Polish shale gas deposits in relation to selected shale gas prospective areas of Central and Eastern Europe

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A b s t r a c t. This paper describes a regional overview of selected Central and Eastern European sedimentary basins which hold the unconventional potential for shale gas and shale oil exploration that have attracted interest in the last few years. Organic-rich fine-grained rocks like black and dark-grey shales, mudstones and claystones with varying ages from Cambrian to Miocene are distributed very irregularly across Europe. A long-lasting, dynamic geological evolution and continuous reconstruction of the European continent resulted in the formation of many sedimentary basins. In some basins, biogeochemical conditions favoured preservation of accumulated organic-rich deposits and led to the generation of hydrocarbons after burial and reaching appropriate maturity levels. Even though shale gas and shale oil exploration in Europe is still in its infancy, shale formations were analyzed before as the source rocks in conventional petroleum systems. Parameters that were used to describe source rocks e.g.: total organic carbon, maturity, thickness, depth of occurrence and areal extent, can indicate preliminary potential for shale gas exploration and allow estimating first resource values. Currently the most intense shale gas exploration takes place in Poland where over 42 wells have been drilled and over 100 concessions for unconventional hydrocarbon exploration have been granted. Upper Ordovician and lower Silurian shales at the East European Craton (Baltic, Lublin and Podlasie basins) are the major targets for unconventional exploration in Poland. In Central and Eastern Europe, evaluation of the unconventional potential of gas-bearing shale formations is carried out also in Ukraine, Lithuania, Austria, Czech Republic, Hungary, Romania, Bulgaria, Moldova and the European sector of Turkey. Despite the fact that each shale rock differs from another by geochemical, petrographical, petrophysical, mechanical and other parameters, some similarities can be seen such as marine type of depositional environment with the predominance of type II kerogen or specific organic matter content. Recoverable resources of shale gas throughout Europe are believed to be as large as 17.67 trillion m^3 (624 Tcf) and Poland, Ukraine, France with United Kingdom are thought to have the greatest resources.

Keywords: *Europe, shale gas, shale oil, sedimentary basins, unconventional hydrocarbons, shale gas potential*

The purpose of this article is to introduce the reader in the most general overview of information on European unconventional hydrocarbon deposits, such as crude oil and natural gas from shales, which have become an attractive object of study for many companies in the oil and gas sector in the past few years due to the development of new stimulation technologies. Shales and other fine clastic rocks enriched in organic matter, such as mudstones and claystones that may contain crude oil and natural gas, are distributed unevenly on the European continent. The broad and irregular distribution of the deposits is an evidence for the development and decline of environments favouring accumulation of fine clastic sediments enriched in organic matter. Migration of fine clastic depositional environments reflects the structural, tectonic and palaeogeographic evolution of the European continent, global or local sea level-changes and biological productivity concentrated in subsurface waters. As a consequence of the dynamic history and repeated restructuring of the European continent, marine areas appeared and disappeared quite frequently and favoured accumulation of sedimentary rocks characterised by a higher content of organic matter. As a result, Europe's hydrocarbon source rocks, which are the targets for exploration of unconventional deposits, are characterised by a high stratigraphic and geographic range, so that their age spans from the lower Paleozoic through the Mesozoic to the Cenozoic in the territories of Poland, Romania, Bulgaria, Hungary and Ukraine (Fig. 1, 2). Apart from those areas, shales of various types and age, which are potential targets for exploration of unconventional resources, are also found in Spain, Austria, the Czech Republic, Lithuania, Germany, France and the UK. In the European sector of the Arctic, on the Svalbard Archipelago and Novaya Zemlya, there are also shales and fine clastic rocks targeted by intense oil exploration.

The common heterogeneity of shales, resulting in their variable geochemical, petrographical, petrophysical and mechanical properties, suggests that shales in Poland are probably so different from their counterparts in Europe and especially the US, that it is likely they will require a very specific approach to the planned stimulation operations. Due to their peculiarity, it is necessary to determine thoroughly their ability to generate, retain and expulse hydrocarbons. Such a research approach should enable understanding of this fine clastic and organic matter-rich depositional system with its biological, chemical and physical conditions, which has transformed into a conventional and unconventional petroleum play as a result of burial. Although the article does not address how to solve the research problems, it can contribute to a fuller understanding of the fundamental differences of selected geological features between the Polish shales and their counterparts from Central and Eastern Europe. The paper focuses primarily on areas with the most prospective Polish and Central and Eastern European shales, which are considered by many authors to be promising for profitable gas production. The most promising shales are those from the Vienna, Pannonian, Dnieper-Donets, Baltic, Podlasie and Lublin

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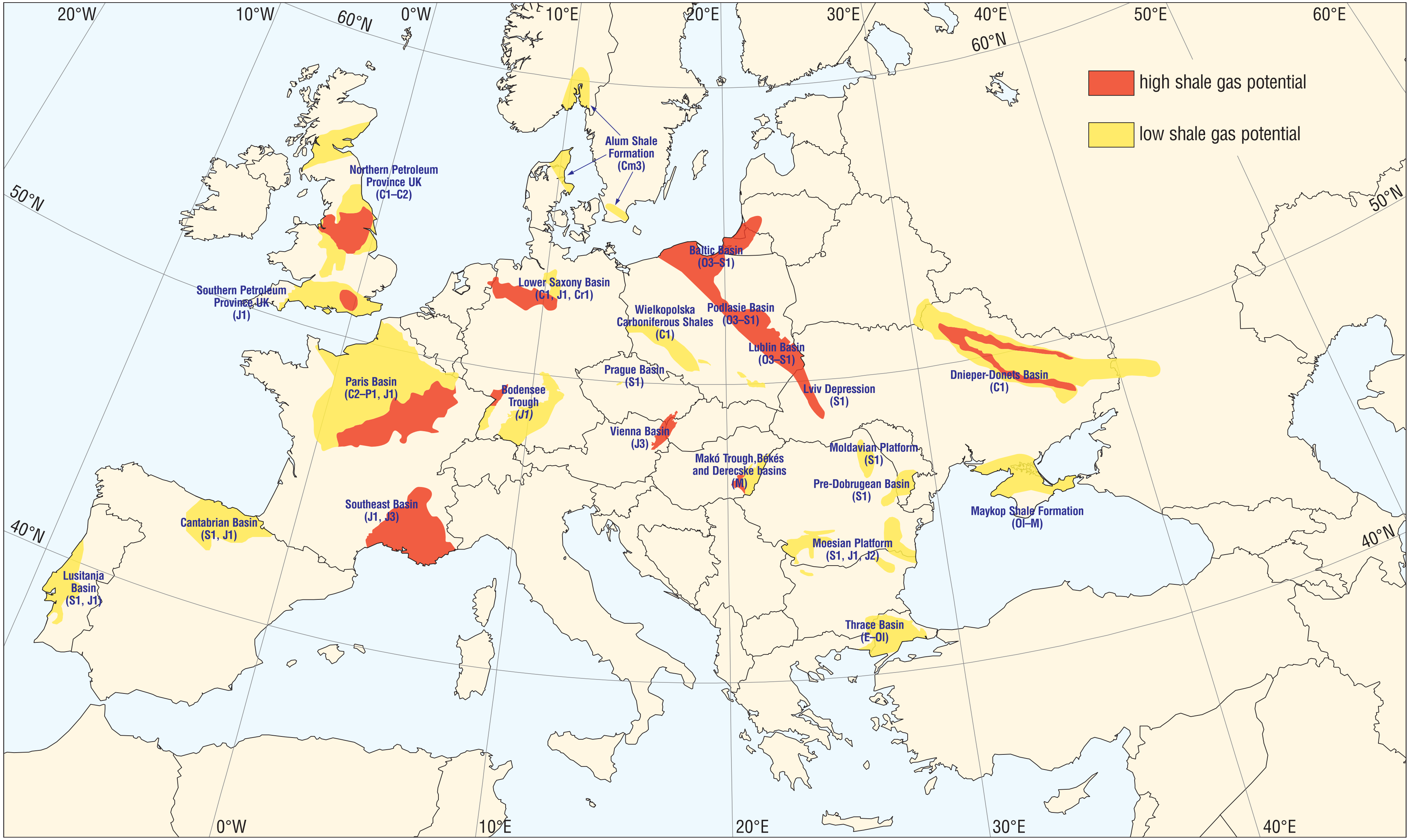

Fig. 1. Major European sedimentary basins with shale gas potential. Compilation based on Szalay & Koncz (1993), Poprawa (2010b), Schulz et al. (2010), Kuuskraa et al. (2011), BGR (2012), Krzesek et al. (2012), Kurovets & Koltun (2012), Sachsenhofer & Koltun (2012), Velicu & Popescu (2012)

basins and from the Lviv Depression (Fig. 1). This group also includes Alum Shales occurring in the area of the Baltic Sea.

SEDIMENTARY BASINS OF POLAND WITH POTENTIAL ACCUMULATION OF SHALE OIL AND SHALE GAS

The most prospective shales in the territory of Poland, which may contain unconventional oil and gas reserves, are found in three sedimentary basins: Baltic, Podlasie and Lublin (Fig. 3). These basins show a similar vertical facies pattern of the lower Paleozoic succession and a relatively simple tectonic setting. Upper Ordovician and lower Silurian shales seem to have adequate geological characteristics to be classified not only as source rocks for conventional hydrocarbon deposits, but also as a promising target for exploration of unconventional hydrocarbon resources. However, due to the lateral facies variability, their hydrocarbon potential is not equal throughout their occurrence area with regard to the presence of unconventional hydrocarbon deposits. In the Caradoc, fine clastic sedimentation prevailed only in the north-western areas of the early Paleozoic basin. In the south-eastern region, carbonate deposition occurred to become predominant in the Ashgill throughout almost the entire early Paleozoic basin. Another change in the sedimentary conditions commenced in the Silurian together with the dominant accumulation of fine clastic rocks (Modliński et al., 2006; Modliński & Szymański, 2008). Facies changes and concomitant variations in the clastic sedimentation rate affected the horizontal and vertical distribution of organic carbon in these deposits and contributed to an increase in its content mainly in muddy and silty facies characterised by low sedimentation rates. Facies migration, which occurred in the late Ordovician and early Silurian and were dependent on both the transformation of the depositional environment along with its biological productivity and changes in the distribution of clastic material in the basin, caused a significant diachronism of clay and mud deposits in the early Paleozoic basin of the western slope of the East European Craton.

A different time span is attributed to the thermal events that controlled hydrocarbon accumulation. As a result, Polish sedimentary basins of the western slope of the East European Craton experienced two thermal events in the Devonian and Carboniferous and in the late Mesozoic (Poprawa & Grotek, 2005; Poprawa, 2010a). The distribution of hydrocarbon source rocks in the western edge of the craton is characterised by a distinct oil- and gas-forming zonation (Fig. 3), reflecting, respectively, the eastern and the western part of the basins (Poprawa, 2010a).

Wide distribution of the Ordovician–Silurian organic matter-rich shales in the Baltic Basin results in the presence of prospective areas in the Baltic Sea, Russia, Lithuania and Sweden. Due to the considerable size of the basin and the wide extent of the Ordovician and Silurian clastics, the rocks were buried to significantly different depths in the individual areas. As a consequence, Llandovery deposits of the Baltic Basin were buried to a depth of 1000 m in eastern Poland and even up to 4500 m in the western limits of their

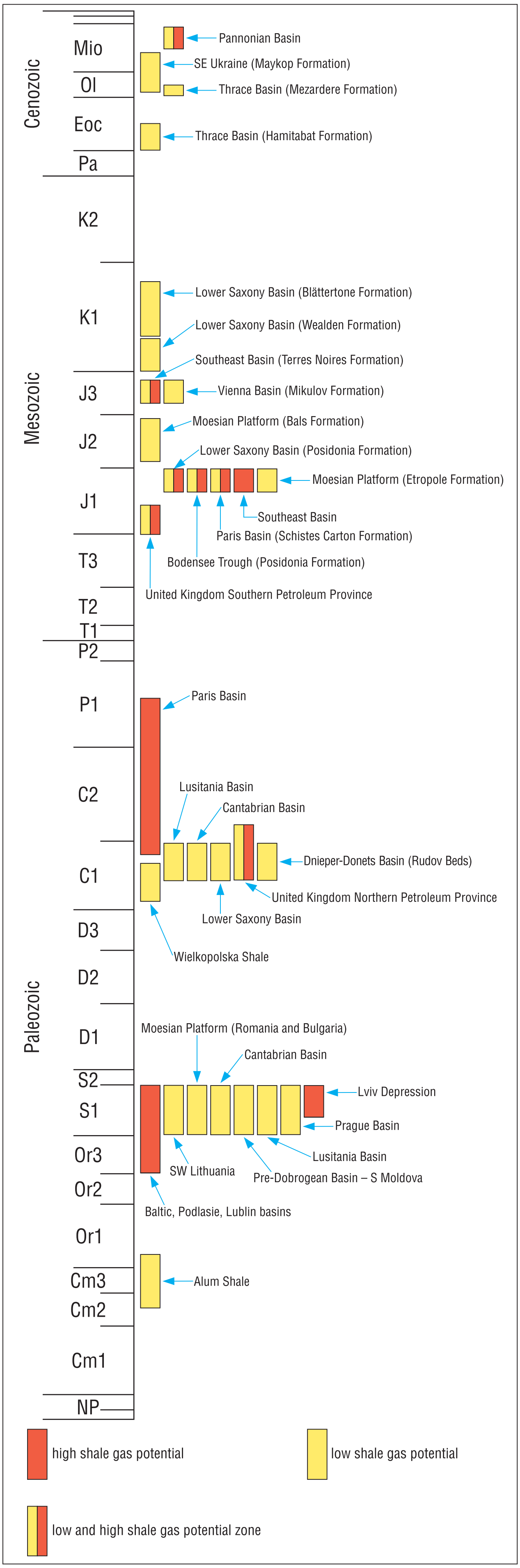

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Fig. 2. Stratigraphic position and location of formations with shale gas potential in Europe

extent. The thickness of the entire Llandovery complex also varies from 20–30 m in the eastern regions to about 70 m in the west. The Wenlock deposits show a much greater thickness that varies widely between the regions from 100–140 m in the eastern part of the basin to 1000 m in the western areas. The thermal maturity is highly variable and ranges from 0.5– 0.6% Ro in the eastern regions to 4.5% Ro in the areas of maximum burial. The content of organic carbon in the Llandovery deposits varies considerably from 0.5 wt% to 11.0 wt%, and the highest values are recorded in the central part of the Gulf of Gdansk. In the Wenlock deposits, the regional differences in organic carbon content are much lower and vary between 0.5 wt% and 1.4 wt% (Skręt & Fabiańska, 2009; Poprawa, 2010a). If considering the average net thickness of the shales, which is about 96 m for the Llandovery, the calculated recoverable gas reserves are around 3.65 trillion m^3 (129 Tcf; Kuuskraa et al., 2011).

Tectonic processes resulted in a break-up of the system of Paleozoic sedimentary basins, so that the Podlasie Basin is now a slightly isolated, individual unit with its specific geological characteristics. The Llandovery deposits are buried to a depth of 500–750 m in the eastern region and nearly 5000 m in the west. The thickness of the Wenlock deposits varies from 80–100 m in the east to 500 m at the western extremes of their occurrence. Thermal maturity expressed as a function of vitrinite reflectance is characterised by a generally similar trend of increasing values towards the west and southwest up to approximately 4.0% Ro in the Llandovery. The same stratigraphic interval in the eastern part of the basin typically shows the thermal maturity values of 0.7–1.3% Ro. The organic matter content varies from 0.6 wt% up to 20.0 wt% in single layers and increases towards the west (Klimuszko, 2002; Poprawa, 2010a). Rough estimate of the net thickness of the Llandovery shales at about 90 m allowed determining the reserves of recoverable gas at 0.4 trillion m^3 (14 Tcf; Kuuskraa et al., 2011).

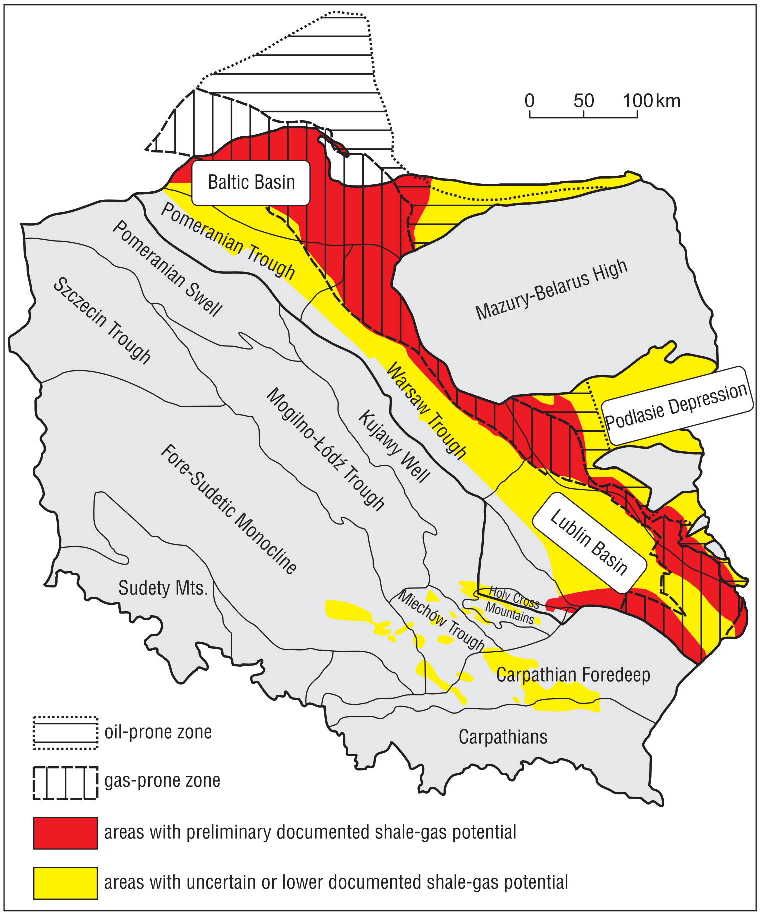

Fig. 3. Areas of potential shale-oil and shale-gas occurrence in the Lower Paleozoic basins in Poland (compilation based on Poprawa, 2010a)

The Lublin Basin is the southeasternmost sedimentary basin (Fig. 3) showing the most complex tectonic structure of all Poland's Paleozoic basins containing packages of fine clastic rocks that may host unconventional oil and gas deposits. Its complicated geological structure is primarily the result of regional tectonic events, which also caused a significant difference in some geological parameters as compared to the other basins, especially in terms of burial and maturity. The maximum tectonic activity was during the Devonian. Significant role in developing the Lublin Basin was also played by younger tectonic events in the early Carboniferous and from the late Carboniferous to early Permian (Poprawa, 2010a). The depth to the Llandovery top surface varies in this area from 1000 m to 4000 m, with an increasing trend from northeast to southwest. The thermal maturity varies from 0.6% Ro to 3.0% Ro, and also shows the same, NE-SW trend. The content of organic carbon in the Ashgill, Llandovery and Wenlock deposits ranges from 0.5 wt% to 4.5 wt% (Poprawa, 2010a). The thickness of the stratigraphic intervals changes in the ranges of 10–50 m and 60–180 m, respectively. The average net thickness of the Wenlock shales in the Lublin Basin is 69 m, and the recoverable gas reserves are estimated at about 1.25 trillion m^3 (44 Tcf; Kuuskraa et al., 2011).

Currently, these three basins are the areas of ongoing advanced drilling operations conducted in order to identify their unconventional hydrocarbon potential. The group that carries out the most intense exploration for unconventional oil and gas deposits includes the following companies: PGNiG, PKN Orlen, BNK Petroleum, Chevron, Conoco Phillips, Eni, San Leon Energy and 3Legs Resources, which have drilled 42 test boreholes over the past few years.

UNCONVENTIONAL DEPOSITS IN UKRAINE

In 2012, the Chevron and Shell E&P companies and the consortium led by ExxonMobil company won the competition for the exploration and production of unconventional gas deposits in Ukraine. Chevron will start work on the Oleska concession area, which is located in the west of the country and includes the Lviv, Ivano-Frankivsk and Ternopil oblasts (provinces). Shell has received a license to conduct exploration in the east of the country, in the Kharkiv and Donetsk oblasts. The consortium of ExxonMobil, Shell, Petrom and Nadra Ukrainy companies will be responsible for the operations in the Skifska concession area, both onshore and off the shore of the continental Black Sea shelf (Fig. 4).

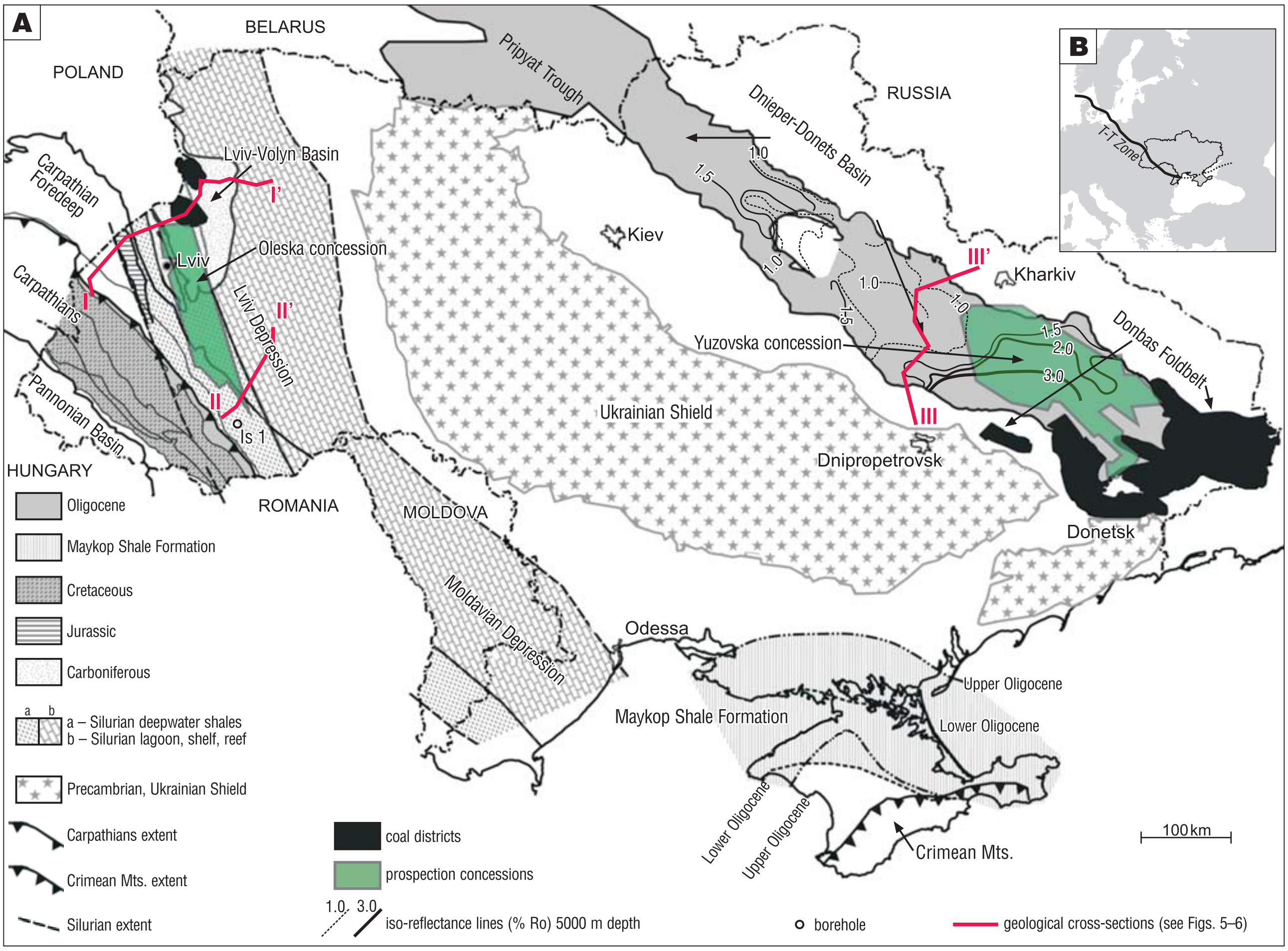

Fig. 4. A – map of Ukraine and Moldova showing position of sedimentary basins with organic-rich fine-grained rocks (after Sachsenhofer & Koltun, 2012, modified); **B** – position of western margin of the East European Craton and Ukraine within Europe (Teisseyre-Tornquist Zone; T-T Zone) (after Sachsenhofer & Koltun, 2012, modified)

Exploration in the Oleska concession area is targeted at Silurian shales of the Lviv Depression that is a continuation of the geological structures in the Lublin region – an area of intense exploration in Poland. The Silurian rocks are part of the succession deposited from the Vendian through Devonian. In the Lviv Depression, they occur as a 200-kilometre long belt stretching along the western border of the East European Craton (Sachsenhofer & Koltun, 2012). The Silurian rocks are represented by shales and limestones. Towards the east, the shales pass into coeval shallow-marine carbonate facies (Sachsenhofer & Koltun, 2012), which are exposed at the surface in many outcrops. The prospective gas-bearing shales are overlain by Devonian, Mesozoic and Cenozoic rocks (Sachsenhofer & Koltun, 2012).

The depth to the shales in the prospective area is 1000–5000 m and their total thickness is 400–1000 m (Kuuskraa et al., 2011).

Due to the occurrence of Silurian deposits within the deep fractures of the Teisseyre-Tornquist Zone, the tectonic setting of the Lviv Depression is complex (Fig. 5). Structural pattern of the Paleozoic succession, developed as a system of tectonic blocks, affects the increase of exploration risk in both the Lublin region in Poland (Poprawa, 2010a) and the Lviv Depression in Ukraine.

There are limited data on the content of organic matter in these shales. The content of organic matter found in the samples from the Is 1 borehole (Fig. 4) is 0.24–0.68 wt% (Sachsenhofer & Koltun, 2012). A high degree of thermal maturity and the presence of type II kerogen indicate that the initial organic matter content was above 3 wt% (Kotarba & Koltun, 2006).

If we assume that the Silurian shales from the Lviv Depression are lithologically similar to the coeval shales in the Lublin region, it can be concluded that the present-day average organic matter content is in the range of 1–1.7 wt%.

Results of studies on alterations of conodonts (CAI) and thermal maturity expressed as a function of vitrinite reflectance suggest that the Lower Paleozoic deposits of the Lviv Depression show the degree of alteration corresponding to the oil window generation (CAI 1.5–2; 0.7–1.3% Ro). The shales which are buried at greater depths fall in the gas generation window (CAI 3–4; 1.3–3.5% Ro) or are thermally overmature (CAI >5; >3.6% Ro) (Drygant, 1993; Sachsenhofer & Koltun, 2012).

Oil and gas shows in the Silurian formations were observed during drilling operations in the vicinity of Derazhnia, Slobidka, Lisna, Davideny and Krasnoyilsk (Kurovets et al., 2011), however, it is necessary to drill new boreholes and acquire a set of detailed geological, geochemical and geophysical data to assess the natural gas potential in so far poorly studied Silurian shales of the Lviv Depression.

The concession license granted to the Shell concern covers the south-eastern part of the Dnieper-Donets Basin (DBB), where the best prospects for exploration of unconventional deposits are associated with Carboniferous black shales and hard coals seams.

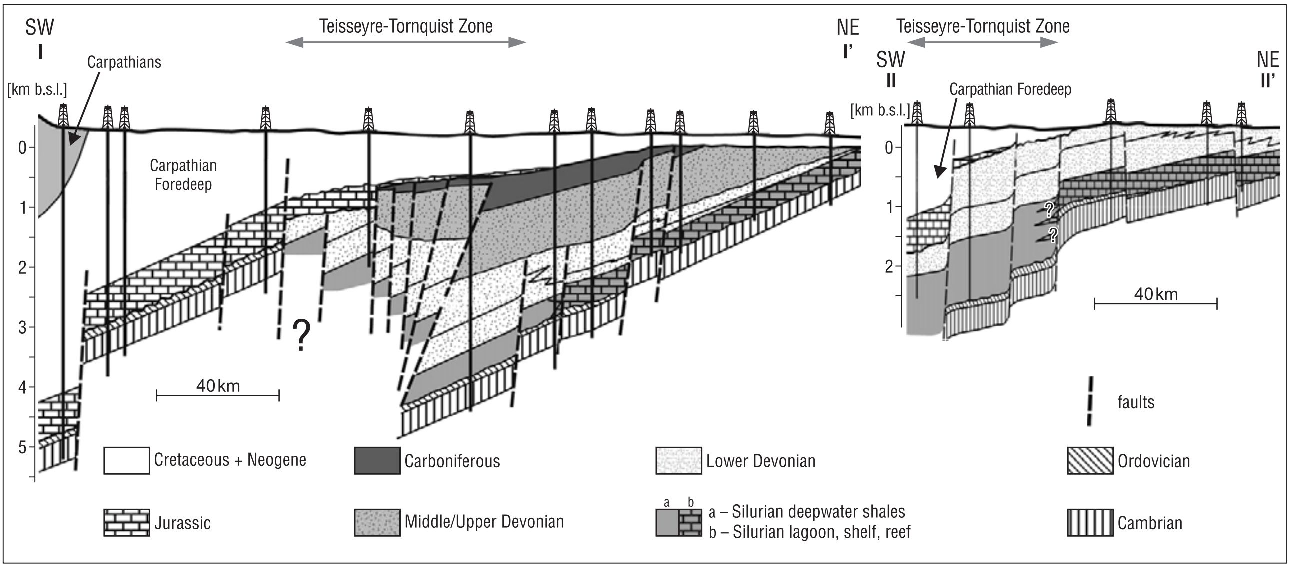

Fig. 5. Cross-sections I–I' and II–II' through the Lviv Depression. See Fig. 4 for location (after Skompski et al., 2008; Drygant, 2010, modified)

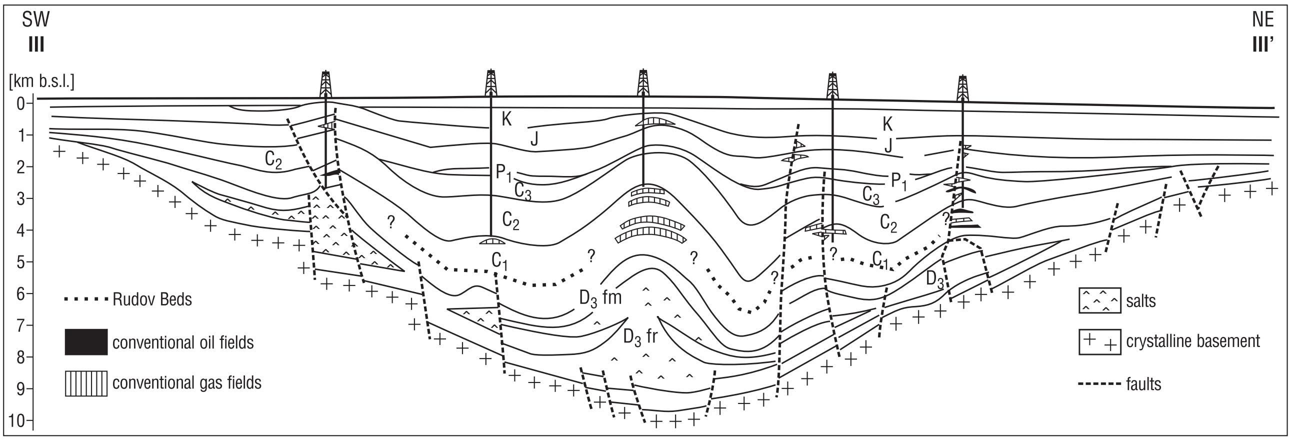

Fig. 6. Cross-section III–III' through the Dnieper-Donets Basin. See Fig. 4 for location (after Law et al., 1998; Ulmishek, 2001, modified)

The Dnieper-Donets Basin is a NW-SE-trending Devonian rift structure located in the East European Craton in the territories of Belarus, Ukraine and Russia (Schulz et al., 2010). The basin fill is the thick (about 4000 m) Upper Devonian series and the overlying Carboniferous–Cenozoic succession whose thickness increases to 15 000 m towards the southeast (Fig. 6) (Schulz et al., 2010). The Carboniferous succession in of the DDB is characterised by the presence of numerous transgressive-regressive sequences that consist of black shales rich in organic matter (an average of 2–4 wt%) containing type III and II kerogen (Schulz et al., 2010; Sachsenhofer & Koltun, 2012). The highest content of organic matter is observed in the so-called Upper Visean Rudov Beds – up to 12 wt%, and the average value is 5 wt% (Schulz et al., 2010). The Rudov Beds, attaining a thickness of up to 70 m and thermal maturity corresponding to at least the oil generation window, are presumed source rocks for many conventional fields, and therefore are considered to be the most promising in terms of exploration of unconventional gas deposits in the DDB (Sachsenhofer & Koltun, 2012).

The aim of operations carried out by the consortium led by ExxonMobil includes identification of the production potential of Oligocene–Lower Miocene shales of the Maykop Formation, which are the source rocks for conventional deposits in the Black Sea, the Caucasus and the Caspian Sea (Sachsenhofer & Koltun, 2012).

According to the Advanced Resources International company, the total natural gas reserves estimated for the Lviv Depression and the Dnieper-Donets Basin amount to 5.6 trillion m^3 (197 Tcf), with recoverable resources being equal to 1.2 trillion m^3 (42 Tcf; Kuuskraa et al., 2011).

UNCONVENTIONAL DEPOSITS OF HUNGARY

The Neogene Pannonian Basin of Hungary (Fig. 7), overlapping the Paleogene basin and larger units of the Alpine foldbelt (Dolton, 2006), extends from north to south at a width of 500 km, and from east to west at a length of 600 km. This basin consists of many extensional sub-basins associated with uplifted basement blocks, such as Makó, Békés, Derecske and others.

Source rocks in this area are represented by organic matter-rich Triassic shales and marls of the Kössen (Rhaetian) and Veszprém (Carnian) formations (Kókai & Pogácsás, 1991). According to Pogácsás et al. (1996), the total content of organic matter in the Kössen Formation deposits is 3–20 wt%, and in the Veszprém Formation – 3–5 wt%. Type I and II kerogen, mainly of marine origin, is dominant. At least five conventional oil deposits have been

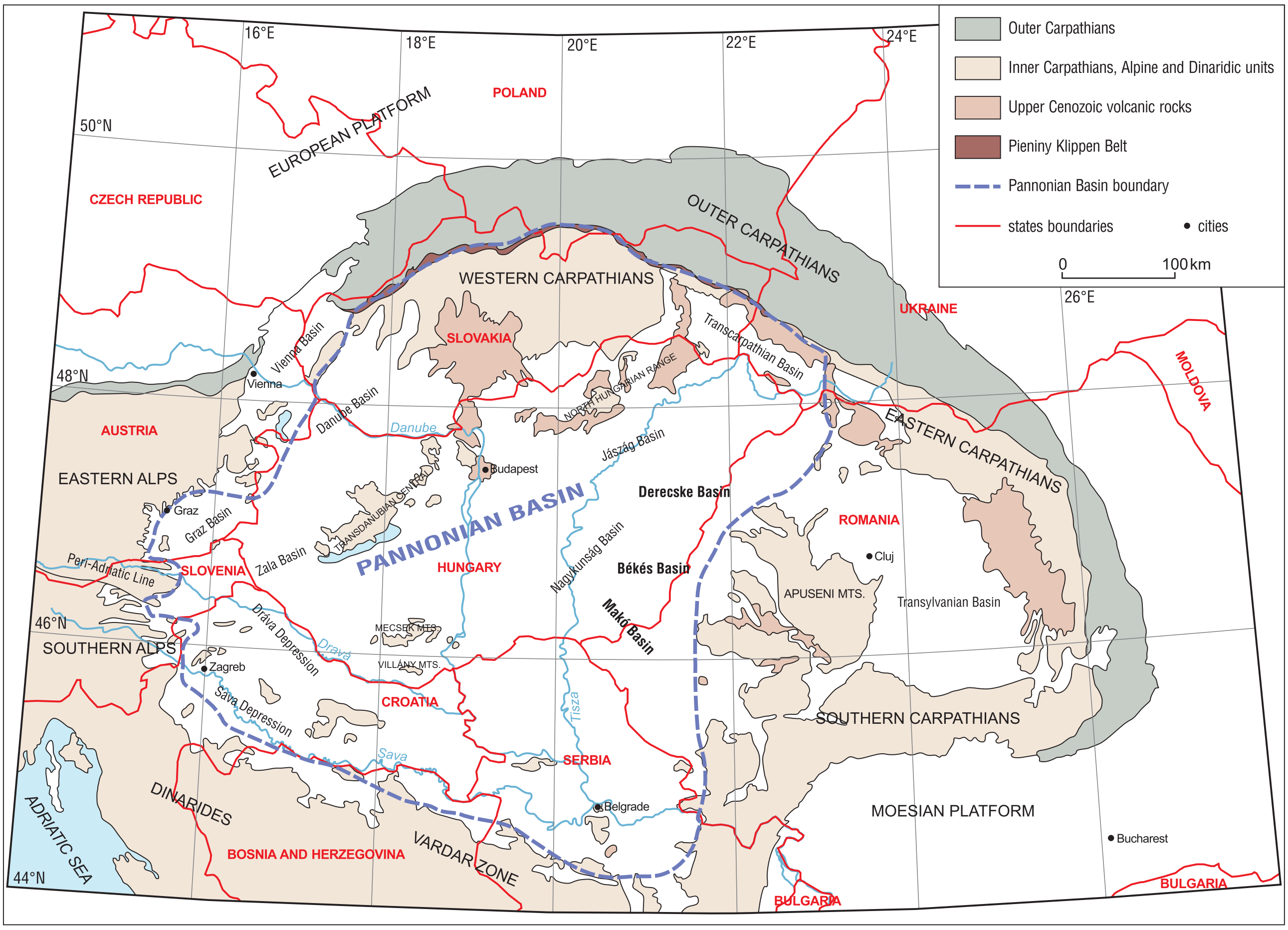

Fig. 7. Position of the Pannonian Basin within Europe with tectonic and geographic units (Dolton, 2006)

discovered in the Triassic deposits, including the large Nagylengyel oil field (Dolton, 2006).

The source-rock level is also the Upper Jurassic platformal carbonates and marls coeval with the Mikulov Formation of the Vienna Basin. Their geochemical proxies of source rock potential and maturity have values similar to those of the Mikulov Formation.

Upper Cretaceous and Paleogene shales, marls and marly claystones are the source rocks in the northern part of the Pannonian Basin, but there are just few hydrocarbon deposits discovered in that area.

Miocene rocks are considered to be source rocks for oil and gas over most of the Pannonian Basin (Dolton, 2006). These are marls of the Endrőd Formation, which contain 2–5 wt% of organic matter representing type II and III kerogen. These rocks attain a thickness of approximately 6000 m in the Békés Basin and 7000 m in the Makó Graben. The Endrőd Formation is the most prospective formation in the Pannonian Basin in terms of shale gas accumulation.

The above-mentioned formations are not typical shale gas formations because most of them are carbonate rocks which, despite good geochemical properties, are characterised by poor petrophysical parameters significantly limiting profitability of future production. Currently, the formations containing tight gas, especially of Miocene age, seem the most promising in this area. They are represented e.g. by the Szolnok Formation, composed of sandstones and claystones. Extraction of natural gas from the rocks is favoured by good reservoir parameters, namely high pressure and temperature.

Most of the conventional hydrocarbon deposits in Hungary were discovered in Neogene formations (61%), the remaining are in Paleogene reservoir rocks (Dank, 1987). The production takes place in many areas, especially from large anticlinal traps (Dolton, 2006).

According to Advanced Resources International, the reserves of shale gas in Hungary, Romania and Bulgaria, within the Balkan-Carpathian area, are estimated at 0.54 trillion m^3 (19 Tcf; Kuuskraa et al., 2011). In southeast Hungary and west Romania, within the Makó, Békés and Derecske basins and in the Pannonian Basin, there is currently ongoing exploration work (Fig. 7). The main targets of these operations are shale and tight gas. Research is conducted primarily by the Hungarian companies MOL and TXM Olaj-és Gázkutató Kft.

UNCONVENTIONAL DEPOSITS OF ROMANIA, BULGARIA AND MOLDOVA

In Romania, in addition to the Pannonian Basin area, hydrocarbon exploration is carried out in Silurian and Jurassic shales of the Moesian Platform in the south of the country, and in Silurian shales of the Scythian and Moldavian platforms near the border with Moldova (Krezsek et al., 2012).

The Moesian Platform is an elongated latitudinal structure surrounded to the north and west by the Carpathian Mountains, and to the south – by the Balkans (Seghedi et al., 2005). It has long been known as a petroleum province with many conventional deposits in Devonian, Triassic, Jurassic, Cretaceous, Upper Miocene and Pliocene formations (Pawlewicz, 2007). In the Moesian Platform, unconventional hydrocarbons may occur in Silurian shales of the Tandarei Formation and Dogger shales of the Bals Formation (Tari et al., 2011; Krezsek et al., 2012). The Tandarei Formation is represented by black graptolitic shales, about 600 m thick, while the Bals Formation is a sequence of black bituminous claystones interbedded with sandstones with a thickness of about 400 m and the organic matter content of approximately 1.2–2.0 wt% (Stefanescu et al., 2006). Shales of the Bals Formation are overlain by the Carpathian nappes and occur in the northern part of the Moesian Platform. Modelling of hydrocarbon generation has shown that the Dogger shales are in the oil and gas generation window at a depth of 4000–6000 m, and therefore exploration may not be profitable (Krezsek et al., 2012).

In the Moldavian and Scythian platforms, Silurian deposits are represented mainly by Wenlock and Llandovery clay shales in which gas shows were reported (Stefanescu et al., 2006).

Exploration licenses in these areas have been granted mainly to the Romanian company Petrom, but also foreign companies, like Chevron, are interested in the exploration of Romanian unconventional deposits.

In the Bulgarian part of the Moesian Platform, conventional deposits were discovered in Triassic carbonates and Lower–Middle Jurassic clastics (Pawlewicz, 2007). The exploration of unconventional hydrocarbon deposits is focused on Silurian shales as well as Liassic shales of the Etropole Formation (Tari et al., 2011). At the beginning of 2012, the process for granting new exploration licenses was suspended in Bulgaria and drilling operations using hydraulic fracturing techniques have been prohibited.

Moldova may also have unconventional gas deposits. Silurian shales with a high organic matter content and significant thickness occur in the south of the country, within the so-called Pre-Dobrogean Basin (Sliaupa et al., 2006). The possibility of exploration for shale gas in southern Moldova is considered by the Canyon Oil & Gas company.

The research of hydrocarbon potential of shales in Romania, Bulgaria and Moldova is currently at a very early stage and there is no data to determine whether the extraction of hydrocarbons from unconventional deposits will be possible in these countries.

UNCONVENTIONAL DEPOSITS OF LITHUANIA

In the Lithuanian sector of the Baltic Basin, lower Silurian shales have been selected as potentially containing unconventional oil and gas resources (Fig. 8) (Zdanaviciute & Lazauskiene, 2009).

The Silurian succession of the Lithuanian sector of the Baltic Basin is represented in the west by black and grey

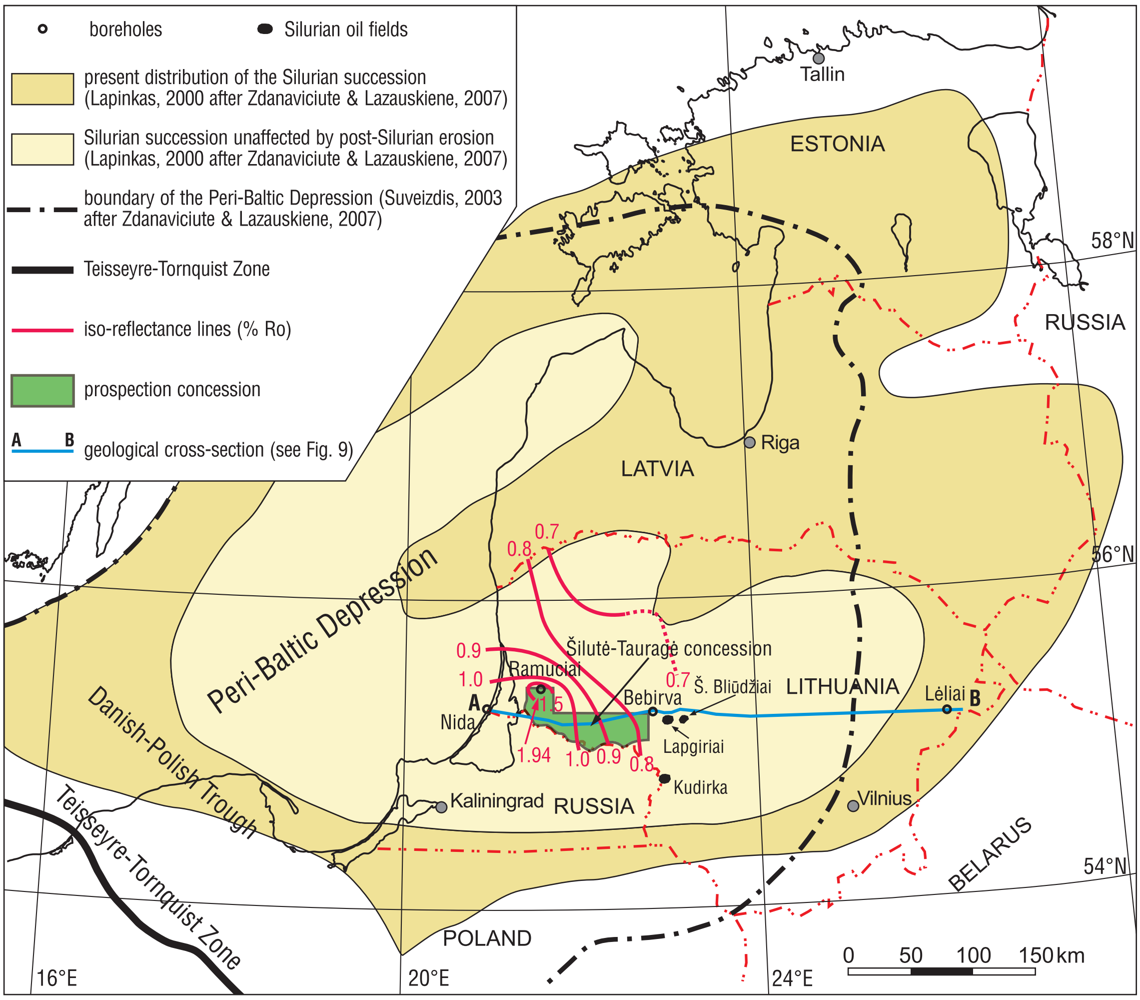

Fig. 8. Generalised map of the distribution of the Silurian succession in the Peri-Baltic Depression with the distribution of vitrinite reflectance values in the Silurian strata in Lithuania (after Zdanaviciute & Lazauskiene, 2007, modified)

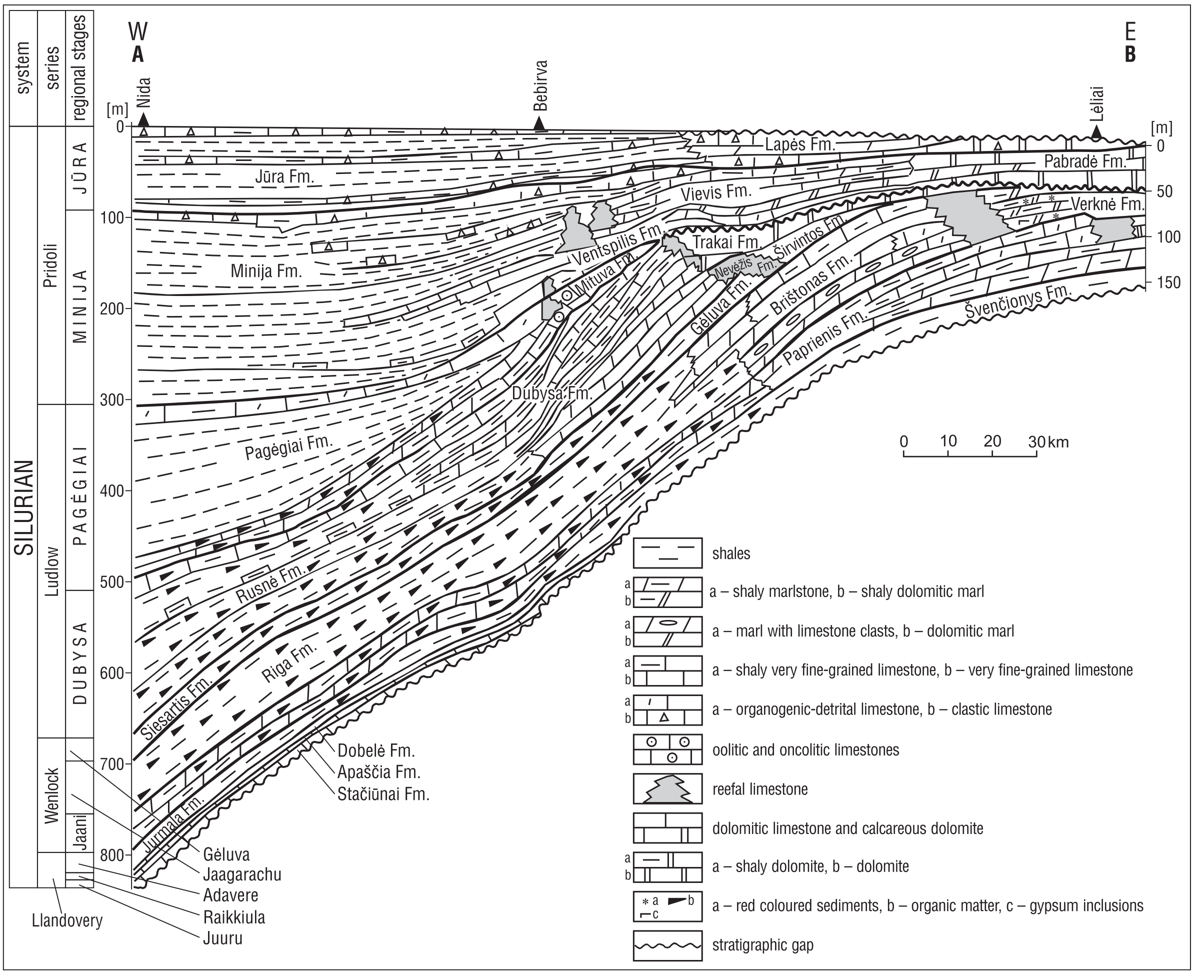

Fig. 9. Geological cross-section through the Silurian succession in Lithuania. See Fig. 8 for location (Lapinkas, 2000 after Zdanaviciute & Lazauskiene, 2007, modified)

deep-shelf shales. In the central and eastern areas, the succession is composed of open-shelf marls and limestones as well as lagoonal facies (limestones and dolomites) (Fig. 9) (Zdanaviciute & Lazauskiene, 2009).

The beds of lower Silurian rocks dip southwestwards. In eastern Lithuania, their base is at a depth of about 200 m, whereas in the west – at 2050 m (Zdanaviciute & Lazauskiene, 2009). The thickness of the shale series ranges from 110 m to 160 m (Zdanaviciute & Lazauskiene, 2009).

The organic matter content in the Silurian deposits is highly variable, ranging from 0.7 wt% to 19.2 wt%; the middle Llandovery–lower Ludlow complexes are richest in organic matter (Zdanaviciute & Lazauskiene, 2009; Lazauskiene, 2012). Results of pyrolysis analyses indicate that the organic matter contains sapropelic kerogen of type II (Zdanaviciute & Lazauskiene, 2009).

The thermal maturity of the deposits ranges from 0.56–0.7% Ro to 0.9–1.2% Ro. The highest value was recorded in rocks from the Ramuciai-1 borehole (1.94% Ro), where magmatic intrusions are reported (Zdanaviciute & Lazauskiene, 2009). Thermal maturity of these rocks increases towards the southwest, which is related to the depth of burial (Fig. 8) (Zdanaviciute & Lazauskiene, 2009). Over a large area, the shales have reached a thermal alteration level corresponding to the oil generation window, and in the south-western part of the country, they may be in the phase of dry gas generation window (Zdanaviciute & Lazauskiene, 2009). According to Poprawa (2010a), it is possible that the Lithuanian shales contain oil. The presence of small conventional oil accumulations in upper Silurian reef bodies in the central-eastern part of the country (Fig. 9; Brangulis et al., 1993; Zdanaviciute & Lazauskiene, 2007) seems to confirm this hypothesis, as the deeply buried Silurian shales in the southwest are probably the source rocks for this conventional petroleum system.

In 2012, in Lithuania, a competition was announced aimed at finding an investor to carry out exploration and production in the Šilutė-Tauragė Block located in the southwest of the country. The lower Silurian shales attain the greatest thickness and thermal maturity in that area (Satkūnas et al., 2012). Based on press reports, it can be assumed that the concession will be granted to Chevron, which already has one license for hydrocarbon exploration in Lithuania.

The total natural gas resources in the Silurian shales of Lithuania are estimated at 0.48 trillion m^3 (17 Tcf), of which recoverable reserves amount to 0.11 trillion m^3 (4 Tcf; Kuuskraa et al., 2011).

UNCONVENTIONAL DEPOSITS OF AUSTRIA

The Vienna Basin, located partly in Austria, is one of the most important petroleum provinces being targeted as a potential shale gas reservoir in Central Europe. The first discovery of a conventional oil deposit in the Vienna Basin took place in 1930. Since that time, over 3000 exploration wells have been drilled and the area has become heavily explored mainly by the domestic exploration company OMV. Currently, the province of conventional oil and gas deposits comprises at least 46 oil and gas fields (Schulz et al., 2010).

In recent years, the petroleum industry has raised interest in gas from shales of the Upper Jurassic Mikulov Shale Formation, which are the main source rock for oil and gas in the Vienna Basin (Ladwein, 1988; Picha & Peters, 1998; Adámek, 2005).

The Vienna Basin is approximately 200 km long and 60 km wide and extends from the south-eastern Czech Republic through south-western Slovakia to southern Austria (Fig. 10). The basin is a perfect example of a rhombohedral pull-apart basin that developed on top of the allogenic system of the Alpine-Carpathian terrane overthrust in the environment of lithospheric contraction (Allen & Allen, 2005). The basin was formed in Neogene times as a result of strike-slip tectonics.

The Vienna Basin is filled with Neogene clastic rocks, flysch deposits (from Jurassic to Paleogene) and the Alpine limestone formation (from Permian to Cretaceous).

The Neogene clastics (with a slight proportion of carbonates) attain a thickness of more than 5000 m in the basin depocentre (Ladwein, 1988), south of Vienna and along

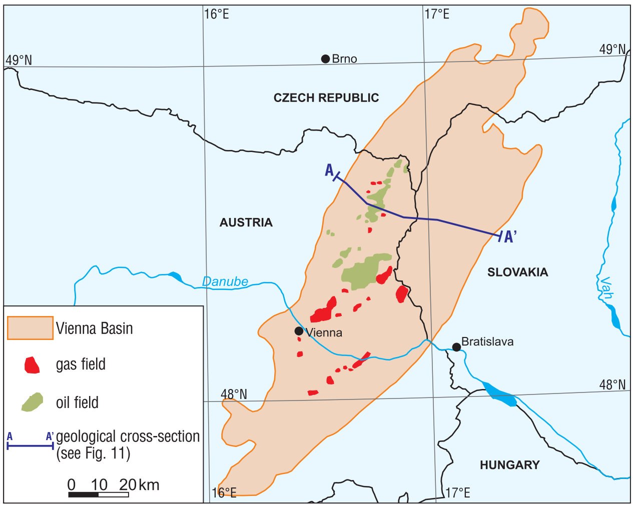

Fig. 10. Location of the Vienna Basin (Kuuskraa et al., 2011, modified)

the northern border of Austria. The potential oil traps are represented by sandstones.

The rocks below are represented by flysch and carbonate deposits composed mainly of Permian, Triassic, Jurassic and Cretaceous limestones and marls with subordinate shales, sandstones and evaporites (Ladwein, 1988). The Mesozoic reservoir rocks that host conventional oil and gas deposits are represented mainly by Upper Triassic dolomites and sandstones.

Based on numerous geochemical studies (Ladwein, 1988; Picha & Peters, 1998; Francű et al., 1996; Adámek, 2005), rocks of the Upper Jurassic Mikulov Formation that underlie the flysch deposits (Fig. 11) have been considered the most important source rocks for oil, gas and condensate in the Vienna Basin. The Upper Jurassic consists of platformal carbonates and basinal marls deposited in a reducing environment (Ladwein, 1988). The Mikulov Formation is not a typical shale formation, because it is mostly composed of mudstones enriched in carbonates with a high content of organic matter which varies from 0.2 wt% to 10 wt% with the average of 1.9 wt% (Adámek, 2005). The kerogen type (II–III) is typical of organic matter deposited in terrestrial and transitional environments at the land-sea interface. The Upper Jurassic source rocks reached the oil generation window at a depth of 4000–6000 m. The main phase of thermogenic gas generation occurred below 6000 m, and the thermal maturity values expressed as a function of vitrinite reflectance were greater than 1.6% Ro (Ladwein, 1988). Gas generation potential of the Mikulov Formation increases southeastwards towards the depocentre of the Vienna Basin (Fig. 11). This potential trend is confirmed by the location of numerous oil and gas fields situated near the basin depocentre, indicating a common vertical direction of hydrocarbon migration in the Early Miocene (Ladwein, 1988).

Gas shows were observed in the Mikulov Formation at great depths (about 7500–8500 m) in the hydraulic fractured vertical section of the Zisterdorf UT 1 borehole (Wessely, 1990). Presumably, the gas inflow is associated with a high reservoir pressure. High pressures at these depths are probably due to continuous expulsion of hydrocarbons.

Good geochemical properties of the rocks make them a perspective reservoir, however, due to the high content of clay minerals in combination with a complex tectonic setting of the basin and a large depth of occurrence of potential

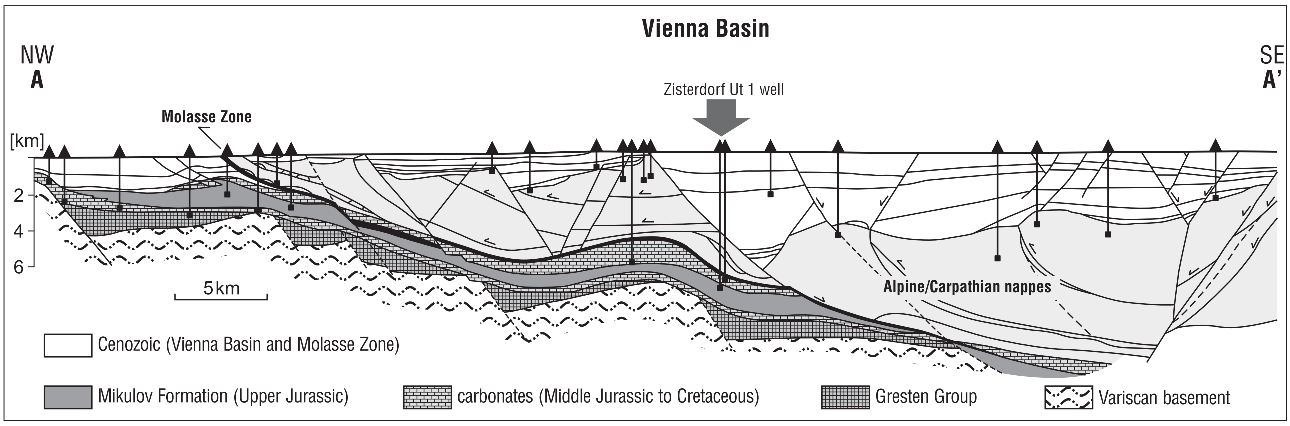

Fig. 11. Geological cross-section of the Vienna Basin showing the Mikulov Formation as a potential shale gas system (after Schulz et al., 2010, modified). See Fig. 11 for location

Table 1. Set of basic geological parameters characterizing Central and Eastern European shale rocks

State	Sedimentary basin	Source rocks age	Lithology	Depositional environment	Organic matter type	Organic matter content [wt%]		Burial [m]	Source rocks net thickness [m]	Thermal maturity [Ro]	Hydrocarbon prospectivity	Technically recoverable resources		
						total	average							
Poland	Baltic	Ordovician–Silurian (Caradoc–Wenlock)	shales	marine	II	0.5–11.0	n.d.	1000–4500	96	0.5–4.5	gas-oil	3.65 Tcm (129 Tcf)*	0.34–0.76 Tcm (max 1.9 Tcm) 12–27 Tcf (max 68 Tcf)**	0–0.027 Tcm (max 0.11 Tcm) 0–0.9 Tcf (max 4 Tcf)***
	Podlasie	Ordovician–Silurian (Caradoc–Wenlock)	shales	marine	II	0.6–20.0	1.5–6.0	500–5000	90	0.7–4.0	gas-oil	0.4 Tcm (14 Tcf)*		
	Lublin	Ordovician–Silurian (Caradoc–Wenlock)	shales	marine	II	0.5–4.5	n.d.	1000–4000	69	0.6–3.0	gas-oil	1.25 Tcm (44 Tcf)*		
Lithuania	Baltic	Silurian (Llandovery–Wenlock)	shales	marine	II	0.7–19.2	n.d.	1950–2120	110–160	0.5–1.9	oil	0.11 Tcm (4 Tcf)*		
Ukraine	Lviv Depression	Silurian (Wenlock–Ludlow)	shales	marine	II	0.2–1.7	1.0	1000–1500	n.d.	0.7–3.6	oil-gas	1.2 Tcm (42 Tcf)*		
	Dnieper-Donets	Carboniferous (Visean)	shales	marine	II. III	2.0–12.0	5.0	n.d.	n.d.	n.d.	oil-gas			
	Maykop Shales	Oligocene–Miocene	shales	marine	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	oil-gas	n.d.		
Romania	Pannonian	Miocene	shales/ marls	marine	II. III	2.0–5.0	n.d.	n.d.	n.d.	n.d.	oil-gas	0.54 Tcm (19 Tcf)*		
	Moesian Platform	Silurian (Llandovery–Wenlock)	shales	marine	II	n.d.	n.d.	2000–4000	n.d.	n.d.	oil-gas			
		Jurassic (Dogger)	shales	marine	II?	0.5–6.0	2.0	1800–4400	n.d.	n.d.	oil-gas			
	Moldavian/ Scythian Platform	Silurian (Llandovery–Wenlock)	shales	marine	II	n.d.	n.d.	n.d.	n.d.	n.d.	oil-gas			
Bulgaria	Moesian Platform	Silurian–Devonian (Llandovery–Gedinnian)	shales	marine	II.III?	n.d.	n.d.	n.d.	n.d.	n.d.	oil-gas			
		Jurassic (Lias)	shales	marine	II?	n.d.	n.d.	n.d.	n.d.	n.d.	oil-gas			
Hungary	Pannonian	Miocene	shales/ marls	marine	II. III	2.0–5.0	n.d.	n.d.	n.d.	n.d.	oil-gas			
Moldova	Pre-Dobrogean	Silurian (Llandovery–Ludlow)	shales	marine	II.III?	n.d.	n.d.	1000–5000	n.d.	n.d.	oil-gas	n.d.		
Austria	Vienna	Jurassic (Malm)	shales/ marls	marine	II. III	0.2–10.0	1.9	2000–8500	80–500?	n.d.	oil-gas	n.d.		
Turkey (c.e.)	Thrace	Eocene–Oligocene	shales	marine	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.17 Tcm (6 Tcf)*		

* Kuuskraa et al. (2011); ** PIG-PIB (2012); *** Gautier et al. (2012).

Explanations: c.e. – European part, n.d. – no data or uncertain data, Tcm – trillion cubic meter, Tcf – trillion cubic feet, one trillion equals 10^{12}.

zones of drilling operations, the Mikulov Formation is today considered uneconomic in terms of gas production. Despite this, the gas potential is currently the subject of research conducted by the OMV company, which performs horizontal drilling work as well as hydraulic fracturing in the already existing boreholes (Schulz et al., 2010).

UNCONVENTIONAL DEPOSITS OF THE CZECH REPUBLIC AND THE EUROPEAN PART OF TURKEY

In the north-western, European part of Turkey, there is the Thrace Basin, perspective in terms of the occurrence of shale gas. The basin hosts two potential shale formations: the Hamitabat Formation (Eocene) and the Mezardere Formation (Oligocene). Due to the young age of these formations, the shales often reach appropriate maturity for gas generation at below 5000 m depth. According to Advanced Resources International, the technically recoverable natural gas resources from the Thrace Basin shales amount to 0.17 trillion m^3 (6 Tcf).

In the Czech Republic, there is a promising area of the Prague Basin. The prospective rock formation is the Ordovician–Silurian shale characterised by a considerable thickness and a high content of organic matter, but typically of low maturity.

SUMMARY

The formation of the European continent in the geological history was periodically accompanied by events and geological processes that controlled deposition of fine clastic sedimentary rocks enriched in organic matter. In Paleozoic and Mesozoic times, these processes certainly included climate changes, changes in the shape and distribution of terranes along with the surrounding seas, and changes in the scale and range of biological productivity. As a result, the European continent is the area where organic facies were deposited during several periods of increased accumulation of organic material in marine environments. Among the most important is the stratigraphically oldest Cambrian period, whose deposits occur in a narrow offshore zone in the Polish part of the Baltic Basin, as well as in Denmark and Sweden. Two slightly younger periods of bituminous shale deposition took place over large areas of Europe at the turn of the Ordovician and Silurian and in the Carboniferous (Fig. 1). The youngest of the periods that favoured shale deposition was the Early Jurassic, when the marine transgression resulted in the development of extensive shallow epicontinental seas. In some areas of those seas, upwelling currents promoted biological productivity and, consequently, the Lower Jurassic fine clastic deposits with a high organic matter content are characterised by the most extensive occurrence.

Despite the stratigraphic diversity of European shales, there are some similarities between them in terms of the range of some basic geological parameters. The vast majority of them were deposited in a marine environment dominated by type II kerogen. The exceptions are the Carboniferous, Jurassic, Paleogene and Neogene shales, which contain also type III kerogen mixed in various proportions with type II kerogen (Table 1). The organic carbon content in all the stratigraphic types is highly variable, ranging from less than 1 wt% to 15 wt%, or in some cases up to 20 wt%, however there is no specific characteristics of the organic carbon content for the individual stratigraphic intervals. The net thickness of shales is subject to so much uncertainty due to their lateral variability and gaps in the geological knowledge, that it is impossible to perform analyses determining the ability of particular sedimentary basins in the specific stratigraphic interval to create organic facies.

In this context, it seems that the data on the basins from the territory of Poland can be much more reliable than those from the other basins that require a more complete recognition.

Resource estimates for crude oil and natural gas from shales for the territory of Poland and other European countries have already been presented by both several consulting firms and research units of several countries. Much of the data differed significantly from each other, depending on the computational methodology adopted. If we take into account the fact that the amount of resources is affected by geological data such as shale thickness and area of occurrence, organic matter content and its thermal maturity, etc., then the comparison of the resource potential of the shales from the Polish basins with other European basins is a very difficult challenge and is only vague (Table 1).

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