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DIAGENESIS AND RESERVOIR PROPERTIES OF THE MIDDLE MIOCENE SANDSTONES IN THE POLISH SEGMENT OF THE CARPATHIAN FOREDEEP

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Abstract: The Upper Badenian and Sarmatian sandstones from eight wells of the Carpathian Foredeep Basin have been studied. The following research methods were used: petrographic analysis with the use of polarizing microscope (staining analysis, cathodoluminescence studies – CL, porosity determinations, fluid inclusion analysis), scanning electron microscope (SEM) investigations and energy dispersive spectrometer studies (EDS ISIS), X-ray diffraction analyses (XRD), isotopic analysis and petrophysical studies.

The sandstones are very-fine to medium-grained subarkosic and sublithic arenites and wackes. The main components of the sandstone grain framework are quartz, feldspars (potassium feldspar and plagioclase), lithoclasts (fragments of carbonate rocks, clastic rocks, granitoids, volcanic rocks and quartz-mica schists) and micas (mainly muscovite). Bioclasts (mainly foraminifera), glauconite, ooids, organic matter and accesory minerals are subordinate. Pore spaces between the grains are filled by matrix and by cement (mostly Fe-calcite, quartz overgrowth, dolomite, siderite and kaolinite).

The Middle Miocene sandstones show good and very good filtration abilities. Sandstones porosity very often exceeds 20% and permeability is above 100 mD. Primary intergranular porosity is considerably more frequent than secondary intragranular porosity (mainly dissolution of feldspar grains) and intercrystalline porosity (clays microporosity). Effects of the following diagenetic processes can be observed in the sandstones: compaction, cementation, dissolution, replacement and alteration. Primary porosity reduction in sandstones was predominantly caused by mechanical compaction by about 26% and cementation, mainly by calcite, by approximately 35% on the average. Some increase in porosity was caused by dissolution of detrital grains, mainly feldspars, and decay of the soft parts of organisms. Diagenetic and related reservoir properties evolution of the Middle Miocene sandstones have been accomplished during eo- and mesodiagenesis.

Key words: sandstones, diagenesis, pore space, reservoir properties, Upper Badenian, Sarmatian, Carpathian Foredeep.

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INTRODUCTION

The Carpathian Foredeep basin has been the subject of hydrocarbon exploration for years (Karnkowski, 1999). In the Carpathian Foredeep, source rocks and reservoir rocks are represented by Middle Miocene strata (Myśliwiec *et al.*, 2004). The majority of the biggest gas fields are related to structural traps, but some traps are connected with stratigraphic architecture and they are more challenging to be localized. In this kind of gas province, one of the most important things is a proper understanding of migration paths. Therefore, the systematic petrographic analysis of petrophysical properties, such as permeability and porosity, allows one to define the ways of gas migration and to identify gas fields in the consequence.

Many gas reservoirs have been discovered in the Middle Miocene sandstones of the eastern part of the Polish Carpathian Foredeep (Karnkowski, 1999). There is a limited number of papers reporting the results of petrographic studies, and even less space is dedicated to diagenesic issues (*e.g.*, Twardowski, 1974; Lenk & Petrykowski, 1980; Ratajczak & Szafran, 1982; Leśniak & Darłak, 1993; Dudek, 1999; Leśniak & Such, 2001; Leśniak *et al.*, 2007). Jasionowski (1999) presented the summary results of diagenesis in the Tertiary sediments of the Carpathians. The Middle Miocene sandstones from the Tarnogród area were studied in detail in 1999–2001 years by A. Maliszewska, A. Kozłowska and M. Kuberska (*e.g.*, Maliszewska *et al.*, 2001a;

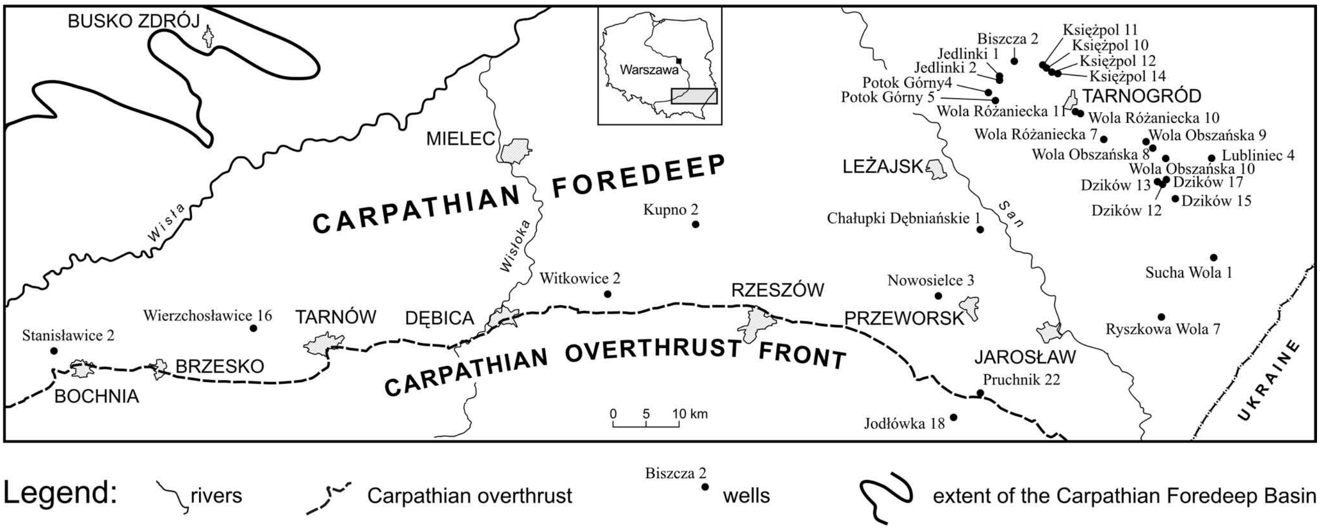


Fig. 1. Location map of the Carpathian Foredeep and the wells included in this study

2001b; 2004). The samples from the depth of about 200 to 1,070 m from 21 wells (between Biszcza and Ryszkowa Wola) were the subject of this research (Fig. 1).

The Miocene sediments from eight wells: Chałupki Dębniańskie 1, Jodłówka 18, Kupno 2, Nowosielce 3, Pruchnik 22, Stanisławice 2, Wierzchosławice 16 and Witkowice 2 located between Bochnia and Jarosław were the subject of the present study (Fig. 1). They occur at depths ranging from 20 to 2,537 m; their thickness varies from 746 to 1,851 m. The aim of this work was to identify textures, mineral composition and the influence of diagenetic processes and the sedimentary environment on the properties of reservoir rocks. Seventy samples of siliciclastic sediments, mainly sandstones, were examined. In addition, the earlier results from the Middle Miocene sandstones from the wells in the Tarnogród area were used for comparison (Fig. 1). The analysed rock samples are mainly of Late Badenian and Sarmatian age.

GEOLOGICAL SETTING AND DEPOSITIONAL ENVIRONMENTS

The Carpathian foreland basin was developed as a result of the Carpathian front movement toward the north during Early to Middle Miocene. The inner part of the Carpathian Foredeep is localized under Carpathian nappes whereas the outer one is placed in front of the orogen (Ney *et al.*, 1974; Oszczypko, 2006). The Polish part of the basin is an element of a large structure along the Carpathian mountains front, extending from the Alpine Molasse Basin in the west to the Balkan basin in the east (Oszczypko *et al.*, 2006).

The Carpathian Foredeep basin is asymmetrical with an erosional boundary in the north and the tectonic boundary in the south. The western part of the basin is characterized by blocky structures, whereas the east part by deep erosional structures (canyons), (Oszczypko, 1996). A sedimentary record, in the majority, is characterized by heterogeneous material supplied from the orogen, with some smaller feeding points from the northern, platform part.

The sedimentary record is interpreted as terrestrial to marine and consists predominantly of fine-grained sandstones, siltstones and mudstones. The oldest deposits are claystones to mudstones of the Skawina Formation (Lower Badenian), documented in the southern and central parts of the basin. Furthermore, a coarse material of the Gdów Formation (Lower Badenian) was deposited in the south close to the Carpathians. The northern margin is characterized by sandstones and claystones interfingered with coal (the Trzydnik and Pinczów formations) (Peryt & Piwocki, 2004).

During the Middle Miocene, in the southern and central parts of the basin saliferous sediments of the Wieliczka and Krzyżanowice formations were deposited (Garlicki, 1994), whereas in the northern part – limestones of the Radruż Formation were developed (Jasionowski, 1997). During the Late Badenian, close to the southern margin, sandstones and mudstones of the Gorliczyn Formation were deposited (Kuciński, 1982), passing northward to limestones of the Żelebsko Formation (Jasionowski, 1997).

Sandstones, mudstones and claystones of the Machów Formation of thickness of about 3 km are the majority of the sediments recorded in the Carpathian Foredeep basin (Alexandrowicz *et al.*, 1982). This succession is characterized by very diverse facies, which were deposited in various depositional environments. This sequence is the main goal of oil and gas fields investigations in the basin. The section was divided into several successions based mainly on geophysical data (Dziadzio, 2000). The lower part of the Sarmatian succession, with a dominance of fine-grained sediments getting coarser towards the orogenic front, is described as basin plain deposits. The middle part is defined as a deltaic environment succession, whereas the uppermost part is interpreted as shallow marine sediment (Dziadzio *et al.*, 2006). This complex arrangement represents a progradational stacking pattern, where deltaic sediments were shifted towards the basin center.

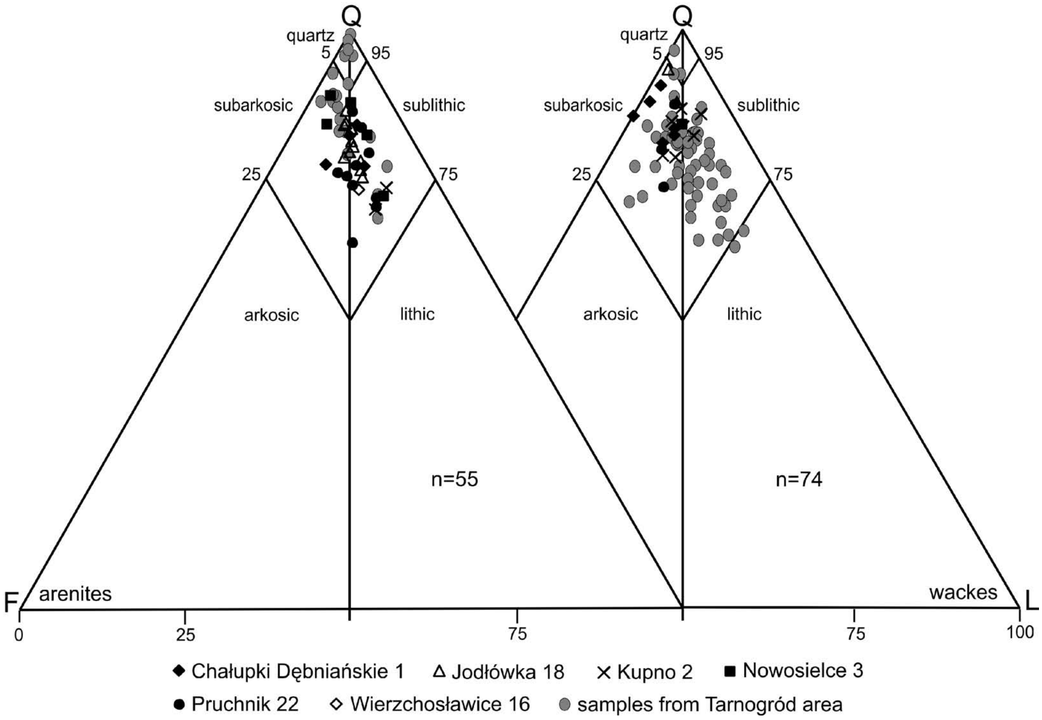


Fig. 2. The Middle Miocene sandstones classified after Pettijohn *et al.* (1972)

Fourteen lithofacies have been distinguished in the studied Middle Miocene deposits. These lithofacies are characteristic for deposition in the deltaic environment. Heterolithes dominated with mudstone and mudstones are typical for prodelta, whereas sandstones lithofacies are typical for proximal mouth bars. Sedimentological features of these lithofacies are characteristic for gravity flows, such as turbiditic currents and unidirectional traction currents, while the absence of wave ripples suggests a river-dominated delta type (pers. comm. P. Lis & A. Wysocka).

METHODS

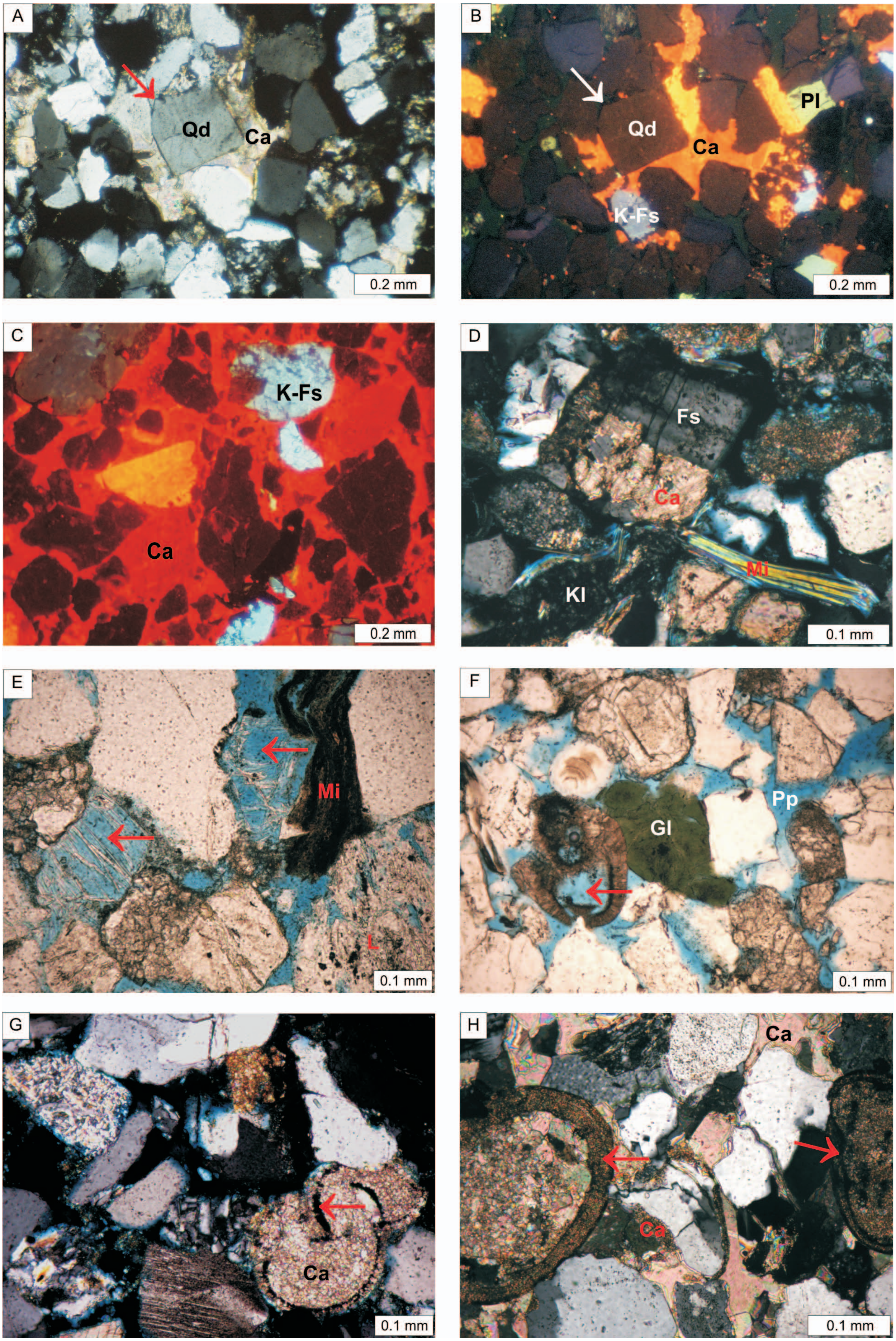
All samples were vacuum impregnated with blue epoxy resin prior to thin section preparation in order to indicate porosity. Modal compositions of fifty-four sandstones were obtained by counting 300 points per thin section using polarizing microscope Nikon Eclipse LV 100 Pol. The pore percentage in sandstones was calculated. Sandstone microlithofacies were distinguished using a version of the Dott classification modified by Pettijohn *et al.* (1972). Thin sections were stained by Evamy solution for carbonate mineral determination. Twelve thin sections were analysed in cathodoluminescence image (CL) using equipment with cold cathode CCL 8200 mk 3, Cambridge Image Technology Ltd. The textural features, grains of feldspar and cements of carbonates, quartz and kaolinite were observed. Studies of crystal habit occurrence and paragenetic relationships were performed on gold-coated samples chips using LEO scanning electron microscope (SEM) with energy dispersive X-ray analyzer. The chemical composition of carbonates and feldspars was determined on eleven polished, carbon-coated thin sections using JEOL scanning electron microscope (SEM) with energy dispersive X-ray analyzer. Backscattered electron images (BSE) were made on LEO scanning electron microscope (SEM). Fluid inclusions in authigenic carbonates were examined in ten double-polished thin sections using Linkam THMS600 heating-cooling stage mounted on polarizing microscope Nikon Eclipse LV 100 Pol. Mineralogical composition of less than 2 μm fraction of the sediment (clay minerals) was determined by X-ray diffraction analyses (XRD), using Philips X'Pert PW 3020 diffractometer (Cu Kα radiation and semiconductor detector). The analyses were performed on oriented samples, air-dried and subsequently glycolized and heated at 550°C. All mentioned analyses were carried out at the Polish Geological Institute – National Research Institute.

Carbon and oxygen stable isotope analyses were performed on eight calcite cemented sandstone samples. Determinations were conducted by the team of Professor S. Hałas at the Maria Curie-Skłodowska University in Lublin. The values of $\delta^{13}C$ were expressed in the scale of the VPDB, and $\delta^{18}O$ results were obtained in the VPDB and VSMOW scales. The team of Dr. G. Leśniak (Oil and Gas Institute in Kraków) made petrophysical studies – measurements of porosity, permeability and parameters of the pore space of rocks (porosimetric analysis).

RESULTS

Composition of sandstones

The sandstones are very fine- to medium-grained, moderately to poorly sorted. The grains are angular to subrounded. The studied sandstones represent subarkosic and subli-


A
Qd
Ca
0.2 mm
B
Qd
Ca
Pl
K-Fs
0.2 mm
C
K-Fs
Ca
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Kl
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F
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0.1 mm
G
Ca
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H
Ca
Ca
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thic arenites and wackes according to the Pettijohn *et al.'*s (1972) classification (Fig. 2). They correspond to the Middle Miocene sandstones of the Tarnogród area, but the wackes prevail over arenites at Tarnogród (Maliszewska *et al.*, 2001b, 2004). In addition, quartz arenites and quartz and lithic wackes occur in the Tarnogród region (Fig. 2).

Medium- to fine-grained sublithic and subarkosic arenites, sporadically subarkosic wackes, are typical for the proximal delta. Very fine-grained subarkosic, rare sublithic and quartz wackes and fine- to medium-grained subarkosic arenites are found in the distal part of mouth bars. The fine-grained sandstones often have lamination marked by clay minerals, mica flakes and organic matter.

Quartz is the main component of grain framework, the content of which ranges from 19 to 70 vol%. The monocrystalline quartz predominates over the polycrystalline quartz, which includes fragments of cherts (average about 1 vol%). Small quartz grains are mostly angular, while grains of the bigger fraction are characterized by a better roundness. Feldspars occur in all analysed sandstone samples in an amount from 1.7 to 12.3 vol%. There are mainly potassium feldspars, represented by microcline and orthoclase, which show blue colour in cathodoluminecence image (Figs 3A–C). Sodium-calcium plagioclase characterized by green colour in the CL, appears less frequent (Fig. 3B). Some feldspar grains have been partially or completely replaced by albite and/or calcite (Figs 3C, D), or dissolved (Fig. 3E).

The rock fragments are a common component of sandstones, and their content varies from 0 to 18.3 vol%. The fragments of sedimentary rocks, mainly limestone, rarely claystones, siltstones and sandstones dominate (0–9 vol%). Fragments of metamorphic rocks (0–3 vol%), represented by mica and quartz-mica schists are less frequent. The fragments of igneous rocks: granitoids (0–3.3 vol%) and eruptive rocks, mainly volcanic glaze (0–2 vol%), were observed, too.

Micas occur in various amounts (0–17.7 vol%), with a muscovite predominance over biotite. Calcite bioclasts were observed in similar quantities in the analysed sandstones, from 0 to 3.3 vol%. Locally, *e.g.* in the Wola Różaniecka area, their content exceeds 20 vol% (Maliszewska *et al.*, 2001b). It seems likely that foraminifera are the most common bioclasts (Figs 3F, G). In addition, there occur fragments of bivalve and brachiopod shells, skeletons of echinoderms and branches of bryozoans. The other components of content less than 2 vol% in sandstone are: organic matter, accesory minerals (mainly zircon and apatite), ooids and glauconite. Glauconite forms oval, green grains of various size that are affected by varying degrees of chloritization and pyritization (Fig. 3F). Locally, ooids were observed in the studied sandstones (Pruchnik 22 well). They form grains less than 0.5 mm in diameter and are composed of only one lamella around a nucleus, usually the quartz grain or the carbonate particle (Fig. 3H).

The Middle Miocene sandstones contain a matrix (from 0 to 47 vol%) and a cement (from 0 to 40 vol%). The matrix is composed of a mixture of clay minerals, quartz dust, iron hydroxides and muds, the content of which locally reaches 11 vol%. XRD analyses of clay minerals showed the presence of smectite, illite and chlorite (Fig. 4). Illite-smectite minerals with a variable content of both components and kaolinite were also identified in the sandstones of the Tarnogród area (Maliszewska *et al.*, 2001b). Mainly carbonate minerals and less quartz and clay minerals form the cement in the Middle Miocene sandstones.

Diagenetic minerals

Carbonate cements are mostly calcite and subordinately dolomite/ankerite and siderite. Two calcite cement generations are present. Micritic calcite precipitated on the surface of grains and in primary pores is the first generation. Sparite or poikilotopic calcite which precipitated in primary and secondary pore space in sandstones is the second generation (Figs 3A–C, 5A–D). The content of calcite cements is unequal and varies from 0 to over 36 vol%. Calcite replaces feldspar grains and rock fragments often forming pseudomorphs (Fig. 3D; Figs 5A, C). Poikilotopic calcite surrounds and hence post-dates quartz overgrowth and dolomite/ankerite rhombohedrons (Figs 3A, B, 5A–C). The chemical composition of calcite is: 92.7–98.8 mol% $CaCO_3$, 0–4.6 mol% $FeCO_3$, 0–1.8 mol% $MgCO_3$ and 0–2.5 mol% $MnCO_3$ (Table 1). It represents mainly Fe-calcite which becomes purple in Evamy solution and is characterized by red-orange and orange-yellow colours in CL (Figs 3B, C). Fluid inclusions in the calcite cement were observed in the Pruchnik 22 well. They are relatively rare and their size oscillates from < 1 μm to about 2 μm. The fluid inclusions are distinctly one-phase and occur as two types – transparent and dark. The inclusions do not create a bubble when freeze, however, their one-phase character points to low temperatures of the cement formation – below 50°C. The

Fig. 3. Photographs in polarizing microscope (PL) and cathodoluminescence (CL). **A.** Calcite cement (Ca) that partially replaced quartz overgrowths (arrow) on quartz grain (Qd); Jodłówka 18 well, depth 2,403.5 m, PL – crossed nicols. **B.** CL image of sample shown in Figure 3A; Yellow-orange luminescence of calcite (Ca), blue luminescence of potassium feldspar (K-Fs) and green of plagioclase (Pl). Non-luminescent authigenic quartz (arrow) and brown quartz grains (Qd). **C.** Fragment of sandstone, CL image. Orange and yellow luminescence of calcite cement (Ca) and blue luminescence of potassium feldspar (K-Fs). Nowosielce 3 well, depth 1,010.4 m. **D.** Selective replacement of feldspar grain (Fs) by calcite (Ca) and mica flake (Mi) altered to kaolinite (Kl). Pruchnik 22 well, depth 668.2 m, PL – crossed nicols. **E.** Secondary porosity resulted from dissolution of feldspar (arrows), lithoclast (L) and mica (Mi) grains. Sample impregnated with blue resin. Jodłówka 18 well, depth 2,454.5 m, PL – without analyzer. **F.** Secondary porosity in foraminifera shell (arrow) and primary porosity (Pp) in sandstone; glauconite grain (Gl). Sample impregnated with blue resin. Jodłówka 18 well, depth 2,442.8 m, PL – without analyser. **G.** Foraminifera test filled by calcite (Ca) and pyrite (arrow). Pruchnik 22 well, depth 1,407.5 m, PL – crossed nicols. **H.** Ooids (arrows) and micrite and poikilotopic calcite cement (Ca) in sandstone. Pruchnik 22 well, depth 662.6 m, PL – crossed nicols

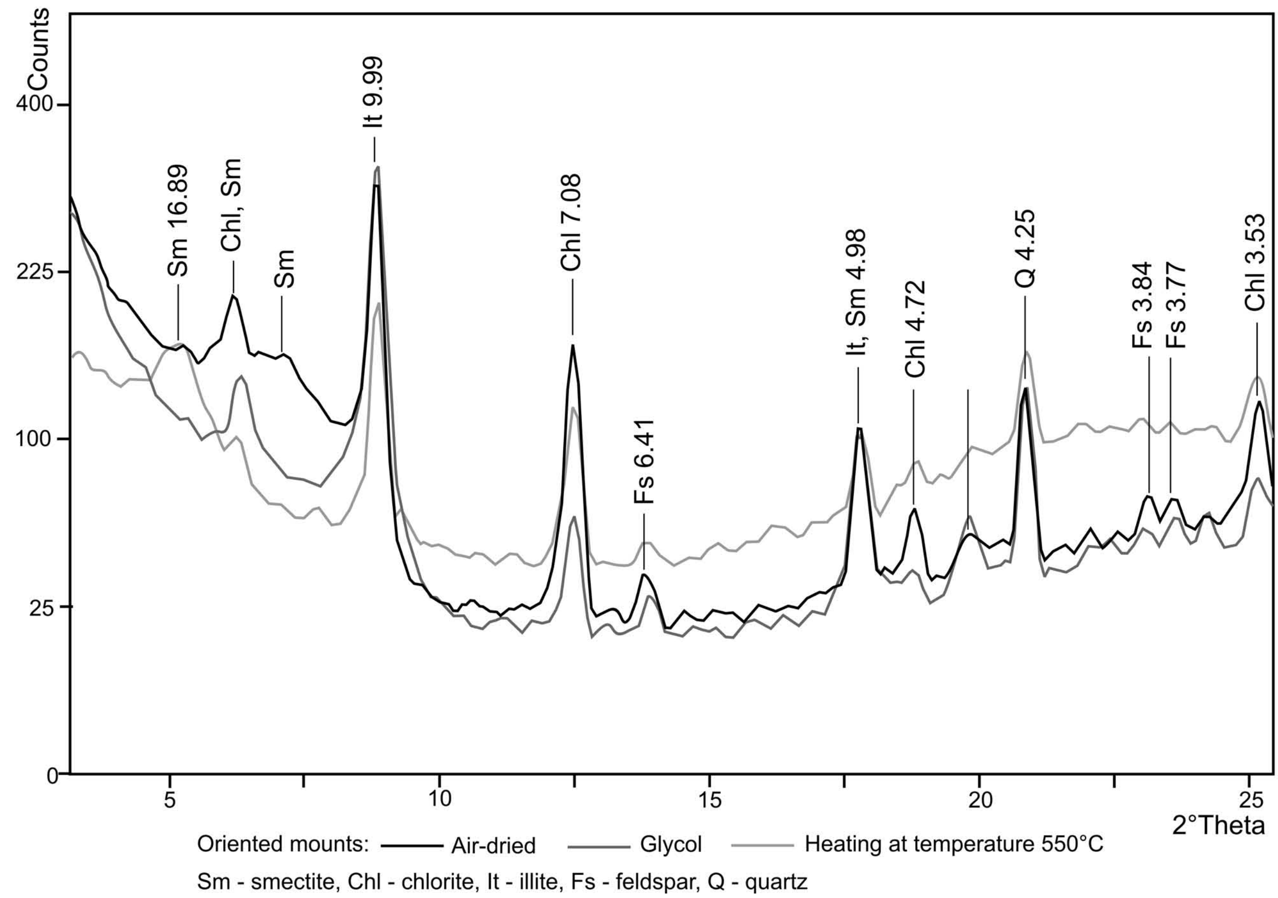

Fig. 4. XRD pattern of clay fraction of sandstone; Chałupki Dębniańskie 1 well; depth 687.3 m

eutectic temperatures suggest the $NaCl-CaCl_2-MgCl_2-H_2O$ system, while the ice melting temperature proves the fluid salinity of about 13.52% NaCl eq. The $\delta^{18}O$ data from calcite vary from –8.6 to –5.5‰$_{VPDB}$ and the $\delta^{13}C$ values are in the range of –5.7 to –1.7‰$_{VPDB}$ (Table 1, Fig. 6). These values are within the range of isotopic determinations of carbon and oxygen in calcite cement from the Middle Miocene sandstones of the Tarnogród area (Maliszewska *et al.*, 2001a). Dolomite/ankerite occur in the sandstones as pore-filling rhombohedrons (Figs 5A–D, 7A). Some of crystals show zonation with a core containing less Fe than rims (Figs 5C, D; Table 1). Maliszewska *et al.* (2001b) and Leśniak and Such (2001) have already shown the presence of ankerite rhombohedrons in the Middle Miocene sandstones of the Carpathian Foredeep. The chemical composition of dolomite minerals is: 52.4–61.4 mol% $CaCO_3$, 18.1–44.3 mol% $MgCO_3$, 0–21.0 mol% $FeCO_3$ and 0–1.6 mol% $MnCO_3$ (Table 1). The dolomite/ankerite crystals are surrounded by Fe-calcite (Figs 5A–C). Siderite occurs as scattered microcrystalline crystals in the sandstones. Siderite varies widely in composition, being enriched in magnesium, and represents sideroplesite (Table 1). Sideroplesite rhombohedrons growing on the grain of rhodochrosite composition were observed locally in the well Chałupki Dębniańskie (Table 1, Fig. 5E).

The quartz cement is commonly less than 1% of the whole rock, and only rarely reaches 2.4 vol%. It occurs as partial to complete syntaxial overgrowths around the quartz grains. The boundary between the overgrowths and the detrital core is either poorly defined or delineated by fluid inclusions or thin clay coatings. It is not easy to discriminate quartz overgrowth from detrital grains in thin sections in polarizing microscope but the real image of quartz cement can be observed in cathodoluminescence (CL). Quartz overgrowths are characterized by dark-brown luminescence or no luminescence while the quartz grains have brown and blue colours (Figs 3A, B). In SEM images, authigenic quartz overgrowths are very well visible as rhombohedral crystals and prisms on detrital quartz grains (Fig. 7B). Quartz cement is replaced by calcite (Figs 3A, B) and locally covered by dolomite/ankerite (Fig. 7A).

Authigenic clay minerals observed under the polarizing microscope and scanning electron microscope (SEM) are: kaolinite, chlorite and illite. Kaolinite occurs as booklets and vermicular stacked pseudohexagonal crystals (Fig. 7C). Vermicular kaolinite is locally distributed in intergranular and intragranular space of the Middle Miocene sandstone. Blocky habits are also noticed in some samples at the depth below 2 km in the Jodłówka 18 well. Kaolinite is surrounded by quartz overgrowths and hence it pre-dates the quartz. Occasionally, kaolinite locally replaces detrital feldspar and muscovite (Fig. 3D). Chloritic clays (chlorite or mixed-layer chlorite-smectite) occur as small flakes developed into honeycomb-like texture that coat the framework grains (Fig. 7D). Iron content higher than the magnesium content is shown by SEM in the chemical composition of

Table 1

Chemical composition of carbonate from microprobe analyses and isotopic ratios of carbon and oxygen

Well	Depth (m)	Point of analysis	$MgCO_3$ mol%	$CaCO_3$ mol%	$MnCO_3$ mol%	$FeCO_3$ mol%	$\delta^{13}C$ ‰VPDB	$\delta^{18}O$ ‰VPDB	$\delta^{18}O$ ‰VSMOW	Carbonate type
Chałupki Dębniańskie 1	852.0	I 1	0	96.8	1.2	2.0				Fe/Mn-calcite
		2	1.3	98.2	0	0.5				Fe-calcite
		3	42.2	57.1	0.4	0.3				deolomite
		II 1	1.4	98.2	0	0.4				Fe-calcite
		2	35.8	55.3	1.6	7.3				Fe-dolomite
		3	7.4	3.6	0.9	88.1				sideroplesite
		4	35.9	47.5	0.6	16.0				ankerite
	946.5	1	2.4	7.1	90.5	0				rodochrosite
		2	18.6	2.6	2.2	76.6				sideroplesite
		3	1.8	96.4	0.9	0.9				Fe-calcite
Jodłówka 18	2,294.5	1	42.7	56.7	0.4	0.2				dolomite
		2	20.6	61.4	1.6	16.4				ankerite
		3	1.0	97.5	0.6	0.9				Fe-calcite
		4	42.4	57.6	0	0				dolomite
		5	44.0	52.4	0.3	3.3				Fe-dolomite
	2,406.0	I 1	0	98.5	0	1.5	-2.42	-5.51	26.38	Fe-calcite
		2	1.8	92.7	0.9	4.6				Fe-calcite
		3	0.7	98.8	0.1	0.4				calcite
		II 1	1.9	93.1	2.5	2.5				Fe-calcite
		2	18.1	59.3	1.6	21.0				ankerite
	2,448.4						-3.15	-8.61	21.98	calcite
Kupno 2	849.0	1	44.3	54.3	0	1.4				dolomite
		2	1.0	98.2	0.8	0				calcite
		3	16.2	9.7	0.1	74.0				sideroplesite
Nowosielce 3	1,010.4	1	0	99.7	0.3	0	-5.72	-8.49	22.11	calcite
		2	1.4	94.8	0.4	3.4				Fe-calcite
		3	40.1	59.4	0.5	0				dolomite
		4	28.7	53.1	1.5	16.7				ankerite
	1,350.5						-3.05	-6.46	24.20	calcite
Pruchnik 22	660.9	1	0.7	97.1	0.4	1.8	-1.71	-7.51	23.12	Fe-calcite
		2	1.5	97.7	0.8	0				calcite
		3	1.8	95.4	0	2.8				Fe-calcite
		4	1.7	93.9	0.3	4.1				Fe-calcite
	662.6						-1.72	-7.36	23.27	calcite
	670.5						-1.79	-5.76	24.92	calcite
	1,422.5	1	1.0	96.7	0	2.3	-2.90	-6.86	23.79	Fe-calcite
		2	1.4	95.3	0.8	2.5				Fe-calcite

these minerals. Chlorite was identified in one sample in the Kupno 2 well only. Illite is formed of plates and filamentous crystals which cover the authigenic quartz, calcite and fill the pore space in the sandstone (Fig. 7E). This form of occurrence could suggest a very late crystallization of illite. The filamentous illite was observed only at the depth below 1.9 km in samples from the Jodłówka 18 well.

Minor diagenetic minerals include pyrite, rhodochrosite and feldspars. Pyrite occurs as scattered framboids filling primary and secondary pores (dissolved bioclasts) in the rocks (Figs 3G, 7F). Rhodochrosite occurring in nodules is very rare (Fig. 5E). Authigenic feldspars occur as K-feldspar overgrowths on partly to completely albitized and sericitized plagioclase grains (Fig. 5F). The K-feldspar overgrowths are surrounded by, and hence predate, quartz overgrowths that have been developed on the adjacent quartz grains. Chemical analyses showed that diagenetic K-feldspar contains: 63.19% SiO_2, 18.91% Al_2O_3, 15.38% K_2O, 1.64% Na_2O and 0.57% MgO. Ratajczak and Szafran (1982) mentioned the presence of the feldspar overgrowths on detrital grains in the Middle Miocene sandstones of the eastern part of Carpathian Foredeep.

Porosity

The porosity of rocks varies from 14.73 to 30.59% with an average of 24.9% in the studied area (Table 2). Porosity reduction appears to be depth controlled; porosity data show a general decrease with depth increase (Fig. 8). The porosity measured in thin sections ranges from 0 to 29.4 vol%. According to Jenyon's (1990) classification, the Middle Miocene sandstones can be concerned as the rocks of a very good porosity. Both primary and secondary pore types are present in the sandstones. Primary intergranular pores are the abundant pores and are affected by compaction and cementation (Figs 7G, H). Secondary intragranular pores were primarily associated with the dissolution of detrital feldspars and rock fragments (Fig. 3E) and minor bioclasts and calcite cement. Some of the secondary pores are inside foraminifer shells (Fig. 3F). Intercrystalline porosity in clay

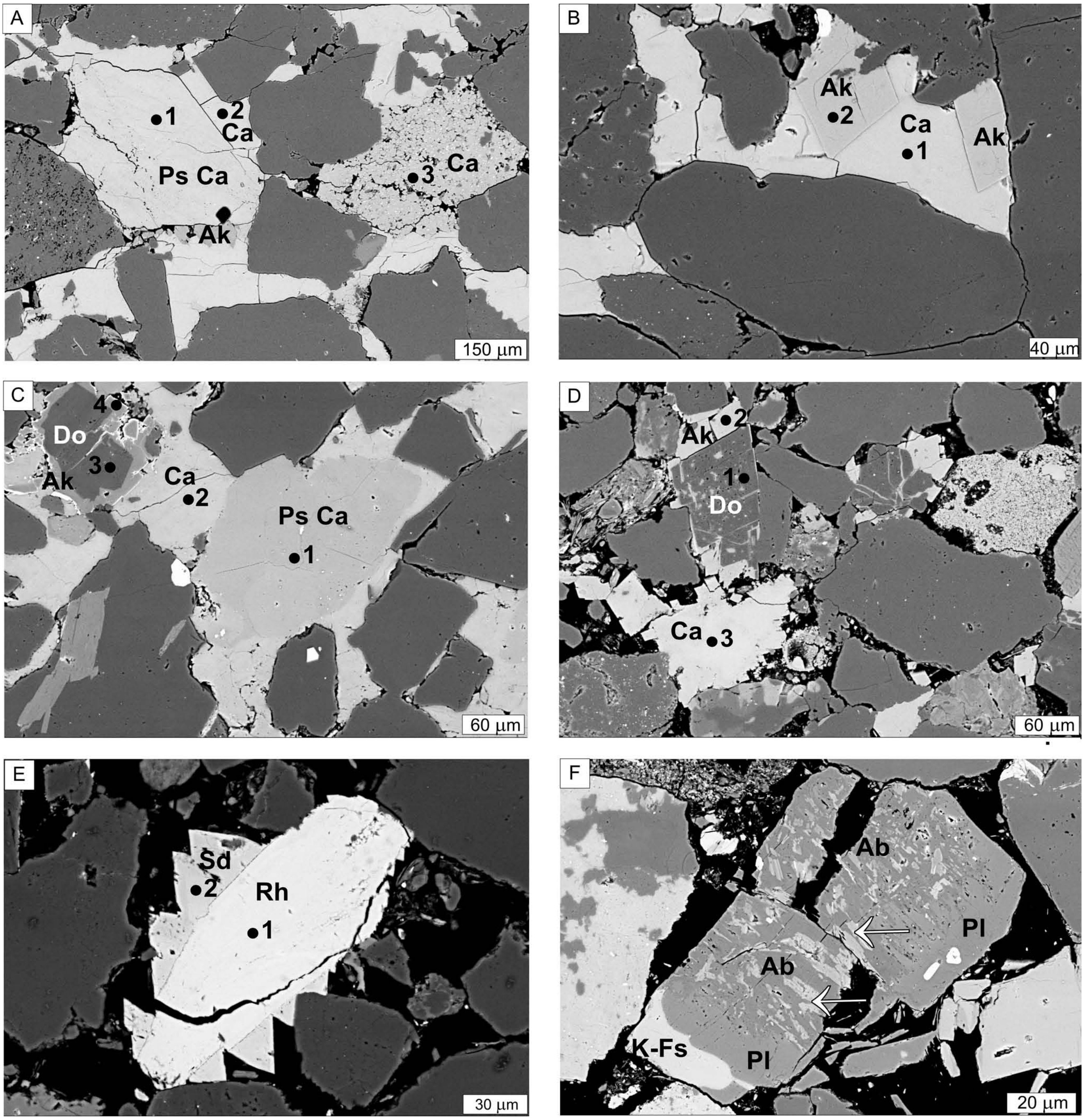

Fig. 5. Scanning electron microscope (BSE) photographs. **A.** Micrite and poikilotopic calcite cement (Ca) in sandstone, calcite pseudomorph (Ps Ca) and rhombohedron of ankerite (Ak); points of chemical analyses (EDS) in calcite (Table 1); Jodłówka 18 well, depth 2,406.0 m. **B.** Rhombohedrons of ankerite (Ak) engulfed by calcite cement (Ca); points of chemical analyses (EDS) in calcite (Table 1); Jodłówka 18 well, depth 2,406.0 m. **C.** Dolomite grain (Do) with ankerite (Ak) outer layer, calcite pseudomorph (Ps Ca) and calcite cement (Ca); points of chemical analyses (EDS) in calcite (Table 1); Nowosielce 3 well, depth 1,010.4 m. **D.** Zonal structure in dolomite (Do)/ankerite (Ak) rhombohedron and calcite (Ca); points of chemical analyses (EDS) in calcite (Table 1); Jodłówka 18 well, depth 2,294.5 m. **E.** Rhombohedrons of sideroplesite (Sd) on rhodochrosite nodule (Rh); points of chemical analyses (EDS) in calcite (Table 1); Chałupki Dębniańskie 1 well, depth 946.5 m. **F.** K-feldspar overgrowth (K-Fs) on albitized (Ab) and sericitized (arrows) plagioclase grain (Pl); Pruchnik 22 well, depth 1,407.5 m

aggregates (micropores) was associated with the presence of clays.

Permeability ranges from 15.98 to 332.27 mD with an average of 135.46 mD (Table 2). Most samples are characterized by a very high permeability (100 mD), according to the classification of Levorsen (1956).

The presented characteristics of the pore space of rocks are based on the following porosimetric measurements: porosimetric porosity (it sets pore volume that may lead the reservoir fluid), the percentage of pores with a diameter 1 µm, size of threshold diameter (it designates pore size, which indicates a continuous flow through the sample) and

Table 2

Petrophysical features of selected Middle Miocene sandstone samples

Well	Depth (m)	Grain density (g/cm3)	Total porosity (%)	Bulk density (g/cm3)	Porosimeter density (g/cm3)	Effective porosity (%)	Average diameter (μm)	Specific surface (m^2/g)	Pores >1 μm (%)	Threshold diameter (μm)	Hysteresis (%)	Permeability (mD)
Chałupki Dębniańskie 1	689.5	2.66	28.90	2.58	1.89	26.76	0.23	2.48	71	15	78	24.06
	850.6	2.66	31.81	2.19	1.72	21.64	0.54	0.93	83	20	82	280.08
	852.3	2.67	28.04	2.64	1.92	27.22	0.54	1.05	83	15	80	142.06
	858.6	2.68	30.47	2.63	1.87	29.02	0.60	1.03	87	20	75	227.28
Jodłówka 18	1,912.9	2.65	19.66	2.64	2.13	19.47	0.44	0.84	83	20	76	73.96
	2,104.4	2.66	15.71	2.62	2.22	15.11	0.31	0.87	64	7	64	15.98
	2,294.5	2.68	14.73	2.63	2.26	14.03	0.19	1.30	47	3	71	0.62
	2,403.5	2.69	17.10	2.69	2.23	17.10	0.61	0.50	85	20	74	57.71
	2,441.8	2.66	20.30	2.60	2.10	19.15	0.71	0.52	82	20	67	154.52
	2,444.6	2.66	20.08	2.61	2.11	19.12	0.42	0.85	78	20	71	141.76
	2,454.8	2.65	19.75	2.62	2.12	19.17	0.83	0.44	84	30	25	127.42
	2,458.3	2.64	20.14	2.59	2.09	19.18	0.86	0.43	83	20	26	136.98
Kupno 2	587.5	2.69	29.93	2.58	1.88	26.96	0.20	2.87	70	15	78	38.36
	591.6	2.67	29.05	2.61	1.90	27.41	0.41	1.40	89	20	60	167.92
	840.9	2.67	29.09	2.60	1.89	27.19	0.29	1.97	78	9	84	64.63
Nowosielce 3	1,172.6	2.68	28.52	2.64	1.92	27.42	1.11	0.52	91	50	21	268.35
Pruchnik 22	659.6	2.68	30.59	2.80	1.82	34.76	0.66	1.16	88	40	26	n.o.
	668.2	2.66	29.58	2.58	1.87	27.39	0.44	1.32	82	20	42	n.o.
	1,407.5	2.69	24.12	2.59	2.02	21.93	0.16	2.76	65	50	57	184.27
	1,420.6	2.66	26.91	2.64	1.94	26.38	1.00	0.54	88	35	33	332.27
Wierzchosławice 16	907.3	2.68	29.06	2.69	1.90	29.35	0.23	1.14	87	20	65	n.o.

hysteresis (the smaller the hysteresis the better filtration properties of rocks). Measured values fall into the following ranges: porosimetric porosity 14.03–34.76%, the average number of pores 1 μm from 41 to 91%, the threshold diameter of 3–50 μm and hysteresis 21–84% (Table 2). The averages of these parameters are: 23.58%, 79%, 22 μm, and 60%, respectively. They prove very good features of the pore space of the Middle Miocene sandstones. Among the analysed rocks, samples of the weakest filter features are in the well Jodłówka 18, where the depth of occurrence of the Middle Miocene sediments is the deepest (below 1.9 km).

In the Tarnogród area the majority of the studied sandstones are also characterized by the high porosity – above 20% (Fig. 8), other good features visible in porosimetric analysis, and the permeability assessed at more than 100 mD (Maliszewska *et al.*, 2001b, 2004).

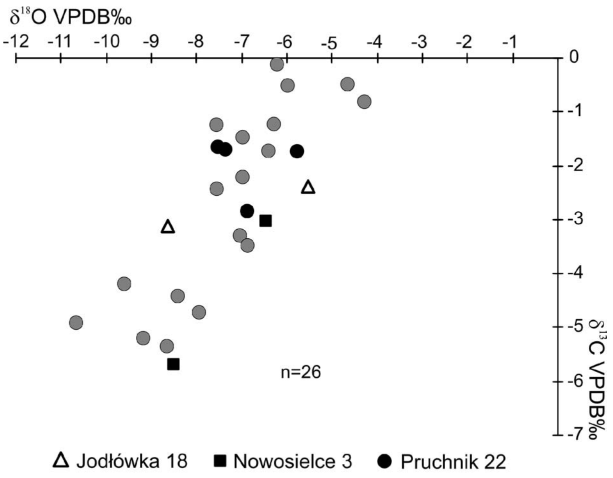

Fig. 6. Plot of $\delta^{18}O_{PVPDB}$‰ versus $\delta^{13}C_{PVPDB}$‰ in calcite cement

INTERPRETATION AND DISCUSSION

There are two stages in the diagenetic history of the Middle Miocene sandstones: eodiagenesis and mesodiagenesis (according to Choquette & Pray, 1970). Eodiagenesis defines early diagenesis, and refers to the period between the end of deposition and the sediment burial to a depth at which the action of surface processes was terminated. Mesodiagenesis corresponds to a period of progressive burial of sediments. A simplified paragenetic sequence of the diagenetic processes in the Middle Miocene sandstones is shown in Figure 9. It was constructed based on petrographic textural relationships, isotopic composition and fluid inclusion of the diagenetic calcite.

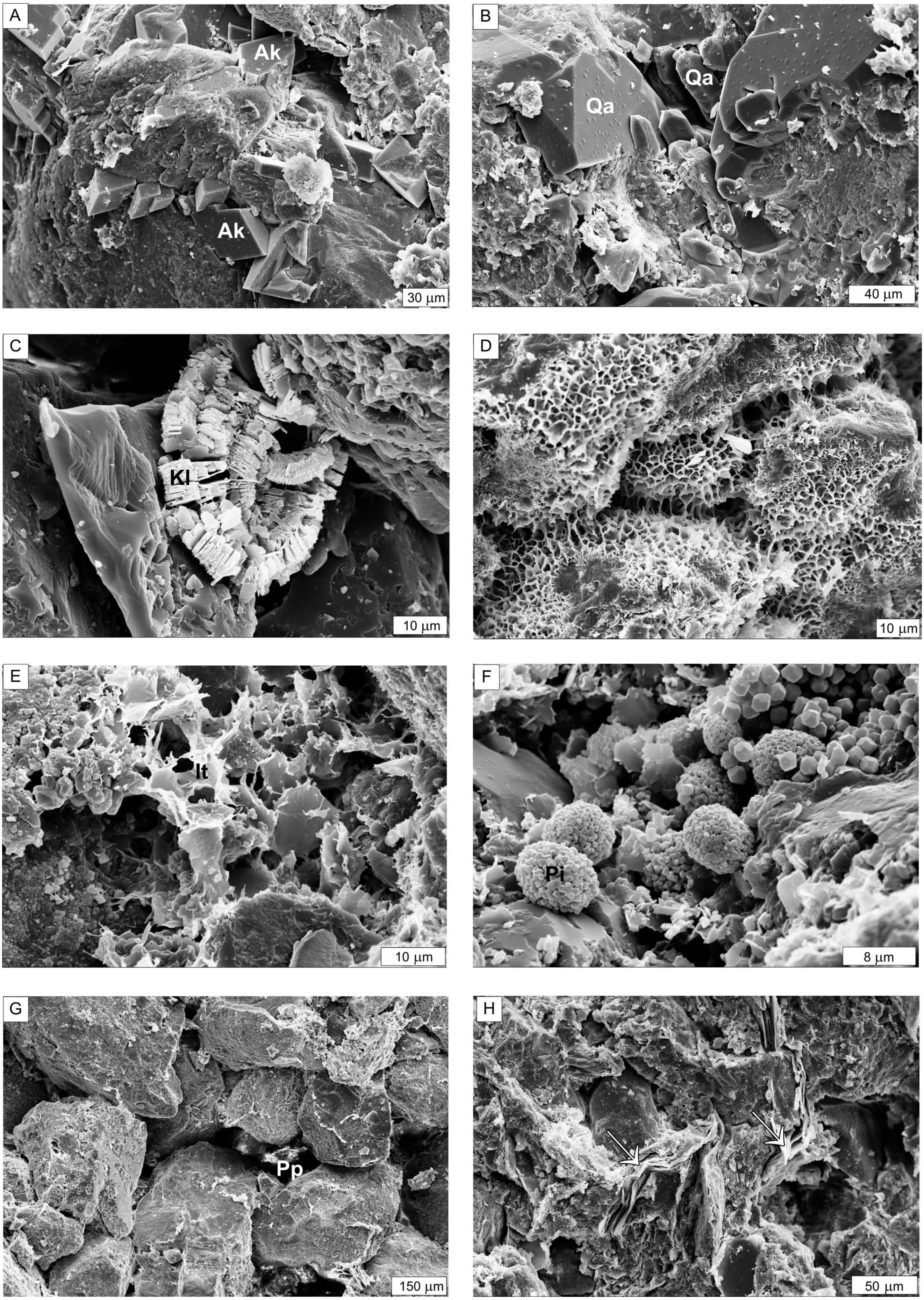
A
Ak
Ak
30 µm
B
Qa
Qa
40 µm
C
Kl
10 µm
D
10 µm
E
It
10 µm
F
Pi
8 µm
G
Pp
150 µm
H
50 µm

Fig. 7. Scanning electron microscope (SEM) photographs. **A.** Rhombohedrons of ankerite (Ak) in pore space of sandstone. Pruchnik 22 well, depth 1,422.5 m. **B.** Authigenic quartz crystals (Qa) developed in primary pores. Jodłówka 18 well, depth 2,403.5 m. **C.** Vermiform kaolinite (Kl). Nowosielce 3 well, depth 1,172.6 m. **D.** Chlorite or mixed-layered chlorite-smectite rims on detrital grains; honeycomb texture of chlorite/chlorite-smectite. Kupno 2 well, depth 586.3 m. **E.** Fibrous illite (It) filling in sandstone pore space. Jodłówka 18 well, depth 1,912.6 m. **F.** Pyrite (Pi) framboids in pore space of sandstone. Jodłówka 18 well, depth 2,104.4 m. **G.** Primary porosity (Pp) in sandstone. Nowosielce 3 well, depth 1,172.6 m. **H.** Mica flakes (arrows) bent as a result of mechanical compaction. Kupno 2 well, depth 840.9 m

Eodiagenesis

Early deposited sediments have been largely affected by the initial phase of physical compaction, which was progressively accelerated with the increasing depth of burial. The plastic deformation of ductile-lithic grains, micas bending and fracture of quartz are the effects of mechanical compaction in the Middle Miocene sandstones (Fig. 7H). The effects of this process lead to loss of the rock porosity.

Chlorite (chlorite-smectite) was formed in the early diagenetic history in the form of rims around detrital grains (Fig. 7D). Chlorite originates through transformation of eogenetic authigenic smectite rims into the disordered chlorite-smectite or into corrensite (Anjos *et al.*, 2003). Magnesium chlorites form when Mg significantly prevailed over Fe and biotite and volcanic rocks fragments were their possible sources. Moreover, highly alkaline environments (evaporitic settings) favored the neoformation of magnesian smectite clays (Anjos *et al.*, 2003).

Eodiagenetic siderite, rhodochrosite and pyrite crystallized when pore water in sediments became significantly depleted in dissolved oxygen. A very fine crystalline form of siderite suggests its early genesis. Siderite precipitated in organic-rich sediments containing significant amounts of reactive iron minerals and in which the pore water was poor in SO_4^{2-} (Morad, 1998). According to Mozley (1989), the elemental composition of siderite was controlled by the chemistry of depositional waters. Meteoric siderites were enriched in Mn, but depleted in Ca and particularly Mg in comparison with siderite in the marine sediments. Rhombohedron crystals of siderite growing on rhodochrosite nodule argue for early rhodochrosite formation (Fig. 5E). Rhodohrosite precipitated in the suboxic zone of sediments enriched in Mn-oxides (Morad, 1998). Framboidal pyrite formed at the early stage of diagenesis (Fig. 7F). Its existence was connected to local conditions, in which the amount of H_2O produced by sulfate-reducing bacteria was higher than the content of reduced iron (Postma, 1982).

Micrite calcite formed at the early stage of diagenesis. Its precipitation on the surface of grains can indicate phreatic or vadose environment (Tucker, 2008). $CaCO_3$ for cement can be sourced internally by the dissolution of metastable carbonate induced by bacterial composition of organic matter, and externally by sea water. Mixing of marine pore water and meteoric groundwater could have also caused a supersaturation with respect to calcium carbonate, and could have evoked carbonate precipitation in the mixing zone (Molenaar, 1998).

Silicate grains such as feldspar, micas and rocks fragments were altered and dissolved by acidic fluids during eodiagenesis (Fig. 3E). Formation of vermiform kaolinite is attributed to the incursion of meteoric water, which affected mainly mica grains, rarely feldspars (Figs 3D; 7C). Aluminum and silica ions released during the dissolution reaction of detrital grains precipitated as kaolinite in acidic environment (Bjørlykke, 1989). Kaolinite formation probably predated the quartz cement. According to Osborn *et al.* (1994) vermicular kaolinite precipitates in temperature from 25–50°C.

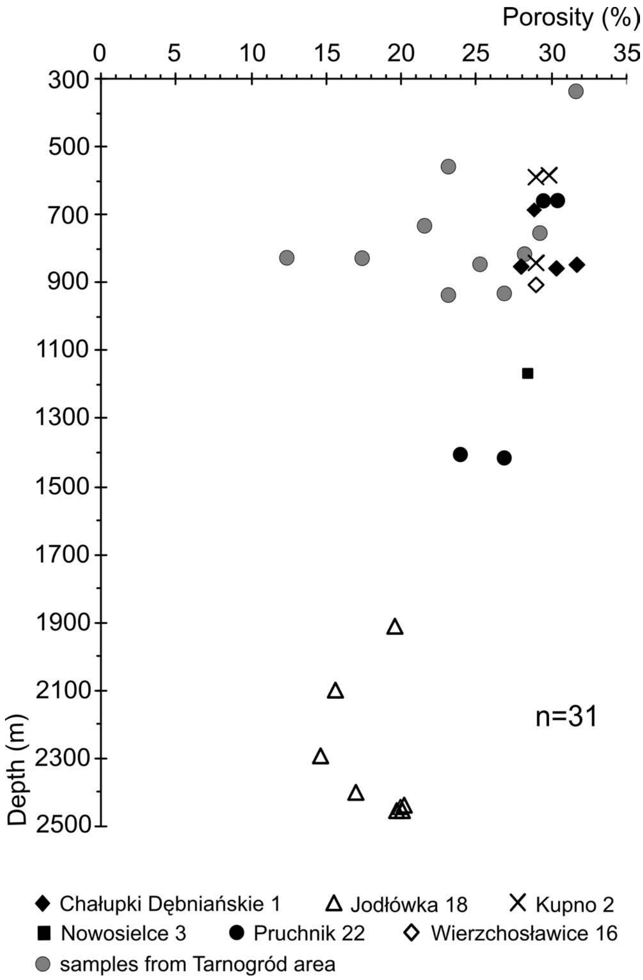

Fig. 8. Plot of porosity versus depth in the Middle Miocene sandstones

Quartz overgrowths on the quartz grains started to form at the end of eodiagenesis (Figs 3A, B, 7B). The presence of single-phase inclusions within the quartz cement indicates its formation at a temperature below 50°C. Small amounts

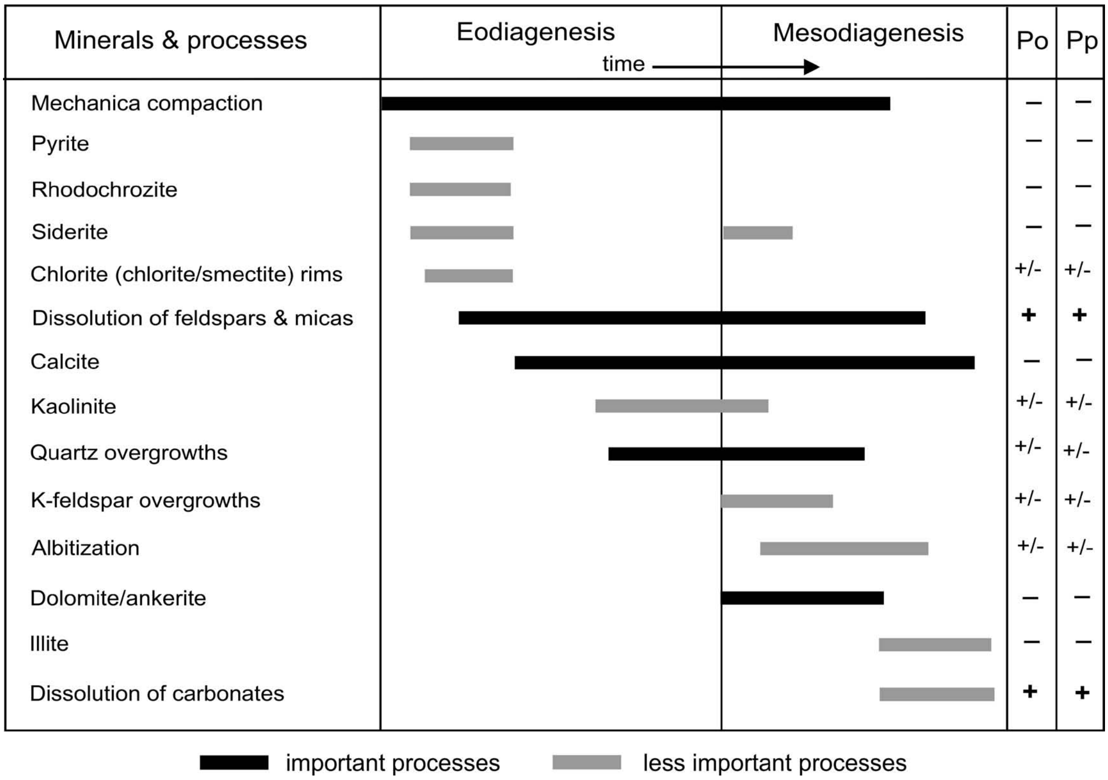

Fig. 9. The diagenetic sequence of the Middle Miocene deposits: Po – porosity, Pp – permeability, +/- - positive/negative influence on development of porosity and permeability of deposit

of quartz cement may have developed slowly at low temperature of about 40°C (Worden & Morad, 2000). The meteoric water containing silica, dissolution of detrital feldspar grains and transformation to kaolinite were the most important source of silica for the quartz cement in the early diage nesis.

Mesodiagenesis

Quartz overgrowths formation was continued. Replacement of quartz and feldspar by carbonates could have a significant importance as silica source for quartz cement at greater depth. Other possible additional source of silica was dissolution of K-feldspar during burial diagenesis. Quartz cement was strongly affected by temperature as its increase accelerates the rate of cementation (Oelkers *et al.*, 1996). The strongest development of the authigenic quartz overgrowths in the Middle Miocene sandstones was found in well Jodłówka 18, where they are most deeply located from all the analysed samples.

Locally, blocky kaolinite replaced of vermicular kaolinite. It is the result of dissolution-crystallization reaction involved by the replacement of vermiform crystals by blocky ones (Ehrenberg *et al.*, 1993). Osborne *et al.* (1994) estimated the crystallization temperature for blocky kaolinite at about 50–80°C.

The K-feldspar overgrowths on detrital feldspar grains postdated quartz overgrowths and predated calcite cement (Fig. 5F). K-feldspar precipitation requires high silica activities and high K^+/H^+ ratios (Morad *et al.,* 2000). Residual brines were the possible source for K^+ in the Middle Miocene sandstones. Additional brines were normally acidic and thus capable of dissolving detrital feldspar (Rossi *et al.*, 2002).

Feldspar albitization is a common form of burial diagenesis in oil field sandstones. The onset of feldspar albitization may be at temperatures as low as 65°C, but the wholesale albitization occurs at temperatures of about 100–130°C (Worden & Morad, 2000). The plagioclase albitization occurs at shallower burial depths and lower temperatures than it is characteristic for the albitization of K-feldspar (Morad *et al.*, 1990). It could explain the co-existence of “fresh” K-feldspar and dissolved/albitized plagioclase in the studied sandstones.

Locally, rhomboedrons of siderite with high content of magnesium (sideroplesite) grow up on a rhodochrosite nodule (Fig. 5E). High-Mg siderites are typically formed at increased temperatures (Morad *et al.*, 1994).

Dolomite rhombohedrons postdated quartz overgrowths and predated calcite cement in the studied sandstones (Figs 5A–C, 7A). According to De Souza *et al.* (1995), rhombohedrons of dolomite and ankerite indicate that these minerals have been formed through direct precipitation from porewaters. The source of the cations Mg^{2+}, Fe^{2+}, Mn^{2+} and Ca^{2+} for carbonates in mesodiagenesis could have been the transformation of detrital clay minerals (illite-smectite) in the clay rocks (Boles & Franks, 1979). Additional dolomite could have precipitated from brines of high concentration and high Mg/Ca ratios (Usdovski, 1994; *vide* Rossi *et al.*, 2002).

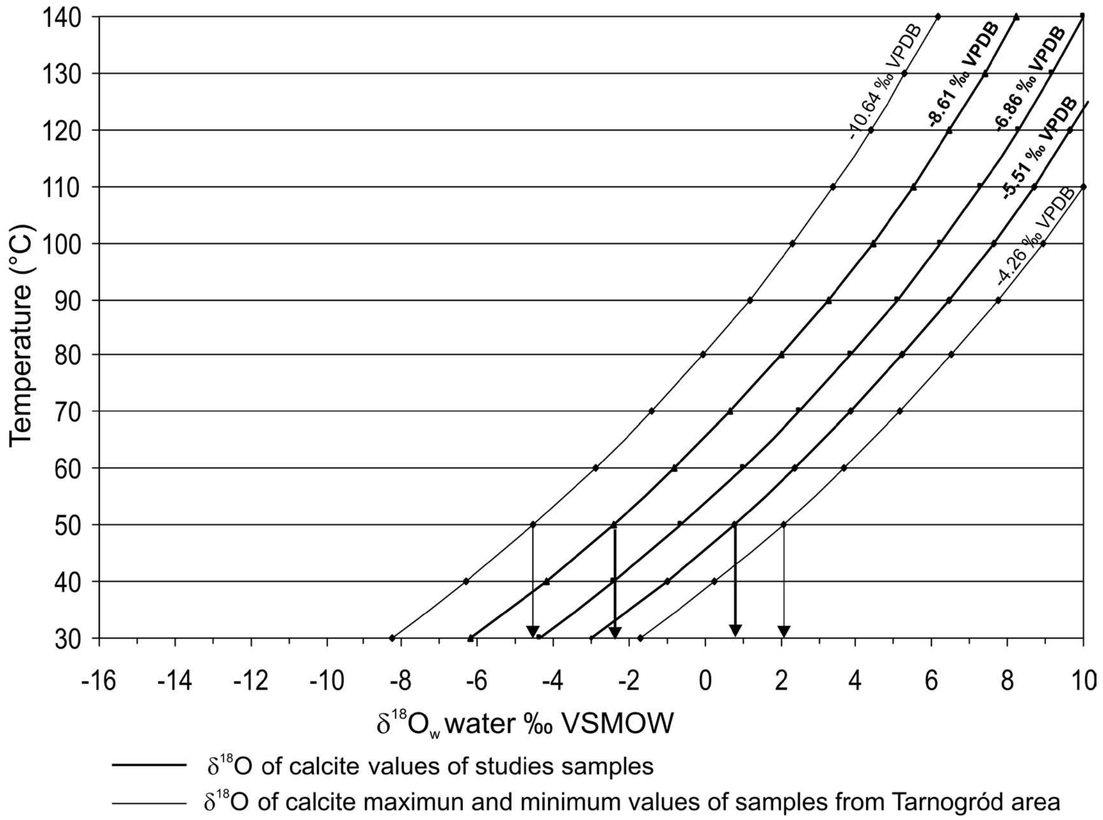

Fig. 10. Plot of $\delta^{18}O$ porewater versus temperature for calcite cement (Friedman & O'Neil, 1977)

Calcite cementation, which began in eodiagenesis, continued during mesodiagenesis. The $\delta^{13}C$ values of calcite, in average of about –2.5‰$_{VPDB}$, suggest derivation of carbon from microbial methanogenesis of organic matter. The calculated precipitation temperature of polikilitopic calcite from the fluid inclusions of about 50°C, was adopted in the fractionation equation of Friedman and O'Neil (1977). The $\delta^{18}O$ data of this calcite indicate its precipitation from pore water, which was a mixture of marine and meteoric waters with $\delta^{18}O_{VSMOW}$ between –2.5 to 1.0‰ (Fig. 10). Microscopic observations of quartz overgrowths and dolomite/ankerite rhombohedrons surrounded by calcite, indicate that some calcite could have crystallized at higher temperatures. This mineral precipitates from the pore water enriched in the ^{18}O isotope as a result of interaction of water – sediment during the burial process of deposits (Longstaffe & Avalon, 1987). Calcite which form in the late stage of diagenesis is usually enriched in iron. In the studied sandstones, calcium needed for the creation of calcite may be derived from the dissolution of previously formed calcite cements, from biogenic carbonates and dissolution of calcium-rich plagioclases. However, according to Morad *et al.* (1990), albitization of plagioclases is a limited source of calcium for the calcite formation. Boles and Franks (1979) point to another important potential source of calcium for calcite cementation in sandstones – the transformation of smectite to illite. According to Hess and Abid (1998), this reaction is also a possible source of iron for the late diagenetic Fe-calcite.

The process of dissolution of the potassium feldspar grains continued during late diagenesis. Organic acids and CO_2 released during organic matter maturation are responsible for the feldspar dissolution process in the deeper sediments (Meshri, 1986). Locally, the calcite cement was dissolved also. According to Moussavi-Haramy and Brenner (1993), the dissolution of carbonate cements was due to the delivery of acidic water and CO_2 produced during the thermal maturation of organic matter in clay sediments.

The growth of fibrous illite on the authigenic minerals (including quartz and calcite) is an evidence of its late crystallization. In the studied Middle Miocene sandstones, the formation of fibrous illite can be connected with the recrystallization of clay minerals from detrital matrix (Amireh *et al.*, 1994). Moreover, the dissolution of K-feldspar during burial diagnesis releases silica, which can precipitate as quartz and illite (Barclay & Worden, 2000). The process of illitization is affected by such factors as the depth of sediment deposition and temperature (Chuhan *et al.*, 2001), as it is confirmed by the local appearance of fibrous illite in the Jodłówka 18 well, at depths below 1.9 km. The formation of illite is associated with a reduced flow of pore waters during deep burial of sediment in close to neutral conditions (Van Keer *et al.*, 1998). Kantorowicz (1990) estimated the crystallization temperature of authigenic illite at about 100°C.

Thermal maturity of organic matter occurring in the Middle Miocene rocks of the Carpathian Foredeep was studied by Nowak (1999). The vitrinite reflectance (R_o) varies in the range of 0.41–0.70%. These values are characteristic of a transitional stage between immature and mature stages. The R_o values suggest the temperatures of about 60 – 80°C, which affected the Miocene rocks.

Evolution of reservoir properties

Reservoir properties of the Middle Miocene sandstones were subject to successive deterioration with an increase in burial depth (Fig. 8). The diagenetic alteration and reservoir evolution of the Middle Miocene sandstones were controlled by detrital composition, depositional facies, changes in the pore-water chemistry and maximum burial depth reached by the sandstones. Effects of the following diagenetic processes can be observed in the sandstones: compaction, cementation, dissolution, replacement and alteration. Compaction (mainly mechanical compaction which includes grain rearrangement and plastic deformation of mica and ductile grains) and cementation were the most important processes, which significantly reduced the primary porosity of the investigated deposits. The most significant role in the cements is played by carbonates, quartz and authigenic clay minerals. The cementation is responsible for reducing porosity in the Middle Miocene sandstone and the calcite cement is the most important one. However, the precipitation of early fringe cements (chlorite/smectite-chlorite rims and quartz overgrowths) bound the sediment, preventing from mechanical compaction, and resulting in preservation of a part of primary porosity. The plot of the total volume of intergranular volume versus cement volume (Houseknecht, 1987) reveals that the compaction has been far more important in the porosity destruction than the cementation (Fig. 11). A position of the projection points of samples in the diagram of Houseknecht (1987) indicates that the reduction of primary porosity of sandstones was mainly associated with the compaction. Calcite cementation was regionally less important due to its unequal extent. However, it strongly reduces porosity and decreases permeability to none. Primary porosity was reduced due to compaction by about 26%, and due to cementation – by approximately 35% on the average (Fig. 11). The effects of compaction and cementation in porosity reduction of the Middle Miocene sandstones of the Tarnogród area were similar (Maliszewska *et al.*, 2004).

Dissolution was another significant diagenetic process affecting porosity of the sandstones and resulting in the formation of secondary porosity. This process exerted an effect mostly on feldspar grains, lithoclasts and the calcite cement (Fig. 3E). Locally, the dissolution of detrital grains (mainly feldspar) has resulted in oversized intergranular pores that display variable degrees of connectivity. The decay of soft parts of organisms, especially foraminifers, was important because many of shell remained empty (Fig. 3F; Maliszewska *et al.*, 2004).

Also, the replacement of *e.g.* detrital grains by carbonates (Figs 3B, D) can reduce porosity. The effect of alteration processes on porosity and permeability is variable. Fibrous illite certainly reduced permeability of rocks (Fig. 7E) and, for example, the formation of kaolinite at the expense of micas may have caused an increase in porosity and permeability (Fig. 3D).

The sandstones of the proximal delta part are characterized by a little higher content of quartz, feldspar and lithoclasts and by lower content of micas, bioclasts and matrix in comparison to the sandstones of distal part. There was no evidence of any difference related to the type and content of cements in the sandstones. The porosity of the sandstones from the proximal delta is mostly higher than the porosity from distal part of mouth bars, often about 30%. The primary porosity prevails over the secondary porosity in all sediments. Effects of compaction and cementation processes are the same in all facies associations.

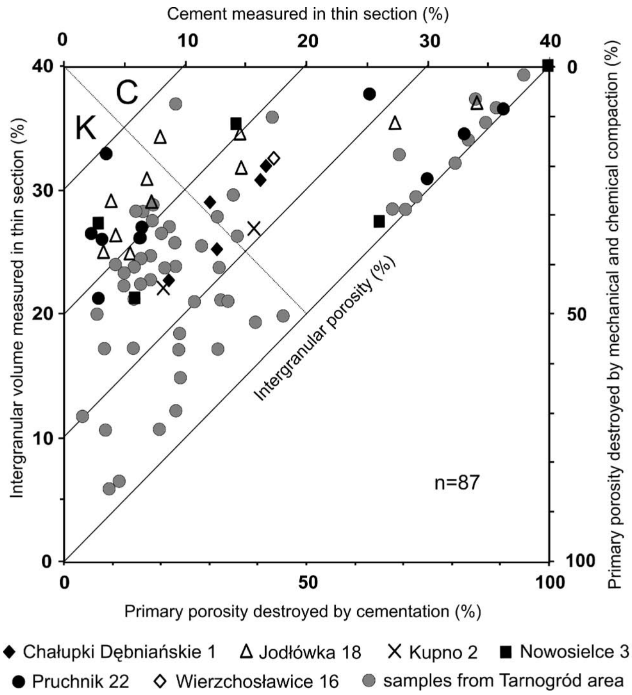

Fig. 11. Diagram of Houseknecht (1987) showing the effect of compaction and cementation on porosity of the Middle Miocene sandstones: C – cementation predominance, K – compaction predominance

Leśniak *et al.* (2007) examined the Middle Miocene sandstones in the Rzeszów area in the Carpathian Foredeep. Their conclusion was that the reservoir properties of the Middle Miocene sandstones are generally steered by the type of sedimentation, grain size diameter and compaction.

CONCLUSIONS

The Middle Miocene sandstones represent very-fine to medium-grained subarkosic and sublithic arenites and wackes. The detrital framework constituents of the Middle Miocene sandstones are dominated by quartz, feldspar and subordinated rock fragments and micas. Cement types recognized in the present study include dominant: Fe-calcite, quartz overgrowths, dolomite, siderite and kaolinite. K-feldspar overgrowth, chlorite (chlorite-smectite) rims, illite, pyrite and rhodochrosite are subordinate cements of sandstones.

The reservoir properties of sandstones is controlled by depositional facies, detrital composition, influx of meteoric waters and the depth of burial reached by the sandstones.

Evolution pathways of diagenetic and related reservoir properties of the Middle Miocene sandstones have been accomplished during eo- and mesodiagenesis.

The eodiagenesis includes mechanical compaction, development of chlorite (chlorite-smectite), pyrite, siderite, rhodochrosite, dissolution of feldspar and micas grains, micrite calcite cementation, crystallization of kaolinite and quartz overgrowths. The mesodiagenesis includes quartz and K-feldspar overgrowths, albitization, crystallization of dolomite/ankerite and magnesian siderite, poikilotopic calcite cementation, dissolution of feldspar grains and calcite cement and development of illite.

The results of investigations can suggest that the Middle Miocene deposits underwent diagenetic processes at a temperature not higher than 100°C. The albitization indicates the temperature of above 65°C and appearance of fibrous illite of about 100°C. However, the results of vitrinite reflectance studies indicate the maximum temperature of about 80°C.

The Middle Miocene sandstones show good and very good filtration abilities. Sandstone porosity very often exceeds 20% and permeability is above 100 mD. Primary intergranular porosity prevails over secondary intragranular and intercrystalline porosity. Porous space parameters measured in porosimeter show the following trend: porosimetric porosity 14.03–14.76%, average amount of pores 1 μm from 41 to 91%, the threshold diameter of 3–50 μm and hysteresis 21–84%.

Effects of the following diagenetic processes can be observed in the sandstones: compaction, cementation, dissolution, replacement and alteration. The porosity of the sediments decreases with increasing depth of burial due to the process of mechanical compaction. Locally, Fe-calcite cementation strongly reduces porosity and decrease permeability to none. Primary porosity was reduced due to compaction by about 26%, and due to cementation – by approximately 35% on the average. Some increase of porosity was caused by dissolution of detrital grains, mainly feldspars and decay of the soft parts of organisms.

Good reservoir properties of the studied sandstones are undoubtedly related to their shallow burial (the majority of samples are from the depth up to 1 km). The best filtration quality is in the purest sandstones with the smallest amount of carbonate cement and the lowest ductile grains content.

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