of interpretation have lower values than those obtained during laboratory measurements. However, they retain the same order of magnitude and may provide a reliable source of information on reservoir properties of the analysed sediments.

The findings indicate that the best petrophysical properties have carbonate rocks of the Upper Jurassic–Lower Cretaceous. They have the highest porosity, up to 18 %, and the highest measured permeability among the analysed stratigraphic complexes equal to 436 mD. Unfortunately, the average values of these parameters are very low, for porosity the median is 1.3% and for permeability only 0.01 mD. Studies has also shown that the filtration properties resulted in microporous structure of pore space. The permeability properties were often upgraded by a system of fractures. Similar reservoir properties, though based on a small population of samples, are observed in the Upper Cretaceous strata. The median values for porosity was 1.5% and similar for the underlying complex of the Upper Jurassic–Lower Cretaceous. Unfortunately, potential reservoir horizons were watered in most analysed wells.

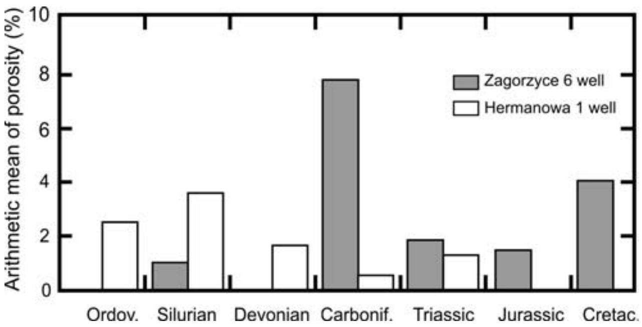

Fig. 13. The results of interpretation of porosity based on well logging in the Zagorzyce 6 and Hermanowa 1 wells. Ordov. – Ordovician; Carbonif. – Carboniferous; Cretac. – Cretaceous

Generally, the obtained results reveal that the Mesozoic carbonate rocks in the analysed area represented a reservoir of the porous–fracture type.

The Palaeozoic complex shows weaker petrophysical properties and is mainly referred to the Devonian–Lower Carboniferous strata. The Lower Palaeozoic horizons display poor reservoir parameters and their range of occurrence was strictly limited to narrow zones in the Tarnów and Rzeszów areas. Therefore, these horizons did not have big reservoir potential.

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REFERENCES

Buła, Z. & Habryn, R. (*eds*), 2008. *Geological-structural atlas of the Palaeozoic basement of the Outer Carpathians and Carpathian Foredeep*. (In Polish, English summary). Państwowy Instytut Geologiczny, Warszawa, 75 pp.

Buła, Z. & Habryn, R., 2011. Precambrian and Palaeozoic basement of the Carpathian Foredeep and the adjacent Outer Carpathians (SE Poland and western Ukraine). *Annales Societatis Geologorum Poloniae*, 81: 221–239.

Darłak, B., Włodarczyk, M. & Gliniak, P., 2004. Badania właściwości zbiornikowych dolnej kredy i górnej jury przy zastosowaniu sieci neuronowych w obszarze Bochnia–Dębica. (In Polish). *Nafta–Gaz*, 60: 457–462.

Dayczak–Calikowska, K. & Moryc, W., 1988. Evolution of sedimentary basin and paleotectonics of the Middle Jurassic in Poland. (In Polish, English summary). *Kwartalnik Geologiczny*, 32: 117–136.

Florek, R. & Zacharski, J., 2008. Wykształcenie węglanowego kompleksu dewońsko-karbońskiego (rejon Bochnia–Tarnów) w aspekcie poszukiwań złóż węglowodorów. (In Polish). In: *Konferencja naukowo-techniczna "Ropa i gaz a skały węgla-*

nowe południowej Polski", Czarna, 16-18 kwietnia, 2008, p. 11.

Gliniak, P., Gutowski, J. & Urbaniec, A., 2005. Budowle organiczne w utworach górnej jury przedgórza Karpat – aktualny stan rozpoznania na podstawie interpretacji materiałów sejsmicznych i wiertniczych w kontekście poszukiwań złóż węglowodorów. (In Polish). *Tomy Jurajskie*, 3: 29–43.

Gliniak, P., Laskowicz, R., Urbaniec, A., Leśniak, G. & Such, P., 2004. The facies development and reservoir properties in Late Jurassic carbonate sediments in the central Carpathian foreland. In: Swennen, R., Roure, F. & Granath, J. (*eds*), *Deformation, fluid flow and reservoir appraisal in foreland fold and thrust belts*. *American Association of Petroleum Geologists Hedberg Series*, 1: 347–355.

Jarzyna, J., Bała, M. & Zorski, T., 1999. *Metody geofizyki otworowej – pomiary i interpretacja*. (In Polish).Wydawnictwo Naukowo-Dydaktyczne, Kraków, 249 pp.

Jawor, E. & Baran, U., 2001. Cenomanian sandstones: recognition and exploratory prospects. (In Polish, English summary). *Nafta-Gaz*, 57: 79–97.

Jawor, E. & Baran, U., 2004. Geological setting and characteristics of Carboniferous strata in the southern part of the Małopolska block. (In Polish, English summary). In: Kotarba, M. J. (*ed.*), *Hydrocarbon generation potential of Carboniferous rocks in the southern part of the Upper Silesian and Małopolska blocks*. Towarzystwo Badania Przemian Środowiska "Geosfera", Kraków: 25–48.

Karnkowski, P., 1999. *Oil and gas deposits in Poland*. Geosynoptics Society "Geos", Kraków, 380 pp.

Kosakowski, P. & Wróbel, M., in press. Burial history, thermal history and hydrocarbon generation modelling of the Lower Palaeozoic source rocks in the Kraków–Rzeszów area (SE Poland). *Geologica Carpathica*.

Kosakowski, P., Więcław, D., Kowalski, A. & Koltun, Y. V., in press. Assessment of hydrocarbon potential of the Jurassic and Cretaceous source rocks in the Tarnogród–Stryi area (SE Poland and western Ukraine). *Geologica Carpathica*.

Kotarba, M. J. & Peryt, T. M., 2011. Geology and petroleum geochemistry of the Miocene strata in the Polish and Ukrainian Carpathian Foredeep and its Palaeozoic–Mesozoic basement. *Annales Societatis Geologorum Poloniae*, 81: 211–220.

Kotarba, M. J., Peryt, T. M. & Koltun, Y. V., 2011a. Microbial gas system and prospectives of hydrocarbon exploration in Miocene strata of the Polish and Ukrainian Carpathian Foredeep. *Annales Societatis Geologorum Poloniae*, 81: 523–548.

Kotarba, M. J., Więcław, D., Kosakowski, P., Wróbel, M., Matyszkiewicz, J., Buła, Z., Krajewski, M., Koltun, Y. V. & Tarkowski, J., 2011b. Petroleum systems in the Palaeozoic–Mesozoic basement of the Polish and Ukrainian parts of the Carpathian Foredeep. *Annales Societatis Geologorum Poloniae*, 81: 487–522.

Krajewski, M., Matyszkiewicz, J., Król, K. & Olszewska, B., 2011. Facies of the Upper Jurassic–Lower Cretaceous deposits from the southern part of the Carpathian Foredeep basement in the Kraków–Rzeszów area (southern Poland). *Annales Societatis Geologorum Poloniae*, 81: 269–290.

Maksym, A., Baszkiewicz, A., Gregosiewicz, Z., Liszka, B. & Zdanowski, P., 2000. Facies and reservoir potential of the uppermost Jurassic and the Lower Cretaceous deposits in Brzezówka–Zagorzyce region versus geologic structure of the southern Carpathian Foredeep. (In Polish, English summary). *Przegląd Geologiczny*, 49: 401–407.

Moryc, W. & Nehring-Lefeld, M., 1997. Ordovican between Pilzno and Busko in the Carpathian Foreland (Southern Poland). *Geological Quarterly*, 41: 139–150.

Moryc, W., 2006. Geological structure of Miocene substratum in Kraków–Pilzno region. Part 2. The Permian and Mesozoic period. (In Polish, English summary). *Nafta-Gaz*, 6: 263–282.

Myśliwiec, M., Borys, Z., Bosak, B., Liszka, B., Madej, K., Maksym, A., Oleszkiewicz, K., Pietrusiak, M., Plezia, B., Staryszak, G., Świętnicka, G., Zielińska, Cz., Zychowicz, K., Gliniak, P., Florek, R., Zacharski, J., Urbaniec, A., Górka, A., Karnkowski, P. & Karnkowski, P. H., 2005. Hydrocarbon resources of the Polish Carpathian Foredeep: Reservoirs, traps, and selected hydrocarbon fields. In: Golonka, J. & Picha, F. J. (*eds*), *The Carpathians and their foreland: Geology and hydrocarbon resources*. *American Association of Petroleum Geologists, Memoir*, 84: 351–393.

Such, P., Leśniak, G. & Budak, P. 2007. Complex methodic of investigations of petrophysical properties of rock. (In Polish, English summary). *Prace Instytutu Nafty i Gazu*, 142: 1–69.

Washburn, R. N., 1921. Note on the method of determining the distribution of pore size in a porous material. *Proceedings of National Academy of Science*, 7: 115–116.

Webb, P. A., 2001. *An introduction to the physical characterization of materials by mercury intrusion porosimetry with emphasis on reduction and presentation of experimental data*. Micromeritics Instrument Corp. Norcross, Georgia, 1–22.

Więcław, D., 2011. Origin of liquid hydrocarbons accumulated in the Miocene strata of the Polish Carpathian Foredeep and its Palaeozoic–Mesozoic basement. *Annales Societatis Geologorum Poloniae*, 81: 443–458.

Więcław, D., Kotarba, M. J., Kowalski, A. & Kosakowski, P., 2011. Habitat and hydrocarbon potential of the Palaeozoic source rocks in the Kraków–Rzeszów area (SE Poland). *Annales Societatis Geologorum Poloniae*, 81: 375–394.