Lower Devonian lithofacies and palaeoenvironments in the southwestern margin of the East European Platform (Ukraine, Moldova and Romania)

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Abstract. Lower Devonian palaeoshelf deposits extend along the western margin of the East European Platform from the Baltic Sea to the Black Sea. These deposits have been studied on the territory of Ukraine (Volyn-Podillyan Plate, Dobrogean Foredeep) and correlated with coeval deposits in Moldova and Romania (Moldovian Platform). The investigation of the Lower Devonian deposits, their thickness, petrographic and lithological characteristics allowed reconstruction of two types of lithofacies and distinguishing two different depositional environments. The first lithofacies belonging to the Lochkovian stage, consists of clayey-carbonate rocks and represents a continuation of the Upper Silurian marine strata. The other lithofacies encompassing the Pragian–Emsian comprises terrigenous reddish-brown rocks, which are roughly equivalent to the Old Red Sandstone, completes the Lower Devonian section. Establishing the occurrence and thickness distribution of the terrigenous lithofacies across the study area is important, because it forms potential reservoir rocks for both conventional and unconventional (tight gas) hydrocarbons. Gas accumulation in these reservoir rocks has been discovered at the Lokachi field.

Key words: Early Devonian, Ukraine, petrographic characteristics, borehole sections, shelf of Baltica.

INTRODUCTION

Forty years ago researchers recognized that large-scale hydraulic fracturing could unlock natural gas held in low-permeability (tight) rocks. Today tight gas is a significant and growing part of USA natural gas production. The development activities and production of gas from tight gas reservoirs in Canada, Australia, Mexico, Venezuela, Argentina, Indonesia, China, Russia, Saudi Arabia and Egypt has been observed during the past decade (Holditch 2006; Gutiérrez et al. 2009; Sahin 2013). Lower Devonian deposits (Pragian–Emsian redbeds) of the East European Platform also represent an important exploration target for the conventional and unconventional gas in Europe (Shogenova et al. 2009). In Ukraine they host gas accumulations in two gas fields in Lower–Middle Devonian of the Volyn-Podillyan Plate – Velyki Mosty and Lokachi, where one of gas-bearing horizons occurs in Pragian–Emsian terrigenous reddish-brown rocks (Fedyshyn 1998; Galabuda et al. 2007).

The objective of this study is to provide petrographic description of the Lower Devonian deposits of Ukraine (Volyn-Podillyan Plate, Dobrogean Foredeep), establish their lithofacies patterns and depositional environments within the southern Baltic shelf, construct lithostratigraphic sections and thickness maps for Lochkovian and Pragian–Emsian strata, and correlate them between the western Ukraine and adjacent areas. The study utilizes also relevant data from Moldova and Romania (Barbu et al. 1969; Paraschiv et al. 1983; Prodan 1987; Mutihac et al. 2007; Seghedi 2012), as well as from Poland, Lithuania, Latvia and Estonia (Pożaryski et al. 1982; Turnau & Jakubowska 1989; Kleesment & Mark-Kurik 1997; Poprawa et al. 1999; Racki & Turnau 2000; Shogenova et al. 2009; Narkiewicz 2011; Filipiak et al. 2012; Mark-Kurik & Põldvere 2012).

GEOLOGICAL BACKGROUND

The area under study spans the following tectonic units in the southwestern margin of the East European Platform: the Volyn-Podillyan Plate, Moldovian Platform and Dobrogean Foredeep (Fig. 1). The sedimentary cover in this territory overlying the Archean–Proterozoic basement is composed of igneous and metamorphic rocks. The basement crops out within the Ukrainian Shield and dips homoclinally towards the Teisseyre–Tornquist Zone. The maximum thickness of the sedimentary cover reaches 10 km in the Volyn-Podillyan Plate and 7 km in the Dobrogean Foredeep (Kruglov & Tsypko 1988; Chebanenko et al. 1990). The sedimentary succession is represented by the Neoproterozoic, Palaeozoic (Cambrian, Ordovician, Silurian, Devonian and Carboniferous deposits in the Volyn-Podillyan Plate, Moldovian Platform

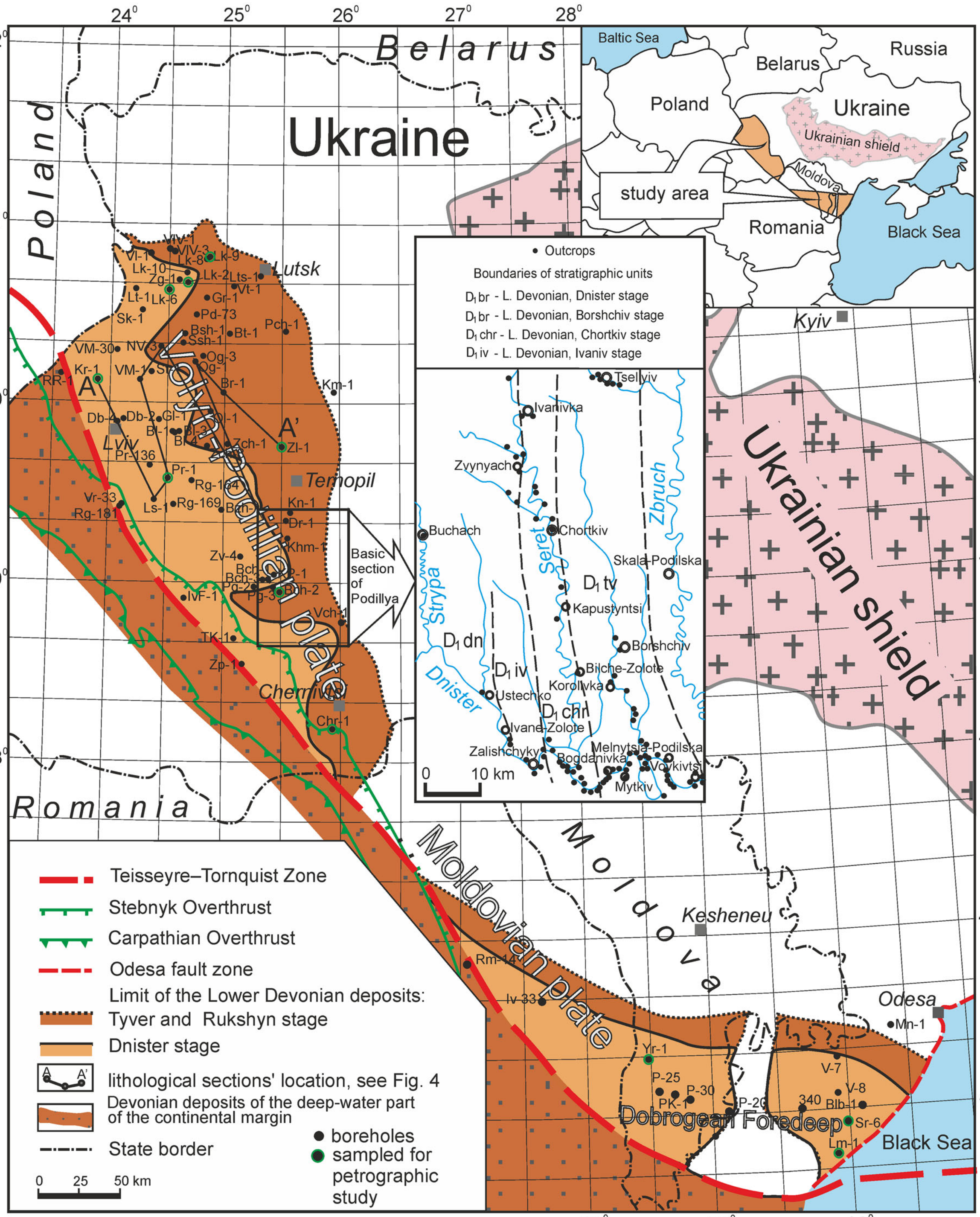

Fig. 1. Location map, showing the generalized distribution of Lower Devonian rocks in the southwestern margin of the East European Platform and the locations of boreholes. For the location of lithological sections see Fig. 4. Boreholes: Bch, Buchach; Bl, Baluchyn; Blb, Balabanivsk; Br, Brody; Bsh, Byshiv; Bt, Berestechko; Bzh, Berezhany; Chr, Chernivtsi; Db, Dublyany; Dr, Darakhiv; Gl, Glynyany; Gr, Gorokhiv; IvF, Ivano-Frankivsk; Iv, Ivanesti; Khm, Khmelivka; Km, Kremenets; Kn, Konopkivka; KP, Koropets-Pyshkivtsi; Kr, Krekhiv; Lk, Lokachi; Lm, Lyman; Ls, Lishchyny; Lt, Litovezh; Lts, Lutsk; Mn, Myrne; NV, Novyi Vytkiv; Og, Ogladiv; Ol, Olesko; P, Valya-Perzhey; Pch, Povcha; Pg, Pidgaytsi; PK, Kangaz; Pr, Peremyshlyany; Rg, Rogatyn; Rm, Roman; RR, Rava-Ruska; Sk, Sokal; Sr, Sarata; Ssh, Sushne; St, Stremin; TK, Tlumach-Kolomya; V, Vugilna; Vch, Verchniakivtsi; Vl, Volodymyrivka; VlV, Volodymyr-Volynsky; VM, Velyki Mosty; Vt, Voyutyn; Yr, Yargara; Zch, Zolochiv; Zg, Zagoriv; Zl, Zalozhtsi; Zp, Zagaypil; Zv, Zavadivka.

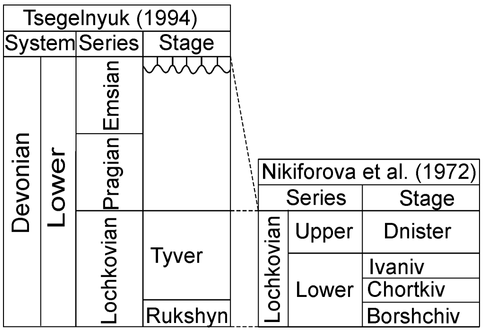

Fig. 2. Stratigraphic scheme of the Lower Devonian deposits of the Volyn-Podillyan Plate (after Nikiforova et al. 1972; Tsegelnyuk 1994).

and Dobrogean Foredeep), Mesozoic (Permian and Triassic deposits in the Dobrogean Foredeep; Jurassic and Cretaceous deposits in the Volyn-Podillyan Plate, Moldovian Platform and Dobrogean Foredeep) and Cenozoic (Palaeogene, Neogene and Quaternary deposits).

The Lower Devonian sequence conformably rests on Upper Silurian deposits. Its lower part is represented by clayey-carbonate rocks, whereas the upper part consists of terrigenous rocks. The thickness of this sequence increases gradually to the west towards the Teisseyre–Tornquist Zone, where it reaches the maximum thickness of over 1900 m.

There are different opinions as to the completeness of the Lower Devonian stratigraphic strata within the Volyn-Podillyan Plate. Nikiforova et al. (1972) recognized there the Lochkovian only, whereas Drygant (2000) argued that Pragian and Emsian deposits are present as well. We accepted the subdivision of Tsegelnyuk (1994), who concluded that the Lower Devonian platform strata in Ukraine are represented by the Lochkovian, which is subdivided into the Rukshyn and Tyver stages, and Pragian to Emsian referred to as the Dnister stage (Fig. 2).

ANALYTICAL METHODS

The study is based on the analysis of well-logs, core samples and thin sections. Thirty-one representative core samples of Lochkovian deposits (marlstones, biodetrital limestones, dolomitized limestones) and Pragian–Emsian siliciclastics (sandstones, siltstones and mudstones) were selected for petrographic examination (Table 1). The samples come from the following boreholes: Buchach-2 (Bch-2), Chernivtsi-1 (Chr-1), Krekhiv-1 (Kr-1), Lokachi-2, -6 and -9 (Lk-2, -6 and -9), Lyman-1 (Lm-1), Peremyshlyany-1 (Pr-1), Sarata-6 (Sr-6), Yargara-1 (Yr-1) and Zalozhtsi-1 (Zl-1) (see Fig. 1 for their locations).

The $CaCO_3$, $CaMg(CO_3)_2$ and clayey material rock-content has been calculated from chemical analyses, performed in the Institute of Geology and Geochemistry of Combustible Minerals of the NAS of Ukraine (Lviv, Ukraine). Thin sections were examined under a polarizing microscope Carl Zeiss Jena. Well-log data along with the results of analytical and petrographic analyses of rocks were used for the lithostratigraphic correlation of the examined sections.

LOWER DEVONIAN LITHOFACIES

Petrographic characteristics

The **clayey-carbonate facies** is represented by marlstones, dolomitized limestones and biodetrital limestones.

Marlstones (Fig. 3**II**D, E, G, H; Fig. 4**II**E, G) are dark grey, clayey, with thin calcite veinlets, pyritized streaks of organic matter and dolomitized. The content of calcite is 48–52%, clayey material amounts to 34–48% and dolomite to 5–10%. Locally, accumulations of silt-size quartz grains and identified relicts of calcareous bioclasts, such as ostracods and tentaculites, are observed.

Dolomitized limestones (Figs 3**II**F, 4**II**F) are dark-grey and consist of 40–47% calcite, 40–45% dolomite and 10–15% clayey material. The rocks often contain stylolitic sutures 1–3 mm in thickness. These are composed of dolomite crystals (0.1–0.3 mm), which usually have rhombohedral shape and calcite.

In dolomitized limestones a significant amount of organic matter is present. It is often pyritized and locally represented by strongly recrystallized bioclasts.

Biodetrital limestones (Fig. 4**II**C, D) are grey, rich in skeletal debris dominated by tentaculites, ostracods, brachiopods and subordinately by corals. There are also single grains of quartz, up to 0.05 mm in size, large phosphate matter accumulations (1–5%) and disseminated pyrite. Chemical analysis showed that the $CaCO_3$ content in these limestones ranges between 63% and 83%. The matrix is microcrystalline to fine-crystalline clayey-carbonates.

The **terrigenous facies** is made up of light grey, greenish-grey and brownish-red, non-calcareous sandstones that locally are interbedded with siltstones and mudstones.

Sandstones (Fig. 3**II**A, B, C; Fig. 4**II**A) are fine-grained with a contact-porous and contact-hydromica matrix, saturated with iron hydroxide. Clastic material is semi-rounded, 0.05–0.2 mm in size, represented by quartz grains (to 80%), feldspar (5–7%) and muscovite flakes (1–3%). Some quartzite and siliceous clasts are also recorded. Accessory minerals, such as zircon and epidote, are observed sporadically. Compositionally, siltstones are similar to sandstones.

Table 1. Petrographic composition of Lower Devonian rocks

Boreholes	Stratigraphy	Lithology	Depth (m)	Components											
				Clastic			Authigenic		Carbonate		Clayey	Accessory			Ore
				Q	Fl	Ms	Gl	Pht	Ca	Dl	Hm	Zr	Ru	Ep	Pr
				Composition (%)											
Krekhiv-1	Lochkovian	Dolomitized limestones	3348.7–3356.6	n.d	n.d	n.d	n.d	n.d	47	40	10	n.d	n.d	n.d	3
Krekhiv-1	Lochkovian	Marlstones	3405.1–3414.7	5	n.d	3	n.d	n.d	48	5	34	n.d	n.d	n.d	5
Krekhiv-1	Lochkovian	Marlstones	3486.6–3497.6	5	n.d	3	n.d	n.d	48	7	34	n.d	n.d	n.d	3
Krekhiv-1	Pragian–Emsian	Sandstone	1916.2–1918.6	78	7	3	n.d	n.d	2	n.d	9	0.5	n.d	0.5	n.d
Krekhiv-1	Pragian–Emsian	Mudstone	2151.1–2158	18	n.d	n.d	n.d	n.d	13	n.d	65.5	n.d	n.d	0.5	3
Lokachi-2	Pragian–Emsian	Sandstone	1267.5–1268	80	7	5	n.d	n.d	3	n.d	6	1	n.d	1	n.d
Lokachi-2	Pragian–Emsian	Sandstone	1337–1337.8	84	5	5	n.d	n.d	2	n.d	5	0.5	n.d	0.5	n.d
Lokachi-6	Pragian–Emsian	Siltstone	1298.9–1302	65	3.5	5	n.d	n.d	10	n.d	16	0.5	n.d	n.d	n.d
Lokachi-9	Lochkovian	Biodetrital limestones	1165–1168.6	1	n.d	n.d	n.d	n.d	80	8	6	n.d	n.d	n.d	5
Zalozhtsi-1	Lochkovian	Biodetrital limestones	501.4–506.5	2	n.d	n.d	n.d	n.d	73	4	7	n.d	n.d	n.d	5
Buchach-2	Lochkovian	Marlstones	453–459	2	n.d	3	n.d	n.d	50	2	35	0.5	n.d	n.d	7.5
Buchach-2	Lochkovian	Marlstones	555–560	3	n.d	3	n.d	n.d	51	2	34	n.d	n.d	n.d	7
Peremyshlyany-1	Pragian–Emsian	Mudstone	1251–1256	10	n.d	n.d	n.d	n.d	15	n.d	70	n.d	n.d	n.d	5
Peremyshlyany-1	Lochkovian	Marlstones	1650–1655	3	n.d	3	n.d	n.d	49	5	37	n.d	n.d	n.d	3
Chernivtsi-1	Lochkovian	Marlstones	612–630	4	n.d	3	n.d	n.d	49	8	34	n.d	n.d	n.d	2
Chernivtsi-1	Lochkovian	Marlstones	690–706	5	n.d	n.d	n.d	n.d	50	6	37	n.d	n.d	n.d	2
Yargara-1	Pragian–Emsian	Mudstone	978–981	8	n.d	n.d	n.d	n.d	15	n.d	74.5	0.5	n.d	n.d	2
Yargara-1	Pragian–Emsian	Sandstone	1030–1058	78	5	3	n.d	n.d	5.5	n.d	8	0.5	n.d	n.d	n.d
Yargara-1	Lochkovian	Biodetrital limestones	1171–1175	2	n.d	n.d	n.d	n.d	69	14	10	n.d	n.d	n.d	5
Yargara-1	Lochkovian	Marlstones	1458–1461	n.d	n.d	0.5	n.d	n.d	49	10.5	35	n.d	n.d	n.d	5
Lyman-1	Pragian–Emsian	Sandstone	1406–1412	80	5	1	n.d	n.d	5	n.d	9	0.5	n.d	n.d	n.d
Lyman-1	Pragian–Emsian	Mudstone	1479–1481	5	n.d	n.d	n.d	n.d	15	n.d	79.5	0.5	n.d	n.d	n.d
Lyman-1	Lochkovian	Biodetrital limestones	1565–1571	5	n.d	n.d	n.d	n.d	63	15	10	n.d	n.d	n.d	7
Lyman-1	Lochkovian	Biodetrital limestones	1816–1821	n.d	n.d	n.d	n.d	n.d	83	5	7	n.d	n.d	n.d	5
Lyman-1	Lochkovian	Dolomitized limestones	2170–2180	n.d	n.d	n.d	n.d	n.d	40	45	10	n.d	n.d	n.d	5
Lyman-1	Lochkovian	Marlstones	1979–1981	n.d	n.d	0.5	n.d	n.d	51	9.5	34	n.d	n.d	n.d	5
Lyman-1	Lochkovian	Marlstones	2180–2200	n.d	n.d	0.5	n.d	n.d	49	9.5	34	n.d	n.d	n.d	7
Sarata-6	Pragian–Emsian	Siltstone	3391–3395	70	5	5	1	1	6	n.d	9.5	2	0.5	n.d	n.d
Sarata-6	Pragian–Emsian	Siltstone	3442–3446	55	3	3	1	0.5	13	3	20	1	0.5	n.d	n.d
Sarata-6	Lochkovian	Biodetrital limestones	3860–3866	3	n.d	n.d	2	2	68	10	10	n.d	n.d	n.d	5
Sarata-6	Lochkovian	Marlstone	4217–4226	n.d	n.d	n.d	n.d	n.d	52	8	35	n.d	n.d	n.d	5
				Average											
	Pragian–Emsian	Sandstone		80	5.8	3.4	n.d	n.d	3.5	n.d	7.4	0.6	n.d	0.6	n.d
	Pragian–Emsian	Siltstone		63.3	3.8	4.3	0.6	0.5	9.7	1	15.2	1.2	0.3	n.d	n.d
	Pragian–Emsian	Mudstone		10.5	n.d	n.d	n.d	n.d	14.5	n.d	72.3	0.25	n.d	0.1	2.5
	Lochkovian	Marlstones		3.8	n.d	2.3	n.d	n.d	49.25	5.7	35	0.06	n.d	n.d	4.3
	Lochkovian	Biodetrital limestones		2.2	n.d	n.d	0.2	0.2	72.7	9.3	8.3	n.d	n.d	n.d	5.3
	Lochkovian	Dolomitized limestones		0.6	n.d	n.d	n.d	n.d	42.3	42	11.6	n.d	n.d	n.d	3.3

Q, quartz; Fl, feldspar; Ms, muscovite; Gl, glauconite; Pht, phosphate; Ca, calcite; Dl, dolomite; Hm, hydromica; Zr, zircon; Ru, rutile; Ep, epidote; Pr, pyrite; n.d., not determined.

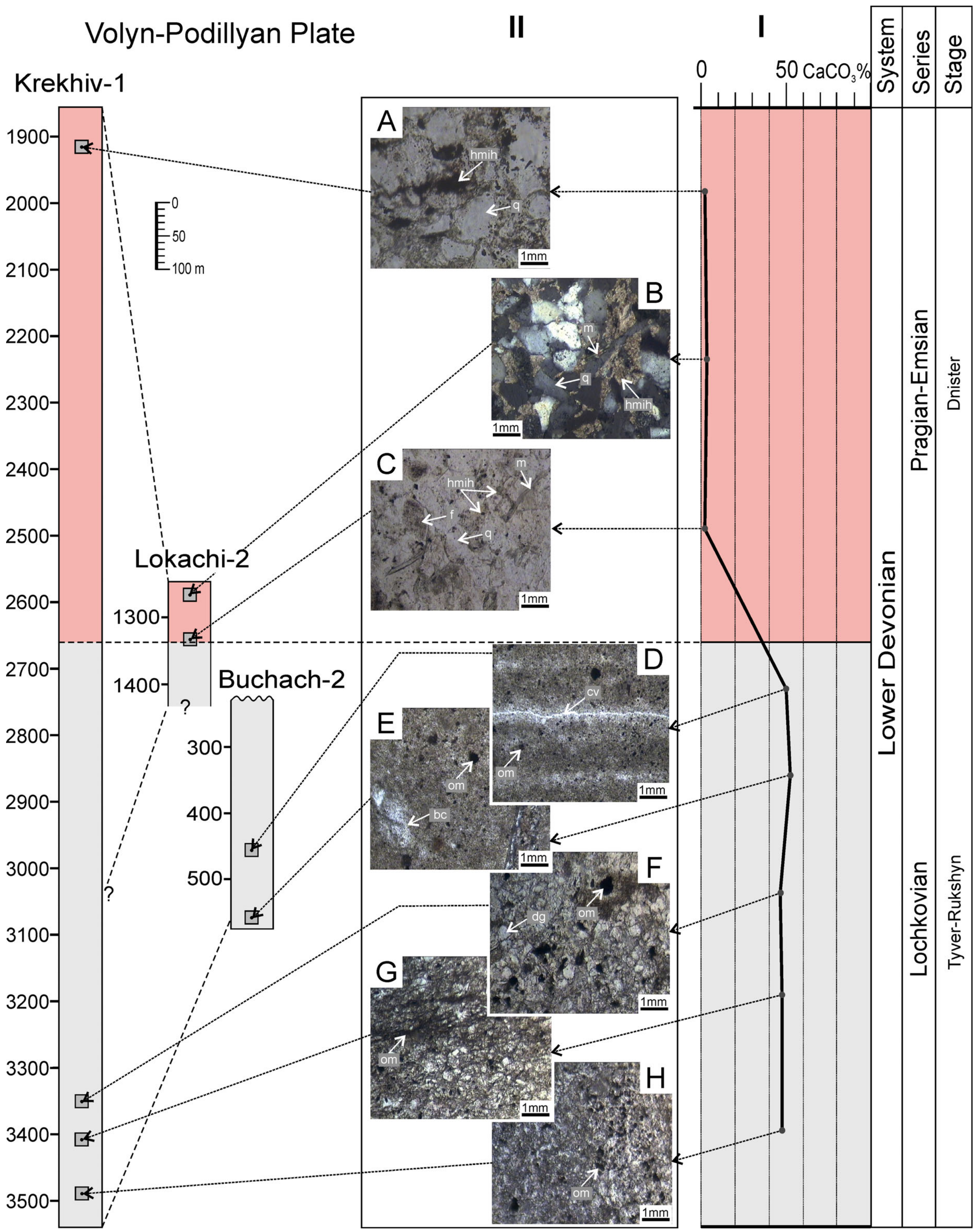

Fig. 3. (**I**) $CaCO_3$ content in the Lower Devonian sequence of the boreholes (Volyn-Podillyan Plate). (**II**) Photomicrographs of the Lower Devonian rocks from the Krekhiv-1, Lokachi-2 and Buchach-2 boreholes (Volyn-Podillyan Plate). Photomicrograph B was made without analyser, all the rest – with analyser. A, B, C, sandstones with hydromica matrix saturated with iron hydroxide (hmih), quartz (q), feldspar (f) and muscovite (m): A – depth interval 1916.2–1918.6 m, B – depth interval 1267.5–1268 m, C – depth interval 1337–1337.8 m; D, E, G, H, marlstones with pyritized streaks of organic matter (om): D – calcite veinlet (cv), depth interval 453–459 m, E – problematic bioclasts (bc), depth interval 555–560 m, G – depth interval 3405.1–3414.7 m, H – depth interval 3486.6–3497.6 m; F – dolomitized limestones with dolomite grains (dg) and organic matter (om), depth interval 3348.7–3356.6 m.

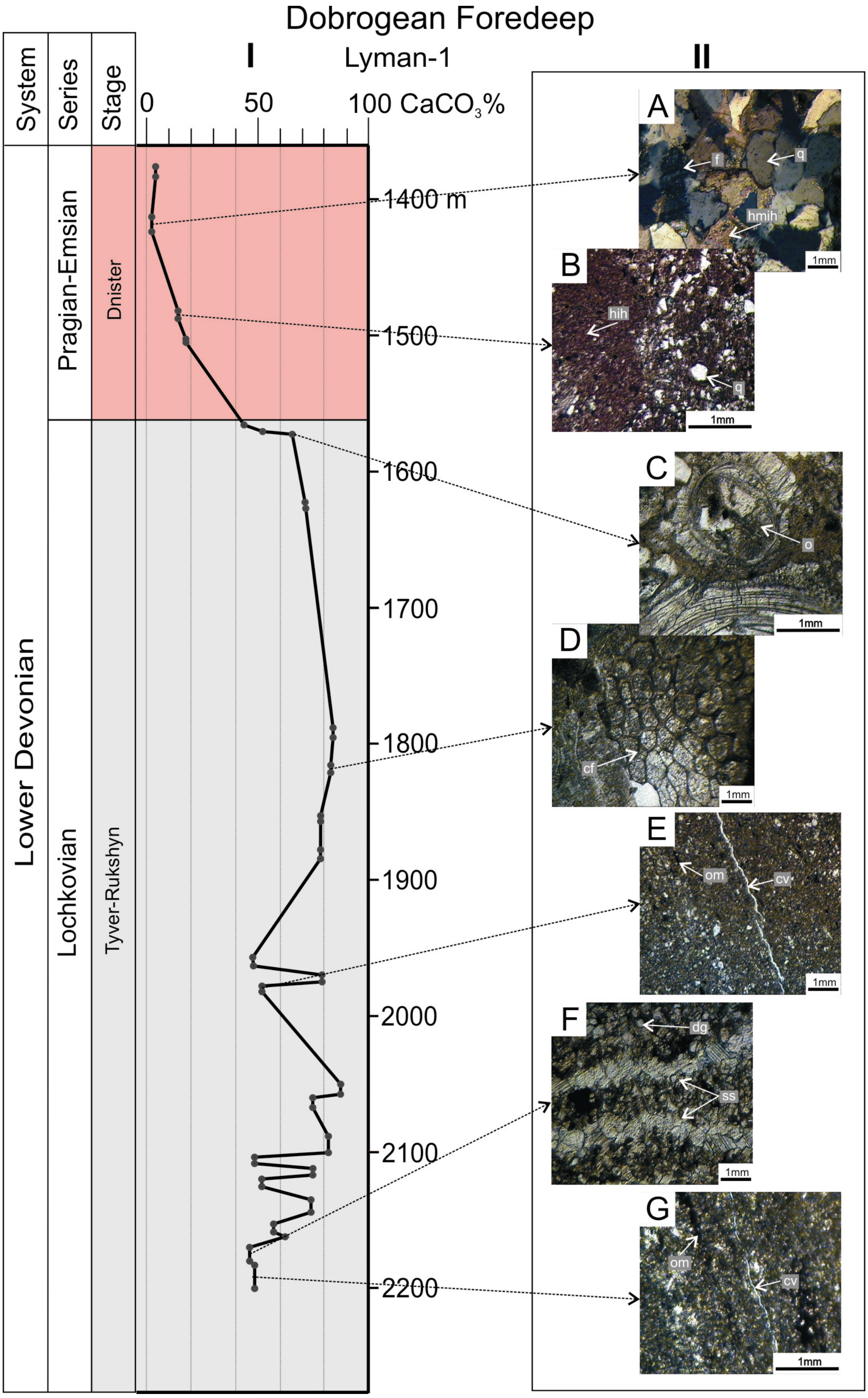

Fig. 4. (**I**) $CaCO_3$ content in the Lower Devonian sequence of the Lyman-1 borehole (Dobrogean Foredeep). (**II**) Photomicrograph of the Lower Devonian rock of the Lyman-1 borehole (Dobrogean Foredeep). Photomicrograph A was made without analyser, all the rest – with analyser. A, sandstones with hydromica matrix saturated with iron hydroxide (hmih), quartz (q) and feldspar (f), depth interval 1406–1412 m; B, mudstones, composed of hydromica saturated with iron hydroxide (hih) and quartz (q), depth interval 1479–1481 m; C, D, biodetrital limestones: C – ostracods (o), depth interval 1565–1571 m, D – coral fragment (cf), depth interval 1816–1821 m; F – dolomitized limestones with stylolitic sutures (ss) and dolomite grains (dg), depth interval 2170–2180 m; E, G – marlstones with calcite veinlet (cv) and pyritized streaks of organic matter (om): E – depth interval 1979–1981 m, G – depth interval 2180–2200 m.

Mudstones (Fig. 4**II**B) are composed of thin flakes of hydromica with oriented texture. As a rule, the rock is saturated with iron hydroxide. Clastic material (0.01–0.07 mm) is unevenly distributed in the mudstones, from a few grains to 25–32% in different parts of the rock. It is mainly represented by quartz. Feldspar and muscovite grains are less common. Small amounts of rhombohedral dolomite grains, as well as fine pyrite, are observed.

K-bentonites (tuffites) occur as numerous, 0.05–3 m thick intercalations throughout the Lower Devonian succession (Fig. 5). They are especially common in clayey-carbonate lithofacies, similarly to the Upper Silurian sequence within the study area (Radkovets 2015). For the basic section of Podillya, K-bentonites are shown after Nikiforova et al. (1972). For the remaining sections they are indicated based on petrographic investigations, well-log analysis and correlation with the basic section of Podillya. Hence K-bentonites of the Dnister Basin in Podillya occur in the Upper Silurian as well as in the Lower Devonian. Huff et al. (2000) have interpreted the Ludlow and Pridoli K-bentonites of the Dnister Basin in Podillya as indicative of active volcanic arcs along the margin of the Rheic Ocean.

A total of 97 K-bentonite levels in the form of altered airfall volcanic ash beds (Histon et al. 2007) have also been recorded from the Upper Ordovician (Ashgill) to Lower Devonian (Lochkov) sequences of the Carnic Alps, Austria. These ash beds suggest widespread rifting-related volcanism in the enigmatic Palaeo-Tethys (von Raumer et al. 2002, 2003), which opened during the Silurian period between the northern margin of Gondwana and the composite Hun Superterrane. It may have lasted until the end of the Middle Devonian, when these terranes amalgamated and the closure of the Rheic Ocean began. Lower to Middle Devonian marine strata in the Appalachian foreland basin feature up to 80 or more thin K-bentonites that represent ancient volcanic ashes. According to Ver Straeten (2004), the middle Lochkovian, early Emsian and early Eifelian were times of peak volcanic activity in eastern North America, related to times of increased tectonism in the Acadian orogen.

Correlation of borehole sections

Figure 5 shows the lithological features and spatial distribution of Lower Devonian lithofacies in twelve well sections. Stage boundaries are based on well-log data, distribution of K-bentonite beds and the results of petrographic investigations. The main reference section for correlation is that from Podillya (Nikiforova et al. 1972) that was constructed on the basis of 87 outcrops along the Dnister River and its tributaries. These outcrops are now under water as a result of the damming of the river valley related to the construction of the Dnister hydroelectric power plant.

The correlation shows (Fig. 5) that the Lochkovian sequence (clayey-carbonate lithofacies) dips monoclinally and its uppermost part was partly eroded away (boreholes Ogladiv-1, Brody-1, Zalozhtsi-1, Vugilna-7). The Pragian–Emsian deposits of terrigenous lithofacies are spread to a lesser extent than Lochkovian and are more eroded (Chebanenko et al. 1990). Despite erosion, in the deeper part of the section the Pragian–Emsian deposits reach a significant thickness to over 800 m. This fact is very important because we are considering the terrigenous reddish-brown rocks as potential gas reservoir rocks as in the Lokachi field (Fedyshyn 1998; Galabuda et al. 2007).

Distribution of lithofacies

The Lower Devonian strata within the study area were subdivided on the basis of our investigation into two lithofacies: the clayey-carbonate Lochkovian and the terrigenous Pragian–Emsian facies, which are roughly equivalent in age to Devonian continental deposits, so-called Old Red Sandstones, occurring westwards of the Ukrainian Shield towards the Teisseyre–Tornquist Zone. The clayey-carbonate lithofacies represents the continuation of the Upper Silurian strata. The terrigenous lithofacies completes the Lower Devonian section. Previous studies (Drygant et al. 1982; Chebanenko et al. 1990; Drygant 2000; Kurovets et al. 2012) have shown different thicknesses and boundaries between the clayey-carbonate and terrigenous deposits within the Volyn-Podillyan Plate.

The thickness maps (Fig. 6A, B) of the Lower Devonian were constructed on the basis of our investigations of well-log data, core samples, thin sections and stratigraphic subdivision of the Lower Devonian for the Volyn-Podillyan Plate by Nikiforova et al. (1972) and Tsegelnyuk (1981, 1994) and for the Dobrogean Foredeep by Safarov & Kaptsan (1967), Grishchenko et al. (1986), as well as the information contained in the above-mentioned publications, which were compared with the data from Romania and Moldova (Barbu et al. 1969; Paraschiv et al. 1983; Prodan 1987; Kruglov & Tsypko 1988; Gnidets et al. 2002; Mutihac et al. 2007; Seghedi 2012).

Figure 6A represents the occurrence of the clayey-carbonate lithofacies (Lochkovian) and its thickness within the area from the border of Ukraine with Poland and Belarus to the Black Sea. Clayey-carbonate lithofacies continuously cover the entire territory under study. In the territory of Romania and Moldova the Lochkovian deposits are partly eroded, as well as within the Dobrogean Foredeep. At monoclinal dipping the thickness of this

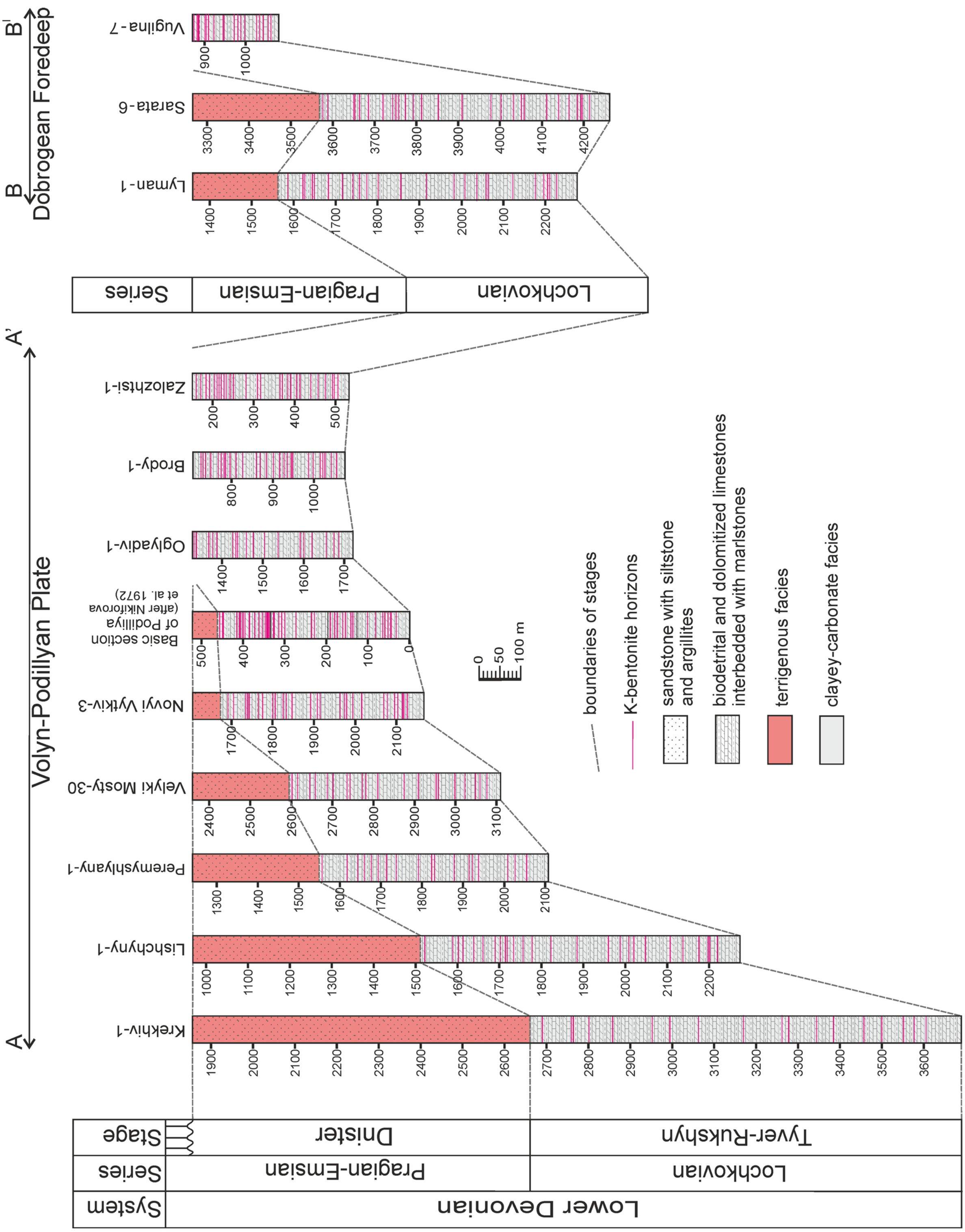

Fig. 5. Lithological sections through the Lower Devonian succession in the Volyn-Podillyan Plate (A–A[1]) and Dobrogean Foredeep (B–B[1]) (see Fig. 1 for location).

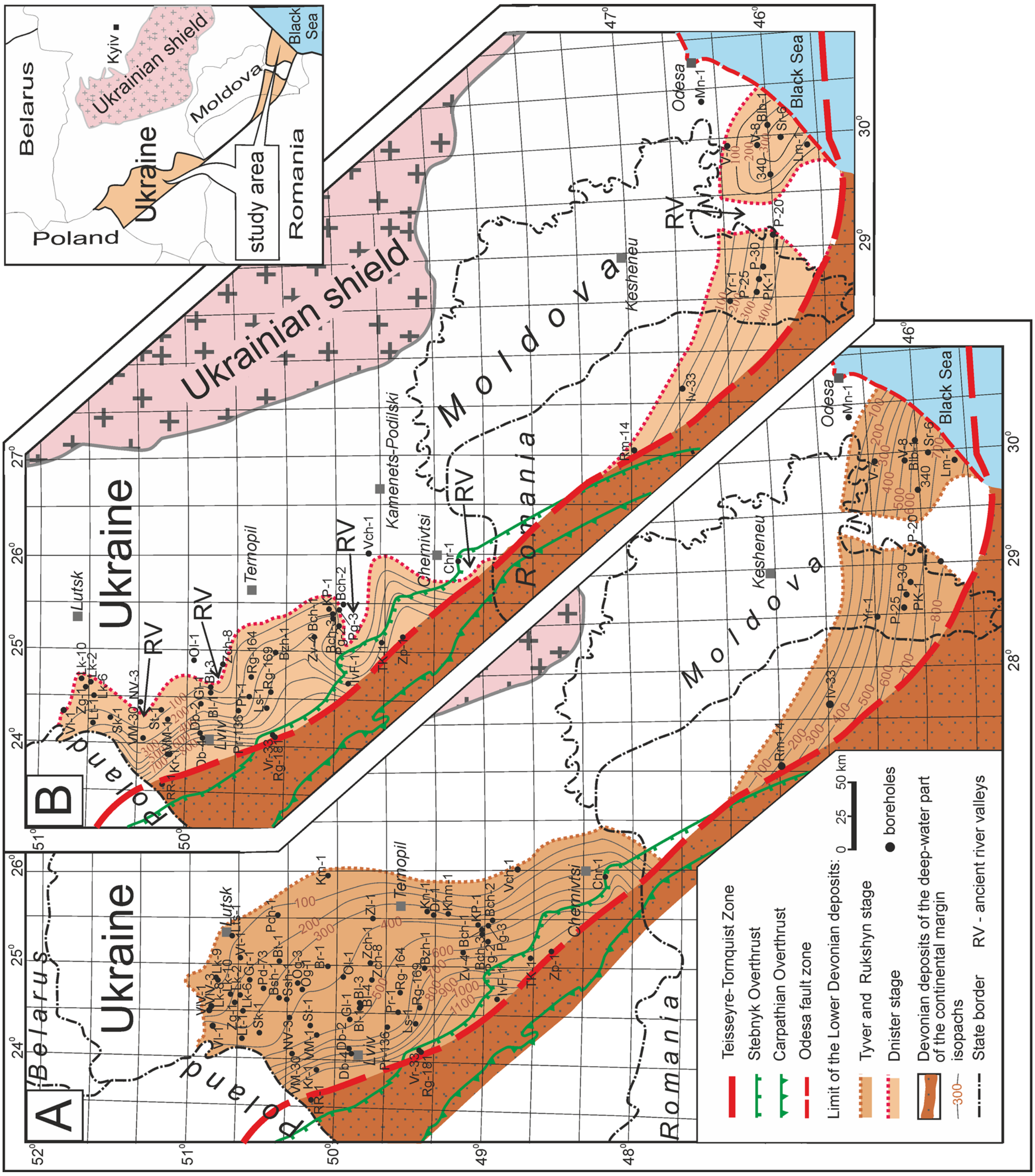

Fig. 6. Thickness maps of (**A**) Lochkovian, clayey-carbonate facies and (**B**) Pragian–Emsian, terrigenous facies within the southwestern margin of the East European Platform.

lithofacies increases gradually up to 700 m within the Dobrogean Foredeep and to over 1100 m at the Volyn-Podillyan Plate.

Figure 6B shows that the Pragian–Emsian terrigenous lithofacies experienced much more advanced erosion than the clayey-carbonate strata so that it now occurs as a narrow band along the Teisseyre–Tornquist line. On the background of general monoclinal dipping of the rocks five local morphostructures are distinguished, which stretch across the Pragian–Emsian strata from northeast to southwest, being almost parallel to each other and representing ancient river valleys (RV in Fig. 6B). According to our petrographic investigations and to Chebanenko et al. (1990) and Tsegelnyuk (1981, 1994), the sediments of the terrigenous lithofacies are the product of erosion of the basement rocks of the Ukrainian Shield (quartz, feldspars, muscovite, zircon, epidote), which accumulated in the sedimentary basin due to the river transport, which had its source from the Ukrainian Shield. In Romania, similarly to Moldova, these strata occur only within the area adjacent to the Dobrogean Foredeep part. The thicknesses of the terrigenous lithofacies are significantly smaller than those of the clayey-carbonate facies. The thickness of the terrigenous lithofacies reaches 400 m within the Dobrogean Foredeep and over 800 m at the Volyn-Podillyan Plate.

Figures 3**I**, 4**I** and Table 1 show the lithofacies-related $CaCO_3$ content in the Lower Devonian sequence for both the Dobrogean Foredeep (Lyman-1 borehole) and the Volyn-Podillian Plate (Krekhiv-1, Buchach-2 and Lokachi-2 boreholes). The difference of its value for two different lithofacies is evident. For the clayey-carbonate lithofacies (Lochkovian) $CaCO_3$ content is significant over the entire succession, ranging from 40% to 87%, whereas in the terrigenous lithofacies (Pragian–Emsian) a decrease in $CaCO_3$ content is observed, varying from 18% to as low as 2%. Hence we can state that for the rocks of the clayey-carbonate lithofacies the minimum $CaCO_3$ content is 40%, while for the rocks of the terrigenous lithofacies its maximum content is 18%. This indicates quite different depositional environments in the Lower Devonian. In the Lochkovian favourable environments existed for carbonate sedimentation, but in Pragian–Emsian time – for the intense deposition of terrigenous material.

FACIES PATTERN IN RELATION TO EARLY DEVONIAN OCEANOGRAPHY AND SEA-LEVEL CHANGES

Global and regional events

The Devonian was one of the most interesting and enigmatic periods in the Earth's history. On the land areas trees and seed plants evolved and forests appeared for the first time (Algeo & Scheckler 1998). During the Silurian to Early Devonian, the Acadian–Caledonian orogeny took place as a result of the closure of the southern Iapetus Ocean and collision of Baltica with Laurentia (Torsvik et al. 1996; Ver Straeten 2004). This collision produced the Caledonian mountains in Greenland, Scandinavia and the British Isles, and the Appalachians in the eastern USA. The new large super-continent, which resulted from this collision and existed during Early Devonian times, is sometimes called Laurussia or Euramerica or the 'Old Red Continent' (Golonka 2007; Golonka & Gawęda 2012). Extensive shallow sandy bays, deltas and inlets across the Old Red Continent provided a prosperous milieu for strange armoured jawless fishes and placoderms (Young 2010).

During the Early Devonian, the study area lay in low southern latitudes (45–52ºS) within the southeastern shelf basin of Baltica (Fig. 7A). In the Lochkovian (Fig. 7B, B'), this sedimentary basin was a continuation of the Late Silurian basin, although the sea level had slightly fallen. The clayey-carbonate sediments with numerous inter-calations of K-bentonites (tuffites) had accumulated as in the Pridoli. In the Silurian and Lochkovian, the climate and tectonic conditions remained the same. It was a warm greenhouse period typified by high atmospheric CO_2 levels (Berner 2001; Royer 2006).

A different depositional story began in the Pragian, showing a dramatic change in climatic and tectonic conditions. From the Lochkovian to Emsian, tempera-tures decreased (Kiessling 2002) and the sea level fell (Vail et al. 1977; Berner & Kothavala 2001; Simon et al. 2007; Haq & Shutter 2008; Joachimski et al. 2009). Cooler climate conditions, with intermediate tempera-tures of about 23 to 25°C, decreasing atmospheric CO_2 and accordingly increasing O_2 concentrations, have been established. Dahl et al. (2010) indicate two episodes of global ocean oxygenation in the Earth's history. The first one took place in the Ediacaran 550–560 million years ago and the second, perhaps larger oxygenation, occurred in the Early Devonian at about 400 Ma.

Depositional environments

The depositional environments within the southeastern shelf basin of Baltica (Fig. 7B, B') have been recon-structed using the maps compiled on the basis of the author's materials, and published data (Kleesment & Mark-Kurik 1997; Narkiewicz 2011; Mark-Kurik & Põldvere 2012), occurrence of the clayey-carbonate facies of the Lochkovian series (Fig. 7C) and the terrigenous facies of the Pragian–Emsian series (Fig. 7C') at the southwestern margin of the East European Platform.

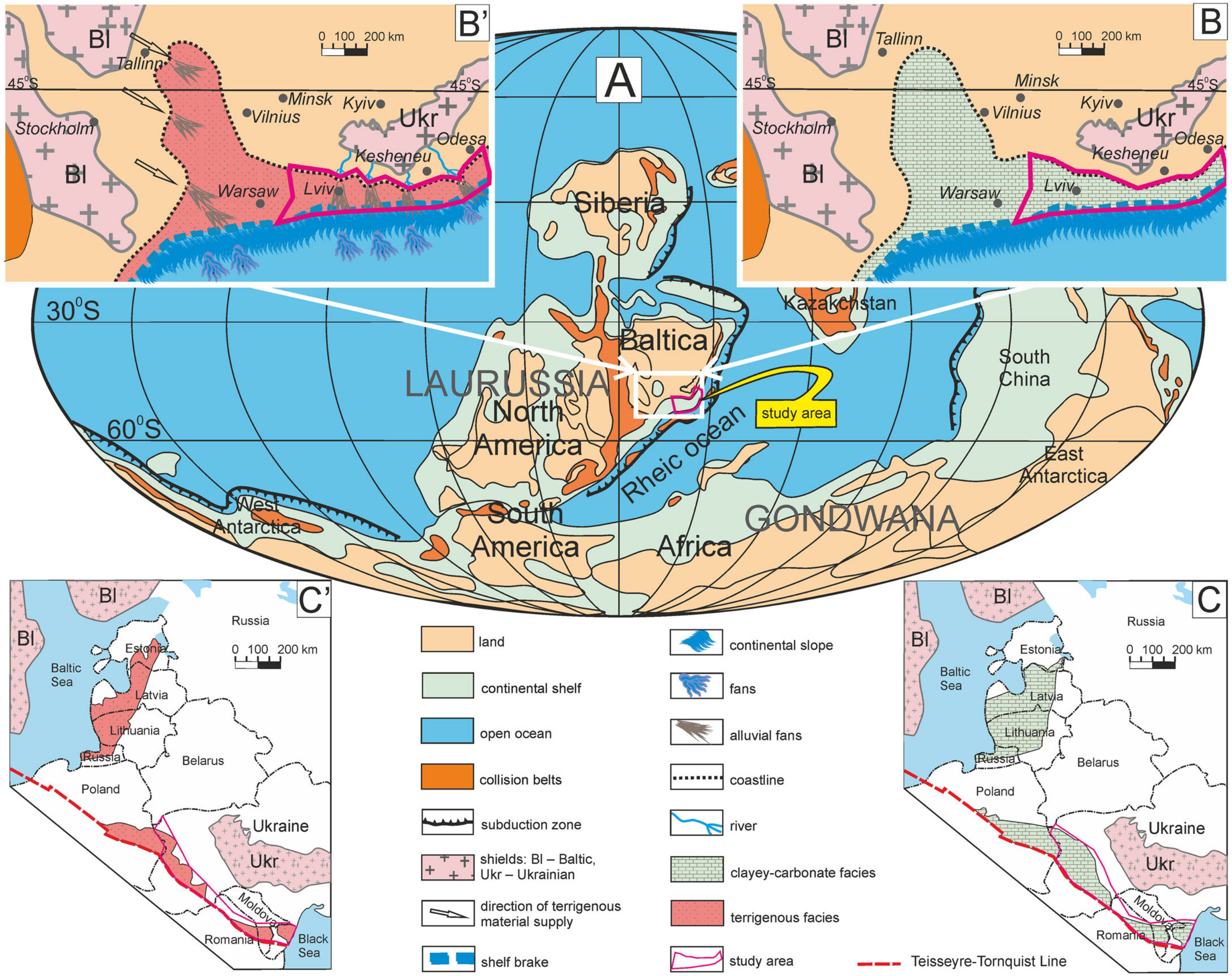

Fig. 7. (**A**) Early Devonian palaeogeography, showing the position of the study area within Baltica (after Golonka & Gawęda 2012). Sketch maps show the model of the southern shelf of Baltica with the occurrence of (**B**) – clayey-carbonate facies of Lochkovian time; (**B'**) – terrigenous facies of Pragian–Emsian time.

Maps of Lower Devonian occurrence within the southwestern margin of the East European Platform show: (**C**) clayey-carbonate facies of the Lochkovian series; (**C'**) terrigenous facies of the Pragian–Emsian series.

The Lochkovian epicontinental basin (Fig. 7B) was a typical carbonate platform (cf. Kiessling et al. 2003), which supported a variety of calcareous biocenoses. These contained abundant brachiopods, pelecypods, tentaculites and ostracods, as well as crinoids, rugose and tabulate corals, gastropods, trilobites, graptolites and conodonts (Nikiforova et al. 1972; Tsegelnyuk 1981, 1994). As a result, sediments with a significant content of $CaCO_3$ (48–87%) accumulated. The presence of numerous streaks of pyritized organic matter in dark grey marlstones indicates favourable conditions for organic matter fossilization. Although a deep-water anoxic environment similar to that of the Silurian organic-rich graptolitic shales (Radkovets 2015) is not evident there, oxygen-poor environments must have existed locally.

In the Pragian, the sedimentary basin reduced its size (Fig. 7B'), the carbonate accumulation ceased and the terrigenous sedimentation begun instead. Numerous rivers supplied clastic material from the Baltic and Ukrainian shields and generated a thick sediment wedge composed of sandstones, siltstones and mudstones. The wedge was erosionally reduced during the late Emsian, but the thickness of preserved sediment generally exceeds 1000 m. These sediments are reddish-brown in colour and were deposited in oxygenated environments irrespective of the source of clastic material, sediment composition as well as tectonic and depositional settings, similarly to the case of the Old Red Sandstone facies widespread in the North Atlantic region (Friend 1969; McClay et al. 1986; Friend et al. 2000; Blomeier et al. 2003).

CONCLUSIONS

Based on the study of well-log data, and lithological and petrographic investigations of Lower Devonian strata within the Volyn-Podillyan Plate and the Dobrogean Foredeep and their correlation with coeval deposits of the adjacent territories of Moldova and Romania (Moldovian Platform), Poland, Lithuania, Latvia and Estonia, an integral concept of the extent of the Lower Devonian, regularities of thickness changes, petrographic composition of rocks and distribution of two facies within the southwestern margin of the East European Platform was developed. These lithofacies belong to different age ranges: the clayey-carbonate facies to the Lochkovian, the terrigenous facies to the Pragian and Emsian. They have been formed in different palaeo-environments. An abrupt change is observed in the petrographic composition of rocks.

The Lochkovian sequence is represented by clayey-carbonate sediments with numerous streaks of pyritized organic matter and $CaCO_3$ content of 48–87%, reflecting favourable environments for the development of calcareous biocenosis and organic matter fossilization. Hence, the Lochkovian showed still no significant change in warm greenhouse climate with high atmospheric CO_2 and in tectonic conditions, which occurred since the Late Silurian. In turn, the Pragian and Emsian comprise distinctly terrigenous sequences, which are reddish-brown in colour with a small amount of $CaCO_3$ (from 2 to 18%), manifesting a different depositional history with oxygenated environments and dramatic change in climatic and tectonic conditions, which started in the Pragian. In spite of different depositional environments, the Pragian–Emsian strata, whether of terrestrial or marine origin, have a common feature – a reddish-brown colour, which gives evidence of the oxic environments within the entire supercontinent Laurussia independently of the tectonic setting.

The terrigenous lithofacies is widespread within the study area and its thickness reaches over 1000 m. These terrigenous deposits are an important tight-gas exploration target in Europe and USA. Thus there is a good reason to consider these strata of the study area as prospective for conventional as well as unconventional hydrocarbons, because these reddish-brown terrigenous rocks of Pragian–Emsian age are the reservoir rocks for gas accumulation at the Lokachi field (Volyn-Podillyan Plate). Besides, numerous oil and gas shows and four oil and gas fields have been discovered in the Middle–Upper Devonian within the Ukrainian territory (Volyn-Podillyan Plate, Dobrogean Foredeep).

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Alam-Devoni litofaatsiesed ja paleokeskkond Ida-Euroopa platvormi edelapiiril (Ukrainas, Moldovas ja Rumeenias)

Natalia Radkovets

Alam-Devoni šelfil tekkinud kivimid levivad Ida-Euroopa platvormi läänepoolsel äärealal alates Läänemerest kuni Musta mereni. Neid kivimeid uuriti Ukraina piires (Volõõnia-Podoolia platoo, Dobrogi äärenõos) ja korreleeriti samavanuseliste kivimitega Moldovas ning Rumeenias (Moldova platvormil). Alam-Devoni kivimite uurimine, nende paksus, petrograafiline ja litoloogiline iseloom võimaldavad rekonstrueerida kaks litofaatsieste tüüpi ning eristada kaks erinevat sedimentatsiooni keskkonda. Esimene faatsies kuulub Lochkovi lademesse, mis koosneb savikatest karbonaatkivimitest, jätkates Ülem-Siluri mereliste setete kujunemise laadi. Teine faatsies kuulub Praha ja Emsi lademesse ning koosneb punakaspruunidest terrigeensetest kivimitest, mis on Alam-Devoni ülemisest osast tuntud Old Redi liivakivi analoog. Terrigeense litofaatsiese leviku ja paksuse uurimine on oluline, kuivõrd see on potentsiaalne reservuaar nii traditsiooniliste kui ka ebatraditsiooniliste (kinnisgaas) süsivesinike maardlate kujunemiseks. Niisuguseid gaasimaardlaid on avastatud Lokachi piirkonnas.– –