Annales Societatis Geologorum Poloniae (2011), vol. 81: 363–373.

PETROPHYSICAL PROPERTIES OF THE PRE-MIOCENE ROCKS OF THE OUTER ZONE OF THE UKRAINIAN CARPATHIAN FOREDEEP

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Kurovets, I., Prytulka, H., Shyra, A., Shuflyak, Y. & Peryt, T. M., 2011. Petrophysical properties of the pre-Miocene rocks of the Outer Zone of the Ukrainian Carpathian Foredeep. *Annales Societatis Geologorum Poloniae*, 81: 363–373.

Abstract: The paper summarizes the results of various laboratory studies of core material, including porosity, permeability, lithological-facies and structural and textural characteristics of more than 1,000 samples of Mesozoic and Palaeozoic rocks. The petrophysical parameters of siliciclastic and carbonate rocks are analysed for the total of samples representing different lithologies (limestones *vs*. sandstones) as well as for particular stratigraphic intervals (Upper and Lower Cretaceous, Upper Jurassic, Middle and Lower Jurassic, and Palaeozoic). The terrigenous rocks with intergranular porosity and fracture-cavernous carbonate rocks of reefal facies form the best reservoir rocks within the Mesozoic. The terrigenous rocks of fractured and fractured-porous type that are controlled by the fault-block tectonics provide the best Palaeozoic and Ediacaran reservoirs.

Key words: reservoir properties, sandstone, limestone, Palaeozoic, Mesozoic, Carpathian Foredeep, Ukraine.

Manuscript received 12 May 2011, accepted 3 November 2011

INTRODUCTION

Autochthonous deposits of the Carpathian region, including the substrate of the Outer Zone of the Carpathian Foredeep, are considered to be the prime object for prospection and exploration of oil and gas in western Ukraine (Krups'kiy, 2001; Kolodiy *et al.*, 2004). Although Miocene (Sarmatian) sandstones remain the most important targets for natural gas (*e.g.*, Kurovets *et al.*, 2004), there is a number of hydrocarbon fields related to the Upper Jurassic and Cretaceous deposits in this zone; they include Kokhanivka, Sudova Vyshnia, and Orkhovychy oil fields; Letnia gas-condensate field; and Rudky, Medenychy, Bilche-Volytsia, Uhers'ko, Mala Horozhanna, Hrudiv and Vereschytsia gas fields (Fig. 1) (Kotarba *et al.*, 2011). In the north-western part of the Outer Zone, oil inflows from the Upper Jurassic limestones were found in the Vyzhomlia, Tyniv and Nyklovychi areas (Fig. 1). In the south-western part of the zone under the Carpathian Overthrust, the Lopushna oil field occurring in the Upper Jurassic, Cretaceous and Palaeogene deposits was discovered.

The archival data indicate that oil and gas occurrences were also recorded in the Palaeozoic deposits in areas of Kokhanivka, Rudky, Mostys'ka, Chyzhevychy, Zaluzhany, Derzhiv, Bohorodchany, and Davydeny, among the others. In the core samples from the Cambrian sandstones one can observe oil shows, and during testing of these sandstones the insignificant oil influx has been obtained. Oil and gas shows in the Silurian deposits have been obtained during the well drilling in areas: Derzhiv, Slobidka Lisna, Davydeny, and Krasnoil's'k. In particular, in the latter area, in boreholes 1 and 5 one could observe degassing of the drilling mud. According to archival data, several zones of increased hydrocarbon content were distinguished in the Cambrian section in the Davydeny 1 borehole. Taking into account these data as well as the discovery of the Uszkowce natural gas field occurring in the Ordovician–Silurian deposits (Karnkowski, 1999) and of several gas fields (Lachowice-Stryszawa, Zalesie, Niwiska) in the Devonian deposits of SE Poland (Karnkowski, 1999), the Palaeozoic and Precambrian deposits of the Outer Zone of the Ukrainian Carpathian Foredeep are regarded to be promising for commercial oil and gas exploration.

One of the principal factors of the formation and preservation of hydrocarbon deposits is the availability of the reservoir rocks and fluid-impermeable beds. The reservoir pro-

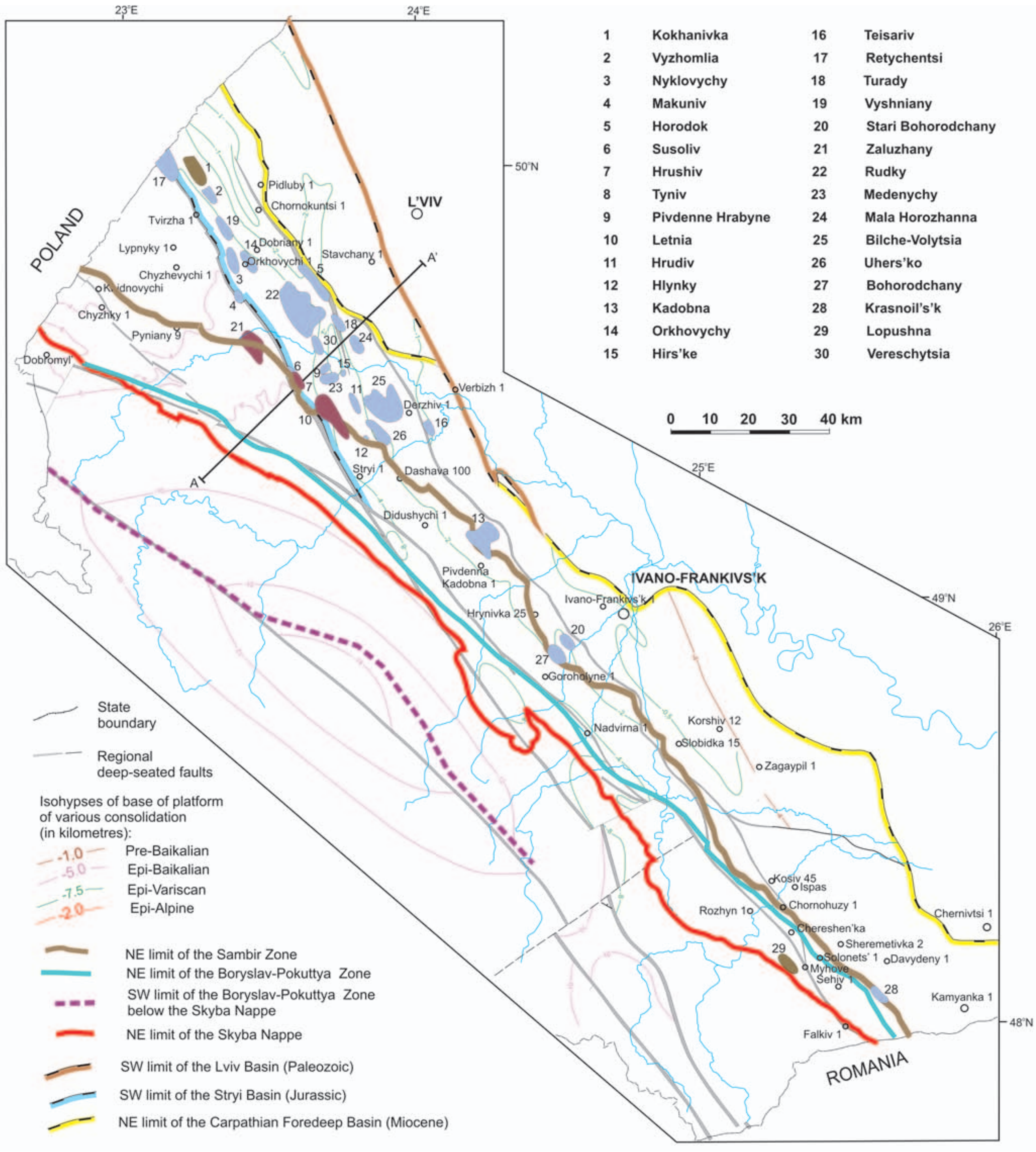

Fig. 1. Tectonic map of the Carpathian oil- and gas-bearing region (from Vul *et al.*, 1998). 1 – 30: Fields of the Bilche-Volytsia oil- and gas-bearing region

perties of the Precambrian and Palaeozoic rocks of the Ukrainian Carpathian Foredeep as well as its Mesozoic deposits were studied rarely (Kurovets, 2001; Lyzun *et al.*, 2004). Therefore, we have analysed reservoir properties of Mesozoic and Palaeozoic rocks in the Outer Zone of the Ukrainian Carpathian Foredeep aiming to establish the basic geological factors controlling the capacity-filtration characteristic.

GEOLOGICAL FRAMEWORK

Figure 1 shows the tectonic position of the Carpathian oil- and gas-bearing region (Vul *et al.*, 1998). The block structure, the availability of multi-storey structural complexes and the dipping of the eroded surface of the pre-Miocene strata towards the Carpathians, in the form of separate steps across the system of longitudinal tectonic fractures,

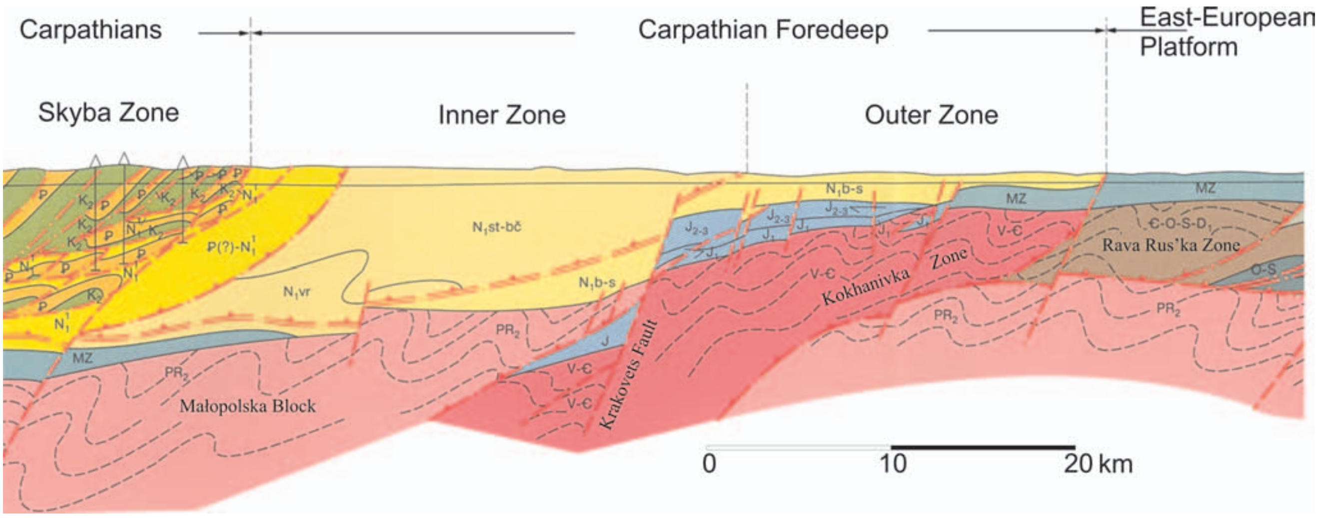

Fig. 2. SSW–NNE geological section along A–A' line in Fig. 1 (based on Vul *et al.*, 1998)

Table 1

Petrophysical section of the pre-Neogene of the Outer Zone of the Ukrainian Carpathian Foredeep (based on archival data and the original results shown in Table 2)

Era	Period	Epoch	Stage	Suite	Lithological column	Thickness [m]	Lithotypes of rocks	Petrophysical parameters			
								Porosity %	Permeability, 10^{-3} μm^2	Resistivity Ωm	Acoustic velocity, m/s
Mesozoic	Cretaceous	Upper	Maastrichtian			0-100	Sandstones, aleurolites, claystones, marls, sandy limestones	0.01-28.8	Up to 940	5-300	3500-6250
			Campanian			0-450					
			Santonian								
			Coniacian			0-53					
			Turonian			0-123					
			Cenomanian			0-60					
		Lower		Stavchany		0-210	Lst and clst, interbeds of mls and sst	0.8-21.5	Up to 178	5-100	3500-4250
	Jurassic	Upper	Tithonian-Kimmeridgian	Nyzhniv		150-500	Limestones, dolomites with intercalations of marls, claystones and sandstones	0.1-28.8	Up to 100	20-300	4100-6250
			Oxfordian	Rava-Ruska		150-400					
		Middle	Callovian	Rudky		0-60	Lst, sst, aleurolites, congl	2.2-28.4	Up to 90	10-15	4000-5800
				Yavoriv		0-50					
			Bathonian-Bajocian	Kokhanivka		0-250	Claystones, aleurolites, sandstones	1.9-24.8	Up to 190	5-20	3800-4500
		Lower	Lias	Medenychy		Up to 500	Sandstones and claystones with intercalations of coal	1.0-17.0	Up to 0.5	5-22	3700-5000
Palaeozoic	Devonian	Lower		Dnister		0-800	Intercalations of sandstones, aleurolites and claystones	1.7-4.7	<0.1	60-100	4800-5400
	Silurian	Ludlow				0-1400	Claystones, rare aleurolites, sandstones and limestones	0.9-2.5	<0.1	50-150	4000-5800
	Cambrian					0-1500	Intercalations of sandstones, aleurolites and claystones	0.2-7.0	<0.1	60-350	4400-5500
Proterozoic	Ediacaran					>2000	Shales and phyllites with intercalations of sandstones, aleurolites and claystones	0.4-11.0	Up to 1.0	35-90	>4200

1* - Limestones and lime claystones with intercalations of marls and sandstones, Lst, sst, aleurolites, congl - limestones, sandstones, aleurolites, conglomerates

are characteristic for the Outer Zone of the Ukrainian Carpathian Foredeep (Fig. 2; *cf*. Kotarba *et al.*, 2011).

Within the limits of the Outer Zone of the Ukrainian Carpathian Foredeep, Mesozoic, Palaeozoic and Upper Proterozoic deposits occur below the Miocene (Table 1), the latter including the deposits assumed so far to be of the Riphean age (Kruglov & Tsypko, *eds*, 1988; Stupka, 1993; Mizerski & Stupka, 2005). These deposits are widely distributed in the north-western part of the Outer Zone (Krukenychy Depression) where they occur directly under the Miocene formations and were encountered in many boreholes (Glushko & Kruglov, *eds,* 1977; Stupka, 1993), including several wells located in the Chyzhky and Mostys'ka regions near the border with Poland. However, as stressed by Buła and Habryn (2011), the rocks considered to be Riphean in Ukraine are similar to the Ediacaran flysch deposits of the Małopolska Block in SE Poland, and in addition their Ediacaran age is supported by palynological studies of Jachowicz-Zdanowska (2011).

In the north-eastern part, their distribution is limited by the Krakovets Fault, and towards the southwest the Ediacaran deposits are covered by the Sambir unit and then by the Boryslav-Pokuttya unit and Skyba nappe of the Outer Carpathians. The data of seismic survey indicate that the total thickness of the Ediacaran deposits is several kilometres, and only its top part (maximum 199 m in the Tvirzha 3 borehole) was drilled.

The Palaeozoic developed along the north-western margin of the Outer Zone and is composed of the Cambrian, Ordovician, Silurian and Devonian sediments (Drygant, 2000).

The Cambrian rocks are distributed almost everywhere along the Carpathian Foredeep in the form of a 20-km-wide strip (with the exception of the Krukenychy Depression). They are exposed by a number of wells in the region of Pidluby, Kokhanivka, Dobryany, Verbizh, Mala Horozhanna, Derzhiv, Rudky, Dashava, and Davydeny. The greatest thickness of deposits, over 1,200 m, was found in the Derzhiv 1 borehole. The thickness of deposits in the Davydeny 1 borehole is 805 m.

The thin Ordovician deposits are distributed locally. They were encountered by the boreholes in areas of Chornokuntsi, Yavoriv, Kokhanivka, Dobromyl, Rudky, Medynychy, and Dashava.

The Silurian deposits are widely distributed in the Carpathian Foredeep and occur in the form of strip, recorded by boreholes in areas of Pidluby, Derzhiv, Stavchany, and Krasnoil's'k, among others.

The Lower Devonian deposits occur in the far southeast of the Outer Zone where they were drilled by numerous boreholes.

The Mesozoic deposits occur in almost the whole territory of the Ukrainian Carpathian Foredeep, with the exception of its north-western part where directly under the Miocene deposits the Palaeozoic and Precambrian formations occur (Buła & Habryn, 2011). The Mesozoic sequence is represented by Lower Jurassic–Upper Cretaceous rocks (Pasternak *et al.*, 1987; Danysh *et al.*, 2004).

The Lower Jurassic deposits are known from the areas of Pivnichni Medynychy, Hrushiv, Korolyn, Bortiatyn, and Chornokuntsi. The Middle Jurassic deposits occur in the north-western part of the Outer Zone (terrigenous rocks of marine facies – the Kokhanivka suite) and in its south-western part (basal continental facies). The Upper Jurassic deposits, in turn, occur with the exception of the far north-western part of the Outer Zone and are composed of lagoonal and shallow-water marine formations (Karpenchuk *et al.*, 2006; Krajewski *et al.*, 2011).

The Cretaceous deposits developed in the platform facies. In the north-western part of the Outer Zone they are lacking. The Lower Cretaceous deposits were exposed by the majority of boreholes and are best studied in areas of Bilche-Volytsia, Pivnichni Medenychy, Dashava, Kokhanivka, Uhers'ko, and Pidluby. They are composed of grey-green calcareous sandstones, clayey aleurolites, clayey and sandy limestones and dark-grey lime claystones. In the north-west, the organodetrital and pseudoöolitic limestones are widely distributed (Radkovets', 2005).

The Upper Cretaceous deposits occur transgressively on the Lower Cretaceous rocks and are unconformably overlain by the Miocene. Most sections exposed by boreholes are known to occur in areas of Uhers'ko, Bilche-Volytsia, Pivnichni Medynychy and Letnia where their thickness is from 570 to 720 m. The Upper Cretaceous is represented by the Cenomanian–Maastrichtian strata (Pasternak *et al.*, 1987).

The Cenomanian is composed of yellow-grey and grey-green quartz-glauconitic sandstones with an admixture of gravels and pebbles of black flints, and then the sandstones are followed by grey and yellow-grey sandy inoceramid limestones and marls. The Turonian is composed of white and grey bioclastic and micritic, fractured limestones interbedded with marls, clays, fine-grained sandstones and aleurolites. The Coniacian–Maastrichtian part of the Upper Cretaceous section consists of grey and yellow-grey in colour, quartz, fine- and medium-grained, poorly sorted, dense sandstones interbedded with aleurolites, lime claystones, marls and micritic limestones. Rapid lithofacies changes, from sandstones to limestones and claystones, are characteristic. Sandstones and limestones are dominant lithologies in the north-western part of the Outer Zone.

MATERIAL AND METHODS

Investigation included a complex of laboratory studies of the core material including capacity-filtration properties of rocks and their lithological and petrological characteristics. True specific gravity was determined by pycnometric method and the apparent volume weight by hydrostatic weighting. Factor of total porosity is determined by the classical Melcher's (1920) method, and factor of open porosity by the classical Preobrazhensky's (1932) method, in which the volume of open pores is defined by the volume of kerosene being got into porous space, and the volume of the sample by hydrostatic weighting in kerosene.

Permeability is measured by pumping of gas (nitrogen, air) under pressure through the sample of cylindrical shape, and is determined by the volume of gas that passed through the transverse section of the sample at given differential pressure and at given time.

In addition, previous archival data on laboratory studies were compiled. By using statistical methods the petrophysical parameters of more than one thousand samples of rocks from the Mesozoic and Palaeozoic deposits were analysed. Petrophysical parameters of terrigenous and carbonate rocks were analysed separately both for the total samples and for stratigraphical subdivisions of the Upper and Lower Cretaceous, Upper Jurassic, Middle and Lower Jurassic and Palaeozoic. The following reservoir characteristics were analysed: open porosity and absolute permeability, volumetric weight, and carbonate content.

RESULTS

Our original results are summarized in Table 2, and our results and archival data are summarized in Table 1. Below, we present a short presentation of main results for particular stratigraphical intervals and principal lithologies (Figs 3–6).

Table 2

Petrophysical properties of Jurassic and Cretaceous deposits of the Letnia, Makuniv, Nyklovychi and Susoliv areas

Area	Number of measu-rements	Interval [m]	Lithology	Stratigraphy	Open porosity Ro	Permeability 10^{-3} μm^2	Specific density of rock g/cm^3	Carbonate content %	Electrical resistivity Ω m	
									rock	saturated solution
Letnia	103	1,668–2,566	limestone	Upper Jurassic	0.2–8	0.01–1.19	2.46–2.73	41–98.2	6.5–272.2	0.08
	87	1,492–2,876	sandstone		0.9–12.3	0.01–113.7	2.18–2.68	0.8–48.2	3.2–57.5	0.08
	55	1,541–1,850	limestone	Lower Cretaceous	1.4–7.4	0.001–0.52	2.5–2.68	56.3–92.9	6.4–114	0.0495–0.08
	57	1,541–1,850	sandstone		1.5–12	0.1–9.37	2.1–2.7	9.6–49.9	3.5–43.5	0.08
	50	1,285–1,691	sandstone	Upper Cretaceous	1.8–28.8	0.01–2	1.71–2.65	0.7–49.6	2–70	0.0495–0.08
Makuniv	15	2,395–2,416	limestone	Upper Jurassic	0.8–1.4		2.67–2.74	54–72.7	187–295	0.08
	10	1,254–2,357	sandstone		1.6–2.8		2.3–2.64	12.8–20.5	26.2–53.4	0.08
Nyklovychi	60	1,948–2,275	limestone		0.1–5.9	0.02–5.8	2.52–2.71	52–100	18.8–221.3	0.0495–0.08
	75	1,942–2,161	sandstone		0.4–24.6	0.01–175	2.06–2.9	2.3–41.5	11.1–150.8	0.0495–0.08
Susoliv	10	2,637–2,747	limestone		0.9–1.4		2.7–2.71	83.2–87.2	192.5–220.3	0.0495
	16	2,999–3,005	sandstone		1.5–5.4	0.01–75	2.4–2.55	1.2–31.0	79.1	0.08

Ediacaran

The Ediacaran deposits are grey, grey-green and red-brown schists and phyllites interbedded with quartzite-like oligomictic fine- and medium-grained sandstones, aleurolites and siliceous claystones. Claystones are dark-grey to black in colour, strongly cemented, fractured. The rocks are usually crushed and fractured. The dips of beds are often 80 to 90°. Laboratory studies of the core material show low porosity of sandstones and aleurolites that varies from 0.4 to 11%, and permeability does not exceed 0.1 10^{-3} μm^2. In the area of Khidnovychy and Pyniany, porosity of sandstones is 3.6 to 6.9%, and permeability is less than 0.1 10^{-3} μm^2. In the Kniahynychy 2 borehole (3,930–3,933 m), porosity of sandstones is 4.1 to 8%, and porosity of claystones is 0.3 to 2.33%.In the Tvirzha 1 borehole, sandstones at depths of 3,610–3,655 m show porosity of 9–11% and permeability up to 1.0 10^{-3} μm^2. The specific density of rocks is 2.42–2.7 g/cm^3.

The Ediacaran sandstones and aleurolites belong to the low-porous, complicated fractured-porous reservoirs that may contain the hydrocarbon deposits in favourable conditions.

Cambrian

The Cambrian rocks (interbedded sandstones, aleurolites and claystones) are strongly faulted, crushed by a thick network of fractures with slickensides; dips of beds vary from 10 to 90°. Sandstones and aleurolites are light- to dark-grey quartz and oligomictic rocks containing abundant feldspars, fine- and medium-grained, fractured, often resembling quartzites. The thickness of interbeds of sandstones varies from 1 cm to several metres, and in places it exceeds 10 m. Claystones are dark-grey, black in colour, micaceous. Towards the Carpathians, rocks underwent significant katagenetic changes reflected in their density.

With the exception of fractured rocks that are concentrated near the fault zones one can infer the existence of fractured-porous reservoirs in the Cambrian deposits. They are developed mainly within the limits of erosional and tectono-erosional uplifts where rocks have undergone the denudation for a long time and thus various pore types were formed. Just in such reservoirs gas is enclosed in the Cambrian deposits at Cetynia in the Polish Carpathian Foredeep (Karnkowski, 1999).

Porosity in sandy-silty deposits varies from 0.2 to 7%; permeability is less than 0.1 10^{-3} μm^2, except of fractured rocks where it attains the value up to $0.53 \cdot 10^{-3}$ μm^2. In the process of well drilling and during the post-completional flow test the water inflows or insufficient oil and gas showings were obtained at many fields and prospecting areas. In the Dashava 409 borehole, where porosity of the Cambrian rocks is 4.3 to 5.3% and permeability is $0.01 \cdot 10^{-3}$ μm^2 according to laboratory data, the brine inflows were obtained of discharge ranging between 40 and 60 m^3/day. In the region of the Kokhanivka oil field, the oil shows were found in the core samples of sandstones, and during the testing insignificant oil inflow was obtained.

Ordovician

The data on reservoir characteristics of Ordovician grey aleurolites and claystone interbedded with lime-quartz sandstones in the lower part and the organogenic-detrital limestones in the upper part are rare. An analysis of core material has shown that in the Chornokuntsi 1 borehole porosity of sandstones and aleurolites is 0.4–6.7%, and permeability is less than $0.01 \cdot 10^{-3}$ μm^2; in the case of individual fractured samples permeability reaches about $0.35 \cdot 10^{-3}$ μm^2.

Silurian

The Silurian sequence is represented by grey and dark-grey calcareous sandstones with thin (*ca*. 10 cm thick) interbeds of aleurolites, fine-grained sandstones, limestones and marls. The amount of carbonate beds is bigger in the lower

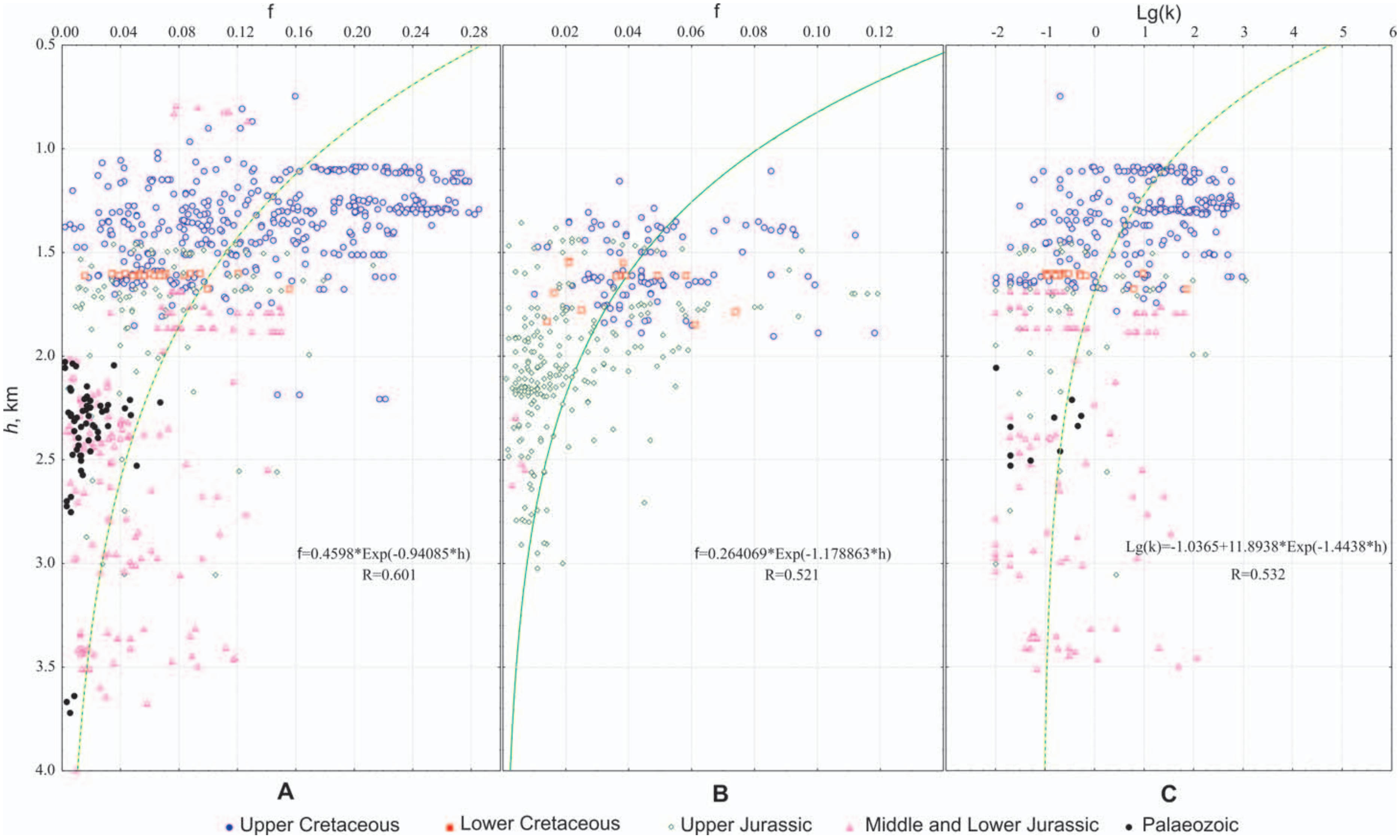

Fig. 3. Relation of porosity for terrigenous (**A**) and carbonate (**B**) rocks and logarithm of permeability for terrigenous rocks (**C**) of the Mesozoic and Palaeozoic deposits of the Outer Zone versus the depth

part of the section. Claystones are strongly cemented, dense and schist-like. These are crushed and dislocated rocks, and one can observe slickensides and fracturing. Porosity of sandstones and aleurolites in the Krasnoil's'k area is 0.9 to 2.5%, and permeability is $<0.1 \cdot 10^{-3}$ μm^2. Lithological and petrophysical characteristics indicate that this complex can serve as a screen.

Lower Devonian

Lithologically, this is a variegated series of mica carbonate-free claystones, aleurolites and fine-grained quartz sandstones. Sandstones are grey in colour, sometimes red, and contain interbeds of sandy dolomites. The thickness of interbeds of sandstones and aleurolites is from several centimetres to several metres. Porosity of sandstones in the Krasnoil's'k area is 1.7–4.7%, and permeability is less than $0.1 \cdot 10^{-3}$ μm^2.

Lower Jurassic

These rocks are alternated grey, calcareous, medium- and variously-grained quartz sandstones and aleurolites, clays and claystones with interbeds of coal. Content of siltstone grains averages 38%. Clastic material (55 to 75%) is composed of quartz grains, 0.02–0.25 mm in size, and also of pelitized feldspars, zirconium silicates, garnets, chlorite and muscovite. Cement consists of silica-hydromica, carbonate, clay, rarely gypsum-anhydrite. The type of cementation is porous, filmy-porous and basal. Aleurolites are composed mainly of quartz grains with small amount of muscovite, fragments of micro-grained silicon earth and grains of peli- tized feldspars. Cement is sideritic, clayey and clayey-sideritic. The type of cementation is porous, basal-porous and basal. One can observe the existence of coalified plant organics in the form of long veinlet-like structures, lenses and dispersed inclusions in great quantity (Fig. 3a). Claystones are dark-grey and black in colour, pyritized, and enclose fragments and thin lenses of coaly material and remains of coalified plant detritus. The thickness of some sandy-siltstone beds reaches 6 m, and coal interbeds are up to 2 m thick. Open porosity of sandstones and claystones varies between 1 and 17%, permeability is less than $0.5 \cdot 10^{-3}$ μm^2, specific density is 2.15–2.65 g/cm^3, and carbonate content is 1–32%.

Porous and fractured-porous sandy-siltstone rocks can be reservoir rocks in the Lower Jurassic deposits. They are connected with fluvial systems and offshore marine facies.

Middle Jurassic

In the lower part of the Kokhanivka suite, the sandstone unit (70 m thick) occurs with rare interbeds of gravelstone and limestone, and in the upper part the claystone unit is present. The sandstones are quartzose, fine-grained, calcareous. Cement is carbonate and clayey-carbonate of the porous type. By mineral composition, aleurolites are similar to sandstones. One can find rocks with siliceous-clayey-sideritic cement of the porous-basal type. Claystones are aleuritic, mica-rich, pelitized, dense.

Porosity of sandstones and aleurolites shows varies widely, from 1.9 to 24.8%. Reservoir rocks with open porosity of 5.5–12.7% predominate. Permeability of the greater part of core samples does not exceed $0.1 \cdot 10^{-3}$ μm^2. Permeability of some samples of sandstones reaches $190 \cdot 10^{-3}$ μm^2 that indicates the occurrence of highly-porous and well-permeable beds in the section. Carbonate content of the sandy-siltstone rocks varies from 1.7 to 45.3%. Porous and fractured-porous sandy-siltstone rocks may be reservoir rocks in deposits of the Middle Jurassic. This is confirmed by the core material sampled from the Kokhanivka 9 borehole (depth 1,089–1,100 m), represented by the quartzite-like sandstone cut by a network of microfractures filled with oil (Dolenko *et al.*, 1969).

Upper Jurassic

There are commercial hydrocarbon accumulations connected with the Upper Jurassic carbonate deposits in the Kokhanivka, Orkhovychy, Rudky, Vereschytsia, Letnia and Lopushna fields. The Callovian Rudky suite is composed of organogenic and oolitic limestones, occasionally sandstones, and the Yavoriv suite of sandstones, aleurolites, gravelstones and conglomerates. The Oxfordian deposits are represented by grey, brown-grey, dark-grey to black limestones interbedded with claystones. The Kimmeridgian deposits are in the lagoonal-dolomitic facies composed of limestones, dolomites, dolomitic marls interbedded with claystones, sandstones, and calcareous breccia. Limestones are light- and dark-grey in colour, sometimes brown, clayey and aleuritic. The Tithonian deposits are grey and dark-grey, bedded, occasionally breccia limestones.

Reef build-ups and the adjacent fore-reef and back-reef facies can be hydrocarbon-reservoir rocks in the carbonate deposits. The Oxfordian bioherms (140 m thick) are confined to the Horodok fault and occur along it in the form of a strip about 10 km wide, and are passing into fore-reef formations in the west and the back-reef ones in the east. Later, during the Kimmeridgian–Tithonian time, the formation of reefs occurred in the zone of the Sudova Vyshnia fault. The width of the barrier reef is there about 10 km, and its maximum thickness is about 1,000 m (Karpenchuk *et al.*, 2006).

In the Upper Jurassic reservoir rocks, various types of porosity occur: intragranular, fracture and fracture-cavernous (Dolenko *et al.*, 1969, Izotova *et al.*, 2005). The reservoir type, its structural, textural peculiarities and capacity-filtration characteristics are closely connected with its depositional facies. Limestones are often cavernous; caverns are from 0.02 to 0.8 mm across. In some cases, caverns are developed throughout the fractures, forming a kind of a chain. The caverns are often filled with oil.

The porosity of limestones varies from 0.1 to 30.21%, depending upon the intensity of the cavern development. The limestones are practically impermeable to showing permeability up to $100 \cdot 10^{-3}$ μm^2 (Fig. 4A). The best reservoir characteristics are found in the reefal limestones occurring in cores of the reefs, and in the carbonate rocks related to the zones of unconformities (Dolenko *et al.*, 1969). Intergranular porosity of the carbonate rocks is low (mainly <5%), and permeability is $<0.1 \cdot 10^{-3}$ μm^2. Therefore, the rocks are

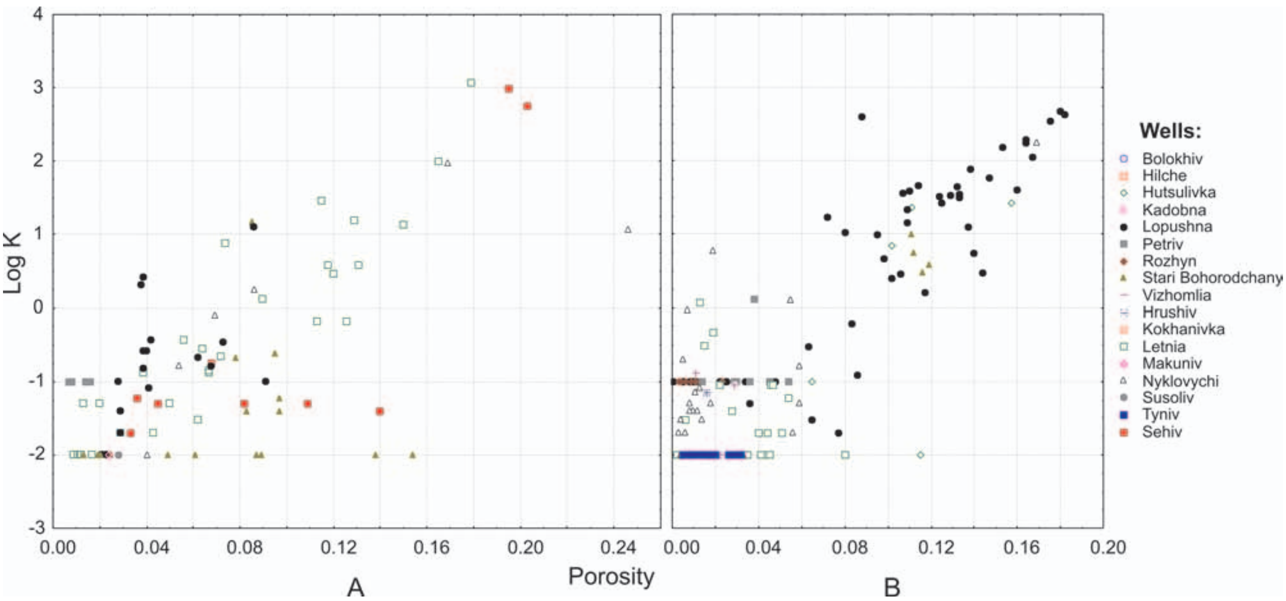

Fig. 4. Porosity and logarithm of permeability for Upper Jurassic deposits (**A** – limestones, **B** – sandstones) in particular fields

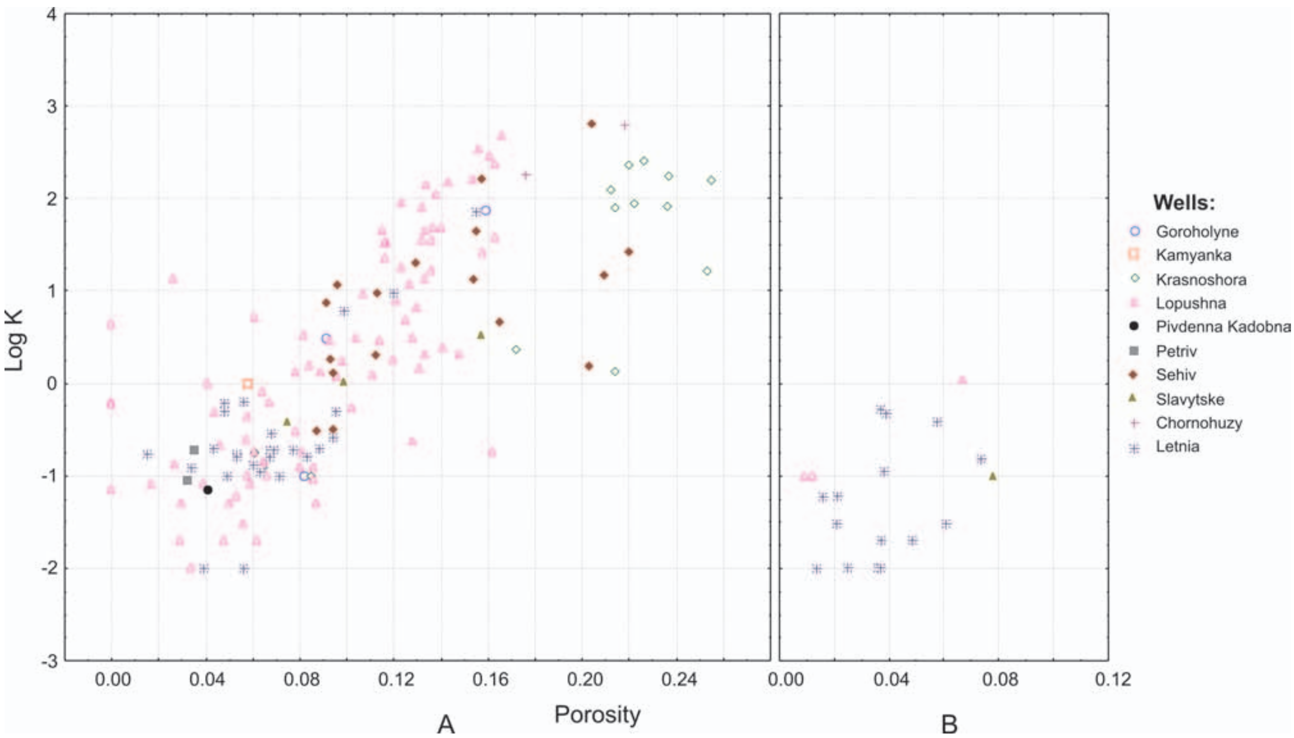

Fig. 5. Porosity and logarithm of permeability for Lower Cretaceous deposits (**A** – limestones, **B** – sandstones) in particular fields

practically impermeable. Individual increased values of porosity up to *ca*. 20–24% are caused by microcavernous character of dolomites. Three principal types of the carbonate reservoir rocks occur in the Upper Jurassic:

1. Low-permeable limestones with small intergranular porosity. The availability of microfractures, causing their permeability, allows us to classify them as complicated low-porous reservoirs of the mixed type;

2. High-porous limestones of organic-detrital type that have high porosity (15–20%) and high permeability (up to $100 \cdot 10^{-3}$ μm^2);

3. Pseudoölitic limestones with high porosity (20–30%), but low permeability. They may be reservoir rocks if there are fluid-conductive fractures available.

The porosity of sandstones and aleurolites varies from 2.2 to 28.4%, in most cases it is 15 to 20% (Fig. 4B). Perme-

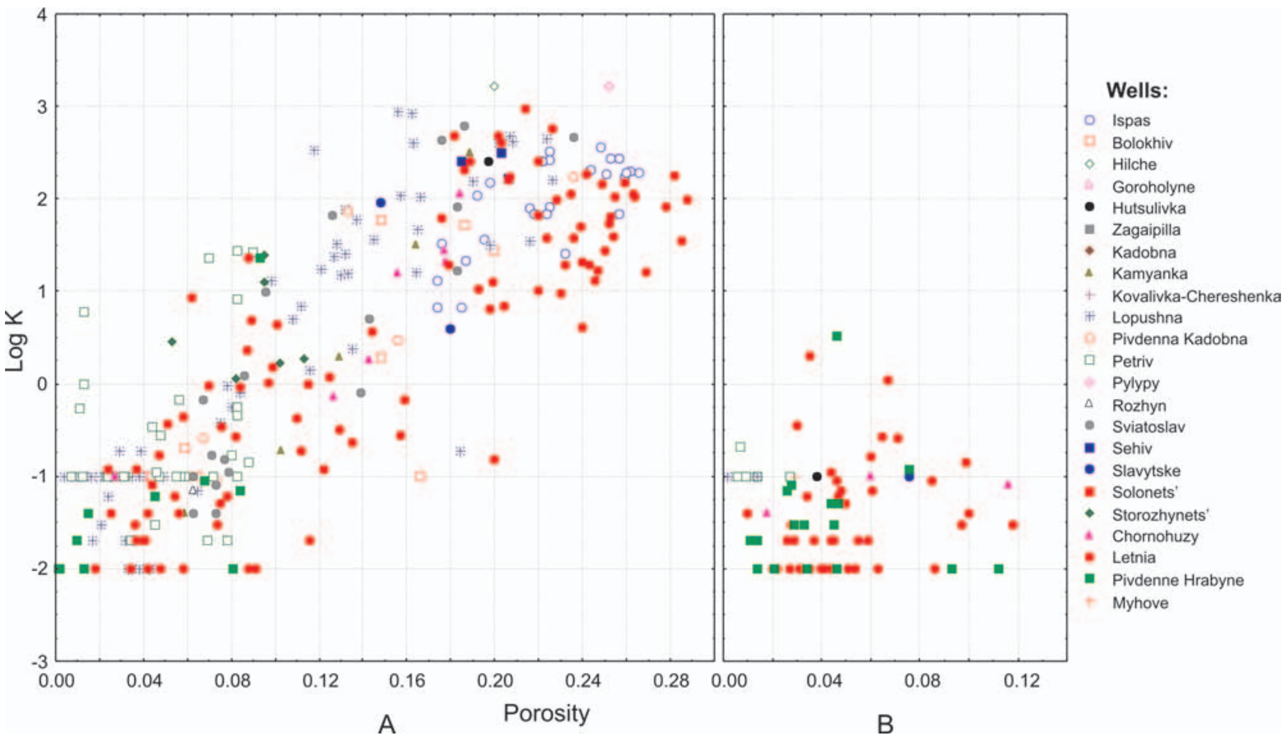

Fig. 6. Porosity and logarithm of permeability for Upper Cretaceous deposits (**A** – limestones, **B** – sandstones) in particular fields

ability of sandy rocks reaches (80–90)·10^{-3} μm^2. The range of the change in density is from 1.96 to 2.74 g/cm^3, but most common are values of 2.3–2.4 g/cm^2. Wide development of carbonate cement (5–40%) in sandstones and aleurolites causes a considerable worsening of their reservoir properties.

Lower Cretaceous

Rocks of the Lower Cretaceous are characterized by a considerable heterogeneity. Porosity of sandstones varies within the limits of 0.8–21.5%, and permeability is (0.01–178)·10^{-3} μm^2 (Fig. 3, 5B). As a rule, porosity of calcareous sandstones is < 9.5%, and permeability is <1·10^{-3} μm^2. Density of sandstones-siltstones varies between 2.17–2.71 g/cm^3. Intergranular porosity of limestones is low (<6%) (Fig. 5A). In the Kokhanivka field, fractured and cavernous limestones are known to be oil-reservoir rocks.

Upper Cretaceous

The porosity of Cenomanian sandstones is 5–16% (Fig. 6B), and that of Turonian limestones is <5.5% (Fig. 6A). The Coniacian–Maastrichtian sandstones contain carbonate and clayey-carbonate cement. The porosity of sandstones ranges between 0.1 to 28.8%, and the permeability is (0.01–940) 10^{-3} μm^2. The rock density is 1.71 to 2.89 g/cm^3. The highest porosity is characteristic of sandstones of the basal cement type from the Uhers'ko and Bilche-Volytsia fields. North-westward and south-eastward of these fields the reservoir characteristics of sandstones become worse (Fig. 6A).

The intergranular porosity of limestones and marls varies mainly from 0.01 to 10%, and for separate samples of rocks from the zones of unconformities it reaches 15.9% (Fig. 6B). The majority of limestones is practically impermeable, and permeability of separate samples reaches 34.6·10^{-3} μm^2.

DISCUSSION

The main geological factors determining the reservoir characteristics of terrigenous rocks and their physical properties are: the mineral composition, the shape, the size of fragmental grains and pores, their mutual location, the intensity of katagenetic transformations and thermodynamic conditions (Aagaard & Jahren, 2010; *cf.* Kurovets & Prytulka, 2001).

The porosity (Φ) of sandstones and siltstones in the Mesozoic and Palaeozoic deposits varies between 0.1 and 28.8%, with the average value of 10.1% (Fig. 4). The coefficient of variation of the porosity is 0.72. The greatest range of variation of the coefficient of open porosity is characteristic of sandstones and aleurolites from the Cretaceous (0.1–28.8%) and the Upper Jurassic (0.4–24.6%), which is caused by a considerable lithological-facies heterogeneity and a different structure of the pore space. The smallest range of variation is recorded for the Palaeozoic terrigenous rocks (0.2–6.7%) that have undergone katagenetic processes to a considerable extent.

In the total analysed set of samples of Mesozoic and Palaeozoic rocks, the permeability (K) varies from 0.01·10^{-3} to 1138·10^{-3} μm^2 and the average permeability is 1.901·10^{-3} μm^2 (*cf.* Table 1, Fig. 3). The lgK-parameter is characterized by the greatest coefficient of variation, equal to 4.80 in comparison with other petrophysical parameters.

The petrophysical characteristics of the carbonate reservoirs are more variable than the terrigenous ones due to sufficient varieties of sedimentation conditions and sensitivity to the processes of lithification, recrystallization and alkalization. As a result of the diagenetic dissolution, caverns and great karst pores are formed in the carbonate rocks. The most intensive dissolution of minerals occurred during the subaerial exposure of rocks and circulation of the reservoir fluids. As a result of recrystallization, the coarse-crystalline calcite was formed, incidentally the volume and the shape of the pore space changed. Most intensively are recrystallized first of all high-permeable organic, coarse-detrital and fragmental and then oolitic limestones. In micritic limestones, the process of recrystallization occurs more slowly (Knishman *et al.*, 2001). In the carbonate rocks fractures are distributed throughout the section. The fracturing and further widening of the fractures by the flow of underground water promoted the origin of new fractures and caverns.

The porosity measured on samples of small size is insufficient, and it characterizes capacity of the rock matrix, because fractures and caverns are practically lacking. The intergranular porosity of the carbonate rocks varies from 0.1 to 15.4%, with the average of 3.0%; rock samples with porosity of 0.1–5% predominate. The coefficient of variation of porosity is 0.87. The greatest range of variation of intergranular porosity is observed in the carbonate rocks of the Upper Cretaceous. The porosity of limestones in the Upper Jurassic deposits ranges within 0.1–11.9% (Fig. 4A), with a mean of 2.3%, and in the Lower Cretaceous – 0.1–7.4%, with a mean of 3.8% (Fig. 5A). Most of samples of the carbonate rocks are practically impermeable: the permeability is $<0.1 \cdot 10^{-3}$ μm^2. However, together with impermeable samples one can observe limestones with permeability of about $73.2 \cdot 10^{-3}$ μm^2. The decrease in porosity and permeability of sandy-clayey rocks with depth of their occurrence is characteristic of the geological cross-section of the Outer Zone of the Ukrainian Carpathian Foredeep. Coefficients of correlation of Φ and lgK with depth are 0.61 and 0.50, respectively (Fig. 3A). The most noticeable changes in capacity–filtration parameters with depth of occurrence are observed in the Mesozoic deposits buried to insufficient depths that did not undergo considerable katagenetic changes. In the Palaeozoic rocks the gradients of changes in petrophysical parameters decrease with increasing depth. The Palaeozoic deposits are at the stage of deep-seated katagenesis. They are strongly consolidated and underwent sufficient structural changes caused by recrystallization of pelitomorphic carbonate and siliceous cement and by regeneration of quartz (Gurzhiy *et al.*, 1983). As a result, changes in petrophysical parameters with depth are practically unnoticed.

In carbonate rocks the change in petrophysical parameters with depth is less noticeable. Thus, the coefficient of correlation between parameters Φ and lgH is 0.56 (Fig. 3B) and direct dependence of decrease in permeability with depth is not observed. The coefficient of correlation between the K-parameter and the lgH-parameter is equal to 0.21.

CONCLUSIONS

The reservoir rocks in the pre-Miocene strata of the Outer Zone of the Ukrainian Carpathian Foredeep contain hydrocarbon deposits. In the Mesozoic deposits, the best reservoir rocks are Cretaceous siliciclastic rocks with intergranular porosity and Jurassic fracture-cavernous carbonate rocks of reefal facies between Lubaczów in Poland and Gai. The greatest hydrocarbon deposits are known to occur in the reef facies located upon most strongly uplifted blocks. If there are favourable structural conditions, the hydrocarbon accumulation may be expected also in the fore-reef and back-reef deposits. In the Palaeozoic and Ediacaran deposits, siliciclastic reservoirs of fractured and fractured-porous types are developed. Their distribution in the geological section is controlled by fault-block tectonics. They are prospective within the limits of the Krukenychy Depression, in which porous-fractured and cavernous reservoir rocks are developed that are widely distributed within the limits of erosion escarpments and in zones of unconsoli- dated rocks confined to the faults.

Acknowledgements

This research was undertaken as a research project No. UKRAINA/193/2006 of the Polish Ministry of Science and Higher Education, carried out at the AGH University of Science and Technology and the Polish Geological Institute – National Research Institute, and was financed from the scientific fund of 2007–2010. Thanks are due to J. Golonka, Y. Koltun and P. Such for helpful comments and suggestions.

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