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# GEOLOGY AND PETROLEUM GEOCHEMISTRY OF MIOCENE STRATA IN THE POLISH AND UKRAINIAN CARPATHIAN FOREDEEP AND ITS PALAEOZOIC–MESOZOIC BASEMENT

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**Abstract:** This thematic issue of *Annales Societatis Geologorum Poloniae* contains a set of papers presenting results of a special research project entitled "Petroleum exploration prospectives and hydrocarbon potential of the Miocene strata and Mesozoic–Palaeozoic basement in the borderland area of Poland and Ukraine", led by research teams from the AGH University of Science and Technology in Kraków and the Polish Geological Institute – National Research Institute in Warsaw. The objective of this paper is determination of the geological and geochemical conditions, 1-D and 2-D modelling of petroleum processes and petroleum systems and their influence on the prospectives of hydrocarbon exploration of the Miocene strata in the Polish and Ukrainian Carpathian Foredeep and its Palaeozoic–Mesozoic basement. In particular, a coherent model of geological structure of the area, based both on the synthesis of the earlier published data and on new results of palynological studies of the Upper Precambrian and Lower Palaeozoic, is given. New data on microfacies of the Upper Jurassic and Lower Cretaceous strata and on sedimentology, geochemistry and micropalaeontology of the Middle Miocene rocks are presented.

**Key words:** petroleum system, prospectives of hydrocarbon exploration, Miocene, Palaeozoic–Mesozoic basement, Carpathian Foredeep, Poland, Ukraine.

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## INTRODUCTION

The Carpathian Foredeep Basin stretches for more than 1,300 km from the Vienna area (Austria) to the Iron Gate on the Danube (Romania). To the west, it is linked with the Alpine Molasse Basin, and to the east, it passes into the Balkan foreland basin. The Carpathian Foredeep is filled predominantly with Miocene siliciclastic sediments, which overlie the basement of the West and East-European platforms covered by Permian–Mesozoic terrestrial and shelf sediments and locally by Palaeogene deposits (Oszczypko *et al.*, 2006, and references therein).

The sedimentary, structural and geodynamic evolution of the Carpathian Foredeep Basin in Poland and Ukraine was previously summarized by Oszczypko *et al.* (2006), whereas aspects of pre-Permian stratigraphy and tectonics in the Polish component were synthesized by Buła *et al.* (2008).

The frontal part of the Polish and Ukrainian Carpathians constitutes one of the oldest petroleum-producing regions in the world. The exploitation of oil started in 1853 in Bóbrka village near Krosno in Poland in the Outer (Flysch) Carpathians, and natural gas production began in 1920 in Dashava village near Boryslav in Ukraine, in the autochthonous Miocene strata of the Bilche-Volytsia Unit of the Carpathian Foredeep (Karnkowski, 1999; Vul *et al.*, 1998a, b; Fedyshyn *et al.*, 2001). At the end of the 1930s, petroleum exploration started in the Carpathian Foreland, and in the years of 1945–1955 petroleum industry in Poland and Ukraine was restored and reorganized. The exploration activity was focused mainly on the Outer (Flysch) Carpathians and partly on the Carpathian Foredeep (Karnkowski, 1994, 1999). Intensive development of petroleum exploration took place in the middle of the 1960s and in the 1970s (Karnkowski, 1999; Fedyshyn *et al.*, 2001; Myśliwiec *et al.*, 2006; Popadyuk *et al.*, 2006).

Part of the Carpathian Foredeep Basin encompassing the south-eastern Poland and western Ukraine has been the focus of a special research project entitled "Petroleum exploration prospectives and hydrocarbon potential of the Miocene strata and Mesozoic–Palaeozoic basement in the borderland area of Poland and Ukraine" led by research teams from the Faculty of Geology, Geophysics and Environmental Protection at the AGH University of Science and Technology in Kraków (leader: M. J. Kotarba) and the Polish Geological Institute–National Research Institute in Warsaw (leader: T. M. Peryt).

The purpose of our studies is to evaluate the hydrocarbon potential of autochthonous Miocene strata of the Carpathian Foredeep and its Palaeozoic–Mesozoic basement in SE Poland (between Kraków and the Polish-Ukrainian border) and western Ukraine (between Ukrainian-Polish border and Ivano-Frankivs'k, and in Lopushna area near the boundary between Ukraine and Romania), to characterize their petroleum system, and to determine exploration prospects. The conditions of hydrocarbon generation, expulsion, migration and accumulation within the sedimentary basins, as well as geological (lithological, sedimentological and tectonic) constraints of these processes have been determined. The possibility of generation of hydrocarbons and their migration from the Lower to Upper Palaeozoic strata in the basement of the Carpathian Foredeep and from the flysch source rocks of the Outer Carpathians to the Mesozoic strata of the basement have also been analysed. Analytical studies of source and reservoir rocks and 1-D and 2-D numerical modelling of hydrocarbon generation, expulsion and migration processes and filling of traps in relation with geological lithofacies analysis and dynamic reconstruction of development of sedimentary basins enabled scientists to establish petroleum systems, regional evaluation of their petroleum value and ranking of areas of prospectivity for conventional petroleum exploration. Such studies are crucial for directing a future exploration for oil and gas in the near-border areas of the Carpathian Foredeep in Poland and Ukraine. The present work synthesises the available geological, geophysical, geochemical, petrological and petrophysical data, at local and regional scales, with the results of new analytical studies and modelling.

The main database used for interpretations consisted of numerical geophysical data (seismic and well log geophysics) acquired during years of petroleum exploration in the Carpathian Petroleum Province. These, aided with geochemical, geothermal and geological data were used for modelling of petroleum processes (generation, expulsion, migration and accumulation), which provided the basis for establishing petroleum systems in the autochthonous Miocene strata of the Carpathian Foredeep and its Palaeozoic–Mesozoic basement.

The principal results of the project are presented in a series of papers enclosed in this thematic issue of *Annales Societatis Geologorum Poloniae* (Buła & Habryn, 2011; Garecka & Olszewska, 2011; Gedl & Peryt, 2011; Jachowicz-Zdanowska, 2011a; Kosakowski & Wróbel, 2011; Kosakowski *et al.*, 2011; Kotarba, 2011; Kotarba & Koltun, 2011; Kotarba *et al.*, 2011a, b, c; Krajewski *et al.*, 2011a, b; Kuberska *et al.*, 2011; Kurovets *et al.*, 2011; Więcław, 2011; Więcław *et al.*, 2011). In addition, some results have already been published previously (Jarmołowicz-Szulc *et al.*, 2011; Jasionowski & Peryt, 2010; Kowalski *et al.*, 2010; Kozłowska *et al.*, 2011; Peryt & Gedl, 2010; Peryt & Peryt, 2009; Peryt *et al.*, 2008, 2010; Więcław *et al.*, 2008, 2010), and will be published in the next volumes of *Annales Societatis Geologorum Poloniae* (Kosakowski *et al.*, in press, a; Lis & Wysocka, in press;Więcław *et al.*, in press, a; Wróbel *et al.*, in press) and other journals (Kosakowski & Wróbel, in press; Kosakowski *et al.*, in press, b, c, d; Kotarba, in press; Więcław *et al.*, in press, b). All these results contributed extensively to the knowledge of both basic and applied nature.

## GEOLOGICAL SETTING

Two centuries of geological studies of the Carpathian Foredeep in SE Poland and western Ukraine resulted in numerous papers and monographs. One of them is the geological atlas of Galicia (*Atlas Geologiczny Galicji*) realized in years 1885–1914, which can be treated as a milestone, greatly contributing to deepening the knowledge of the structure of the foredeep. The sedimentary, structural and geodynamic evolution of the Carpathian Foredeep in Poland and Ukraine was summarized by Oszczypko *et al.* (2006, with references therein).

There exist significant differences in views concerning the palaeotectonic and palaeogeographic evolution of the area of the Carpathian Foredeep during the Proterozoic and Palaeozoic and the age of consolidation of various tectonic units (see Buła & Habryn, 2011 for review). Buła and Habryn (2011) clarified some of the controversies regarding the above-mentioned problems and presented a coherent model of geological structure in the area that is based both on the synthesis of the earlier published data as well as on the results of palynological studies. In particular, they successfully adopted the scheme of geological structure developed previously for SE Poland (Buła *et al.*, 2008, and references therein).

Two regional tectonic units have been distinguished in southern and south-eastern Poland: the Upper Silesian and Małopolska blocks (Buła & Jachowicz, 1996; Buła *et al.*, 1997). They are separated by the Kraków–Lubliniec Fault Zone, and are located in the East-European Craton foreland (Buła & Habryn, 2008). The Małopolska Block represents a tectonic unit of unknown provenance. The Kielce part of the Holy Cross Mountains is included in this block (Pożaryski, 1990; Pożaryski *et al.*, 1992) and, thus, the northern boundary of the Małopolska Block is marked by the Holy Cross Mountains Fault. Buła and Habryn (2011) showed that both the Małopolska Block and the Holy Cross Mountains Fault continue into the territory of Ukraine.

In the Małopolska Block, crystalline Precambrian basement has not been encountered yet. The oldest Precambrian rocks recorded within the Małopolska Block are clayey-muddy and sandy deposits interbedded with conglomerates or sandy gravels that show many features of flysch deposits (*e.g.*, Samsonowicz, 1955; Głowacki & Karnkowski, 1963; Kruglov & Tsypko, 1988; Buła, 2000; Żelaźniewicz *et al.*,

2009). These rocks have undergone strong diagenesis, or slight metamorphism (anchimetamorphism), and previously have been considered as Precambrian (Riphean and Vendian) to early Cambrian in age (Buła & Habryn, 2011, and Jachowicz-Zdanowska, 2011b, with references therein). Now, these deposits are regarded to be of a late Ediacaran age (Buła & Habryn, 2011).

The studies on rock samples previously considered to be of Precambrian or early Palaeozoic ages in western Ukraine (Kruglov & Tsypko, 1988; Drygant, 2000, with references therein) permitted to verify their stratigraphic position in some cases (Jachowicz-Zdanowska, 2011a). In addition, these results indicate that further research on additional boreholes, especially those which were the basis for the stratigraphic subdivisions, but which were lacking a sufficient biostratigraphic framework, is needed.

Another result of the project is a significant progress in the understanding of the Upper Jurassic and Lower Cretaceous strata compared to the former concepts (*e.g.*, Gutowski *et al.*, 2005a, b, 2007; Urbaniec *et al.*, 2010). Krajewski *et al.* (2011a) presented a new correlation of the Upper Jurassic–Lower Cretaceous complex in SE Poland that is based on a detailed microfacies study. In western Ukraine, the microfacies study of coeval deposits made it possible to distinguish fifteen basic facies types corresponding to a narrow basinal zone, slope platform, marginal platform, and inner platform (Krajewski *et al.*, 2011b). Similarly, the study by Lis and Wysocka (in press) refined and modified the previous concepts on sedimentary mechanisms and environments of the Middle Miocene strata (*e.g.*, Kurovets *et al.*, 2004; Dziadzio *et al.*, 2006). Kuberska *et al.* (2011) published the first petrological data on sandstones from the Ukrainian Carpathian Foredeep basin. Some key sections from the basinal part of the Carpathian Foredeep basin in SE Poland and western Ukraine were subjected to detailed micropalaeontological examination (foraminifers and calcareous nannoplankton), which enabled one to correlate the Middle Miocene deposits between the both areas (Garecka & Olszewska, 2011). In general, the new results confirmed earlier concepts based on these two groups of microfossils and developed independently in Poland and Ukraine (*e.g.*, Andreyeva-Grigorovich *et al.*, 1997, 2003; Olszewska, 1999; Peryt, 1997, 1999; Peryt *et al.*, 1998). In addition to the basinal part of the Carpathian Foredeep, some sections from the marginal part of the basin were subject to detailed palaeoenvironmental interpretation of the strata adjacent to evaporites, based on foraminifers and dinoflagellate cysts and carbon and oxygen isotopes of bulk rock samples and individual foraminifer taxa (Peryt & Peryt, 2009; Peryt & Gedl, 2010; Gedl & Peryt, 2011). In particular, diversified palynological and foraminiferal assemblages recorded in strata exposed in the Kudryntsi section (western Ukraine) above the gypsum indicated variable environmental conditions during the late Badenian transgression: restricted environment during beginning of the transgression, and gradual passage into marine environment during its later stages (Peryt & Peryt, 2009; Gedl & Peryt, 2011). The foraminiferal assemblages from the Upper Badenian of the Kudryntsi section contain *Elphidium reginum* (d'Orbigny) and *Elphidium koberi* Tollmann (Gedl & Peryt, 2011). Both species are common for the Sarmatian, and *Elphidium reginum* (d'Orbigny) is regarded as the index species of the biozone in the Lower Sarmatian. The occurrence of *Elphidium reginum* (d'Orbigny) and *Elphidium koberi* Tollmann in the Upper Badenian of Kudryntsi is, therefore, related to specific environmental conditions, which were very similar to those characteristic of the Sarmatian (Gedl & Peryt, 2011).

## PETROLEUM OCCURRENCE, AND GENERATION, MIGRATION AND ACCUMULATION PROCESSES

### Palaeozoic–Mesozoic basement

Twenty-six oil, gas-condensate and gas fields within the Palaeozoic–Mesozoic basement of the Polish part of the Carpathian Foredeep (from 1948), and eleven fields within the Mesozoic basement of the Ukrainian part of the Carpathian Foredeep (since 1944), have been discovered so far (Kotarba *et al.*, 2011c).

The major petroleum reservoir rocks in the Polish part of the Palaeozoic–Mesozoic basement are: Middle and Upper Devonian carbonates, Lower Carboniferous carbonates, Upper Jurassic limestones, Upper Cretaceous (Cenomanian) sandstones, and Upper Cretaceous (Senonian) sandstones locally intercalated with marls (Karnkowski, 1999; Florek *et al.*, 2006; Myśliwiec *et al.*, 2006). Moreover, some small hydrocarbon accumulations were also discovered in the Cambrian sandstones and Ordovician–Silurian strata (Karnkowski, 1999; Kotarba *et al.*, 2011c). The traps in oil and gas deposits of the Palaeozoic–Mesozoic basement are sealed by either the Miocene strata alone, or the Miocene cover and the Upper Cretaceous marls. The Carpathian Overthrust and flysch strata provide an additional seal (Kotarba & Jawor, 1993; Kotarba *et al.*, 2011c).

Eleven fields were discovered within the Mesozoic basement of the Ukrainian part of the Carpathian Foredeep (Vul *et al.*, 1998a, b; Shcherba *et al.*, 1987; Kurovets *et al.*, 2011; Kotarba *et al.*, 2011c). Three of them are oil fields. The Kokhanivka and Orkhovychi fields are heavy oil accumulations in the Upper Jurassic reservoirs and the Lopushna oil field in the south-eastern part of the platform basement under the Carpathian Overthrust is located in the Upper Jurassic, Cretaceous (Albian–Cenomanian) and Eocene reservoirs. Seven fields contain condensate and/or gas in combined Mesozoic–Miocene reservoirs (Kurovets *et al.*, 2011; Kotarba *et al.*, 2011b, c).

In the Palaeozoic–Mesozoic basement of the Polish and Ukrainian Carpathian Foredeep, five petroleum source rock horizons in nine generation and expulsion areas were identified (Fig. 1A): Ordovician–Silurian rocks (III and V areas), Middle-Upper Devonian carbonates (II and IV areas), Lower Carboniferous clastics (Culm) (I and VI areas), Middle Jurassic siliciclastics (VIII area), and Upper Jurassic carbonates (IX area) (Kosakowski *et al.*, in press, c, d; Więcław *et al.*, 2011, in press, a). The Ordovician and Silurian source rock complex with Type-II kerogen occurs in two separate areas: Busko Zdrój–Rzeszów and Tarnogród–Lubaczów. In the Busko Zdrój–Rzeszów area, the best source

rocks containing about 3 wt% of TOC were found in the Nawsie-1 and Hermanowa-1 wells. Favourable source rocks in the Tarnogród–Lubaczów area occur only in a narrow zone in the vicinity of Wola Obszańska, where median TOC of up to 1.74 wt% was recorded (Więcław *et al.*, in press, a). The Middle and Upper Devonian carbonate strata contain small intercalations of source rocks of TOC content more than 1 wt% and showing thicknesses of a few centimetres in the Kraków–Brzesko area, mostly in the vicinity of Grobla. The oil-Type II kerogen dominates, with local admixtures of the gas-prone Type III kerogen (Więcław *et al.*, 2011). The source rocks contain the gas-prone, Type-III kerogen in the Lower Carboniferous clastic facies occurring only in the Polish part of the study area, mostly between Dębica and Rzeszów, beneath the Carpathian Overthrust (Więcław *et al.*, 2011). Their hydrocarbon potential is generally low. The Middle Jurassic strata containing the source rocks capable of generating thermogenic hydrocarbons occur in the Dębica–Rzeszów and the Mostys'ka–Horodok areas. Hydrocarbon potential of the gas-prone, Type-III kerogen of dispersed organic matter is generally low. Admixtures of Type-II kerogen occur locally only (Kosakowski *et al.*, in press, c, d; Więcław *et al.*, 2010). In the Polish part of the basement of the Carpathian Foredeep, the Upper Jurassic carbonates are usually low in organic matter and only locally show medium TOC concentrations. In the Ukrainian part, in the vicinity of Mostys'ka and Horodok, the Upper Jurassic carbonate strata contain oil-prone, Type-II and Type-IIS kerogens favourable for thermogenic hydrocarbon generation (Kosakowski *et al.*, in press, c, d; Więcław *et al.*, 2010). Source rocks of Jurassic strata in the Polish Outer Carpathians were evaluated by Golonka *et al.* (2009).

Using comprehensive, geochemical methods it was possible to explain the genetic relationships between dispersed organic matter and liquid (oils and condensates) and gaseous hydrocarbons accumulated in the Palaeozoic–Mesozoic strata of the Carpathian Foredeep basement between Kraków and Ivano-Frankivs'k (Kosakowski *et al.*, in press, c, d; Kotarba, in press; Kotarba & Koltun, 2011; Więcław, 2011; Więcław *et al.*, 2010, 2011, in press, a, b). Both the 1-D and 2-D modelling of petroleum processes was carried out in sequences of twenty-seven wells and along nine cross-sections (Kosakowski & Wróbel; 2011, in press; Kosakowski *et al.*, 2011, in press, b; Wróbel *et al.*, in press). The results of such modelling enabled for precise identification of source rocks and determination of the time of generation, expulsion, migration and accumulation processes.

Below, some examples of genetic correlation between source rocks and oils, condensates and natural gases and evaluation of petroleum processes are given. Oils and natural gases from the Grobla field were generated from the Type-II kerogen with significant component of the Type-III kerogen of the Devonian source rocks (Kotarba, in press; Więcław *et al.*, 2011). The generation of hydrocarbons from the Devonian source rocks started in the late Carboniferous, but the main stage took place during the Miocene. The accumulation of hydrocarbons in the Upper Jurassic carbonate and the Upper Cretaceous sandstone reservoirs took place almost exclusively in the Miocene.

Oils and gas from the Tarnów deposit and condensate from the Łąkta deposit were produced probably mainly from the Silurian Type-II kerogen (Kotarba, in press; Więcław *et al.*, 2011). Hydrocarbon generation process from the Silurian source rocks started in the early Cretaceous, although the main phase of generation took place during the Neogene (Kosakowski & Wróbel, 2011). The migration and accumulation of hydrocarbons in structural and stratigraphic traps took place in the Neogene as well (Wróbel *et al.*, in press).

Oils and gas from the Nosówka deposit were generated from the Ordovician–Silurian Type-II kerogen (Kotarba, in press; Więcław *et al.*, 2011). The petroleum processes had two significant periods of development: the Jurassic and the Neogene. In the north-eastern part of this area, the analysed source rocks already attained higher maturity in the Jurassic, while in the south-eastern part their maturity in the main phase of the "oil window" was reached at the end of the Neogene. Hydrocarbon generation took place at the end of the Neogene (Kosakowski & Wróbel, in press; Wróbel *et al.*, in press).

The heavy, high-sulphur oils of the Lubaczów, Kokhanivka and Orkhovychi deposits were generated from the Type-IIS kerogen deposited in Upper Jurassic carbonates (Kosakowski *et al.*, 2011; Więcław, 2011; Więcław *et al.*, 2011). The Upper Jurassic source rocks generation process took place during the late Jurassic (Kosakowski *et al.*, in press, c).

### Autochthonous Miocene strata of the Carpathian Foredeep

Hydrocarbon (mostly gas, and gas-condensate, and only locally oil) accumulations occur in the autochthonous Miocene strata (*e.g.*, Karnkowski, 1999; Boyko *et al.*, 2004; Fedyshyn *et al.*, 2001; Kurovets *et al.*, 2011; Kotarba *et al.*, 2011a) of the outer part of the Carpathian Foredeep. Gas accumulations occurring in the Middle Miocene strata (Lower and Upper Badenian and Lower Sarmatian) show a clear pattern and are distributed within three zones extending close to the margin of the Carpathian Overthrust, at the front of the Carpathian orogen, and along the north-eastern limit of the outer Carpathian Foredeep (*e.g.*, Karnkowski, 1999; Krups'kyy, 2001). The largest gas deposits occur in the Lower Sarmatian strata close to the Carpathian Overthrust (Karnkowski, 1999; Fedyshyn *et al.*, 2001).

There are 101 gas and gas-condensate deposits (first discovery in 1945) in the autochthonous Miocene strata of the Polish Carpathian Foredeep, 44 gas and gas-condensate deposits, and one oil deposit in the Bilche-Volytsia Unit of the Ukrainian Carpathian Foredeep (first discovery in 1920). The condensates (Łękawica-1, Pilzno-37, Tarnów-39 and Tarnów-45 wells) and oil (Tarnów-47 well) accumulated in the lower part of the autochthonous Miocene strata of the Polish Carpathian Foredeep and were generated by organic matter dispersed in the Middle Jurassic and Lower Carboniferous clastic facies (Więcław, 2011; Kotarba & Koltun, 2006). They migrated into the Miocene strata through various faults (Kotarba & Koltun, 2006).

The results of stable carbon isotope analyses of methane, ethane, propane, butanes and pentanes, and stable hy-

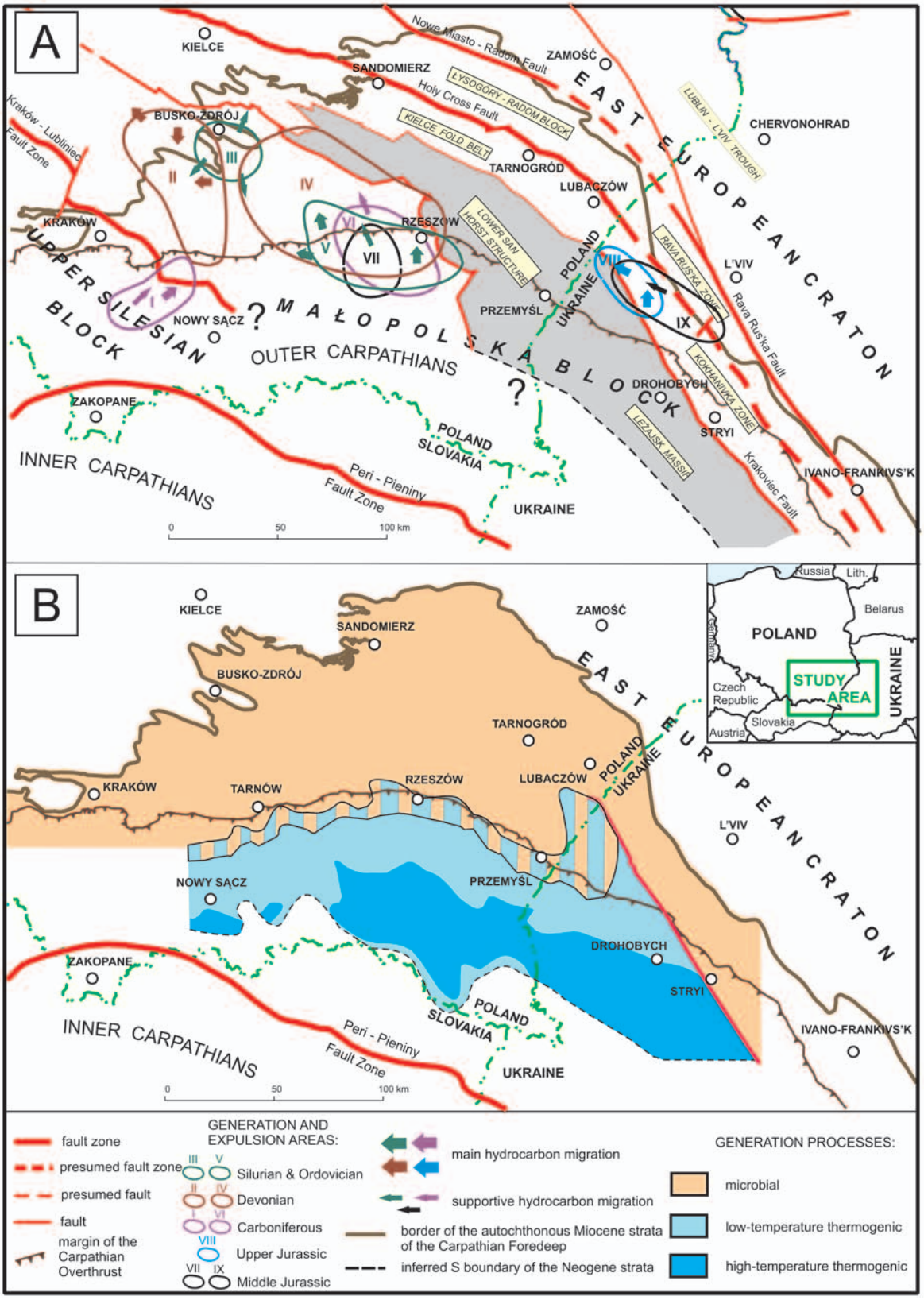


**Fig. 1.** (**A**) Tectonic sketch-map of the Palaeozoic–Mesozoic basement of the Polish and Ukrainian parts of the Carpathian Foredeep with location of generation and expulsion areas from main source rocks: I – Lower and Upper Carboniferous, II – Middle-Upper Devonian and Lower Carboniferous (?), III – Ordovician and Silurian, IV – Devonian, V – Ordovician and Silurian, VI – Lower Carboniferous, VII – Middle Jurassic, VIII – Upper Jurassic, IX – Middle Jurassic. Geology modified after Buła and Habryn (2011) and source rock areas after Kotarba *et al.* (2011c); and (**B**) sketch map of the central and eastern parts of the Polish and Ukrainian Carpathian Foredeep and locations of hydrocarbon generation test areas and zones of microbial and thermogenic processes (after Kotarba *et al.*, 2011a). Lith. – Lithuania

drogen isotope analyses of methane, all indicate that the gaseous hydrocarbons accumulated within the autochthonous Miocene strata of the Polish and Ukrainian Carpathian Foredeep were mainly generated during microbial processes, and sporadically during low-temperature thermogenic processes (Kotarba, 1998, 2011; Kotarba & Koltun, 2006, 2011). In the Lubaczów deposit, gas filled also a trap in the Upper Jurassic carbonates (Kotarba & Koltun, 2006). Genetically, this gas is a typical microbial methane, which migrated to the Upper Jurassic trap from the autochthonous Miocene strata along a fault zone (Kotarba, 1998). In the Ukrainian Carpathian Foredeep, seven fields contain condensate and/or gas and the Orkhovychi deposit contains oil in combined Mesozoic–Miocene reservoirs (Kotarba & Koltun, 2011; Kotarba *et al.*, 2011b). The microbial gases (methane, hydrogen and partly ethane and propane) were generated during microbial processes within the Miocene strata and then migrated to the Upper Jurassic and Upper Cretaceous (Cenomanian) reservoirs in the Mesozoic basement, and to the bottommost Lower Badenian Sandy-Calcareous Series reservoirs of the traps of the above mentioned deposits (Kotarba & Koltun, 2011).

The results of organic geochemistry analyses enabled for the assessment of the dispersed organic matter (DOM) contained in the autochthonous Miocene sequence of the Polish and Ukrainian parts of the Outer Carpathian Foredeep (Kotarba, 1998; Kotarba & Koltun, 2006; Kotarba *et al.*, 1998, 2005, 2011a). In the Upper Badenian strata, total organic carbon (TOC) contents vary from 0.02 to 1.48 wt% (average 0.75 wt%) in the Polish Carpathian Foredeep, and from 0.44 to 2.01 wt% (average 0.96 wt%) in the Ukrainian Carpathian Foredeep. In the Lower Sarmatian strata, the TOC varies from 0.02 to 3.22 wt% (average 0.69 wt%) in the Polish Carpathian Foredeep, and from 0.01 to 1.45 wt% (average 0.71 wt%) in the Ukrainian Carpathian Foredeep. This dispersed organic matter in marine Miocene sediments is gas-prone and terrestrial (humic) in origin.

In the Polish part of the Carpathian Foredeep, high sedimentation rates, together with rhythmic and cyclic deposition of Miocene clays and sands, as well as the vigorous generation of microbial methane resulted in gas produced in claystone beds that was accumulated in the overlaying sandstones, and capped by the succeeding claystones. The migration range of the gas was insignificant. The gas accumulated in numerous traps (compactional anticlines situated above basement uplift, sealed by the Carpathian Overthrust, sealed by faults, stratigraphic pinching out and stratigraphic traps related to unconformities). The generation and accumulation of this gas gave rise to the formation of multistorey gas fields (Kotarba *et al.*, 2011b). North and along the present edge of the Carpathian Overthrust in Ukraine, the Lower Badenian Sandy-Calcareous Series contains twelve gas and gas-condensate deposits, and one oil deposit.

## PETROLEUM PROSPECTIVES

### Palaeozoic–Mesozoic basement

Based on the results of geochemical analyses conducted for Palaeozoic (Więcław *et al.*, in press, a, b) and Mesozoic (Kosakowski *et al.*, in press, a, c) source rocks, oils and gases, and on results of 1-D (Kosakowski & Wróbel, in press; Kosakowski & Wróbel, 2011; Kosakowski *et al.*, 2011) and 2-D (Wróbel *et al.*, in press) modelling of petroleum processes, two separate petroleum systems were established: (i) the Palaeozoic–Mesozoic petroleum system of the western part of the Małopolska Block, and (ii) the Palaeozoic–Mesozoic petroleum system of the eastern part of the Małopolska Block and the western part of the Kokhanivka Zone (SE Poland – western Ukraine) (Kotarba *et al.*, 2011c). The western part of the Małopolska Block has a considerably greater prospective for oil and gas exploration than the eastern part of the Małopolska Block and the western part of the Kokhanivka Zone (Kotarba *et al.*, 2011c). Moreover, based on the same sets of geochemical and modelling data and analysis of petroleum systems, nine areas were established where hydrocarbon generation and expulsion processes proceeded at the largest scale (Kotarba *et al.*, 2011c). Seven generation and expulsion areas occur in the western part of the Małopolska Block and only two areas are present within the basement of the Carpathian Foredeep in south-eastern Poland and western Ukraine (Fig. 1A). These areas could be a starting point for strategy of a future petroleum exploration. As far as the genetic type of source rock and expulsion potential (Kotarba *et al.*, 2011c) are concerned, a greater prospective for oil and gas exploration have I and VI (Carboniferous) and III and V (Silurian and Ordovician) areas in the western part of the Małopolska Block and VIII (Upper Jurassic) can be encountered in the eastern part of the Małopolska Block and the western part of the Kokhanivka Zone (Fig. 1A). Petroleum system in the Polish Outer Carpthians was worked out by Leśniak *et al.* (2010).

### Autochthonous Miocene strata of the Carpathian Foredeep

Over 90-years-long exploration activity in the autochthonous Miocene strata of the Polish and Ukrainian Carpathian Foredeep was mainly focused on its northern part, along the present edge of the Carpathian Overthrust. Gases accumulated in this part of the Carpathian Foredeep are mainly of microbial origin (Kotarba, 1998, 2011; Kotarba & Koltun, 2011). Oil from one Orkhovychi deposit (Ukraine) and from petroleum inflows near Tarnów (Poland) migrated to the Miocene strata from the Mesozoic basement (Więcław, 2011; Więcław *et al.*, in press, b). Recent use of modern, sophisticated 3-D seismic and lithologic-sedimentological methods enabled one to discover several gas fields (Myśliwiec, 2004; Myśliwiec *et al.*, 2006). This long and intense exploration action brought about great effects and it seems likely that only few gas fields are waiting for discovery in that area.

Another situation has been encountered in the autochthonous Miocene strata south of and beneath the Carpathian Overthrust. The Upper Badenian and Lower Sarmatian strata probably prevail there as on the north and along the present edge of the Carpathian Overthrust; thus, they can also contain a similar lithofacies development, and have similar quantity and similar genetic type of gas-prone

kerogen (Kotarba *et al.*, 2011a). Their thickness beneath the Carpathian Overthrust exceeds 1.5 km. Geochemical studies and TTI modelling show that the process of low-temperature thermogenic hydrocarbon generation ("oil window") began at 2,500 metres (Kotarba, 1998; Kotarba *et al.*, 1998; 2011a). At greater depths, more than 7,500 metres, a high-temperature methane generation zone ("gas window") existed within the autochthonous Lower Miocene basin (Kotarba *et al.*, 2011a). Data suggest that in both low- and high-temperature thermogenic zones, considerable quantities of gases might have been generated and accumulated (Fig. 1B). It is, therefore, highly probable that low- and high-temperature thermogenic gas accumulations can be found beneath the Outer Carpathians. This, however, would need drilling down to depths of 4 to 11 km.

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