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Paleocene deposits of the Ukrainian Carpathians: geological and petrographic characteristics, reservoir properties

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Abstract. The Paleocene Yamna Formation represents one of the main oil-bearing sequences in the Ukrainian part of the Carpathian petroleum province. Major oil accumulations occur in the Boryslav-Pokuttya and Skyba Units of the Ukrainian Carpathians. In the great part of the study area, the Yamna Formation is made up of thick turbiditic sandstone layers functioning as reservoir rocks for oil and gas. The reconstructions of depositional environments of the Paleocene flysch deposits performed based on well log data, lithological and petrographic investigations showed that the terrigenous material was supplied into the sedimentary basin from two sources. One of them was located in the northwest of the study area and was characterized by the predominance of coarse-grained sandy sediments. Debris coming from the source located in its central part showed the predominance of clay muds and fine-grained psammitic material. The peculiarities of the terrigenous material distribution in the Paleocene sequence allowed singling out four areas with the maximum development (> 50% of the total section) of sandstones, siltstones and mudstones. The performed petrographic investigations and the estimation of reservoir properties of the Yamna Formation rocks in these four areas allowed establishing priority directions of further exploration works for hydrocarbons in the study territory.

Keywords: *Carpathians; Skyba and Boryslav-Pokuttya Units; Yamna Formation; reservoir rocks; oil and gas prospective areas*

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INTRODUCTION

The Outer Carpathians and their foredeep represent one of the oldest and largest petroleum provinces in the World (Fedyshyn 1998; Ulmishek, Klemme 1990). The geological history of the Carpathian oil- and gas-bearing region goes back about 300 years. Manual production of oil in the Carpathians began in the second half of the 18th century in Boryslav. In the second half of the 19th century, drilling in the region was performed using manual methods, while at the end of that century, mechanical methods of drilling were applied (Zuber 1885; Zeh 1889; Krupskyi 2001; Vishnyakov *et al.* 2014). To date, there have been several thousand exploration and production wells drilled in the Ukrainian Carpathians. A total of 41 hydrocarbons fields have been discovered within the Ukrainian Outer Carpathians (Fedyshyn 1998; Mayevskyi *et al.* 2014).

The Paleocene sequence of the Ukrainian Outer Carpathians and the Carpathian Foredeep are represented by turbidite deposits, which in most of the study area, are made up of thick sandstone layers. Most of the available studies into the Paleocene sediments of the Ukrainian Carpathians focus on problems of geological structure, stratigraphy, tectonics, and description of the existing petroleum fields, while mineralogical, petrographic and lithological aspects are described in less detail (e.g. Dolenko 1962; Dolenko *et al.* 1980; Pylypchuk, Vul 1981; Gabinet 1985; Vialov *et al.* 1988; Havryshkiv 2008; Havryshkiv *et al.* 2007; Krupskyi *et al.* 2014; Vul 2014; Waśkowska *et al.* 2019).

Paleocene sandstones are among the principal reservoir rocks in the flysch succession of the Outer Carpathians. The first oil fields, i.e. Strilbychi, Skhidnytsya and Bytkiv-Babche, were discovered in the Paleocene reservoirs in the second half of the 19th century. In the second half of the 20th century, two more fields of hydrocarbons, i.e. Blazhiv and Tanyava, were found (Fedyshyn 1998). The main aspects of petroleum generation and accumulation in the area of the Ukrainian Carpathians were discussed in earlier publications (Koltun 1992; Koltun *et al.* 1998; Kotarba, Koltun 2006; Ślączka *et al.* 2006; Więcław *et al.* 2012; Kosakowski 2013; Radkovets *et al.* 2016; Karabyn *et al.* 2019).

Presently, all the above mentioned 5 fields in the Yamna Formation reservoirs are operating. However, there are significant preconditions for forecasting and discovering new petroleum accumulations in this turbidite, essentially sandy succession. The thrust-and-fold structure of the Outer Carpathians, which is intensely developed in the Skyba and Boryslav-Pokuttya nappes of the Ukrainian Carpathians, suggests the existence of multiple anticline structures. Hence, the information on the distribution of rocks with good reservoir properties throughout the study territory allows determining directions for further petroleum exploration works.

Since the Paleocene sequence in the study territory has been proved to bear petroleum, the establishment of additional criteria for new hydrocarbons accumulations prospecting is the task of priority importance. Objectives of this study are as follows: to reconstruct the propagation of Paleocene sediments in the Carpathian basin using palinspastic restoration techniques; to establish variations in the Yamna Formation thickness within the Skyba and the Boryslav-Pokuttya nappes of the Ukrainian Carpathians; to estimate proportions of different rock types in the total section; to single out areas with the maximum occurrence of sandstones, siltstones, mudstones; to perform detailed studies of petrographic features and reservoir properties of the Yamna Formation. To accomplish these tasks, we have investigated a considerable number of well-logs distributed throughout the study territory and carried out lithological, mineralogical, petrographic, palaeoceanographic investigations, the combined results of which allowed delineating the potential areas for further oil and gas exploration within the study territory as well as those where petroleum occurrence is less probable. The identification of prospective oil and gas accumulation areas will help planning further exploration works more efficiently and determine first priority exploration targets within the Skyba and the Boryslav-Pokuttya nappes of the Ukrainian Carpathians.

GEOLOGICAL OVERVIEW OF THE STUDY AREA

The Ukrainian Carpathians, constituting the northeastern segment of the Carpathian Arc, are situated between the Polish and Romanian Carpathians (Fig. 1). The thrust-and-fold belt of the Outer Carpathians is bounded by the Carpathian Foredeep in the northeast and the Pieniny Clippen Belt in the southwest. It is made up of terrigenous flysch and is thrust over the southwestern margin of the East European Platform.

The evolution of the Outer Carpathians basin started with the Late Jurassic rifting and extension (Kosakowski *et al.* 2018; Golonka *et al.* 2006) with a consequent post-rift thermal subsidence and deepening of the sedimentary environment, which resulted in the deposition of a thick flysch succession. The generally well-oxygenated depositional conditions, which supposedly prevailed during the Turonian to Eocene, conditioned high rates of sedimentation (Kosakowski *et al.* 2018; Bieda *et al.* 1963; Ślączka *et al.* 1999). Periods of intense turbidite deposition, caused by major sea-level drops, resulted in the formation of thick sandstone sequences in the Paleogene succession, the Paleocene Yamna Formation (the object of our study) being one of them. The compressional deformation of the Outer Carpathians, which took place during the Oligocene to the Early Miocene, led to the formation of the Carpathian thrust-and-fold belt and the Carpathian Foredeep (Kosakowski *et al.* 2018; Ślączka *et al.* 1999).

The Carpathian Foredeep is subdivided into three separate units, i.e. Bilche-Volytsya, Sambir and Boryslav-Pokuttya. A number of tectonic units have been identified within the Ukrainian Outer Carpathians (Fig. 1): Skyba, Krosno, Dukla, Porkulets, Chornogora, Rakhiv and Magura (Shakin *et al.* 1976; Kruglov *et al.* 1985; Hnylko 2011). The study area covers the Skyba and the Boryslav-Pokuttya Units, where the Yamna Formation represents one of the main reservoir rock sequences for hydrocarbons accumulations in the Carpathian petroleum province.

The Boryslav-Pokuttya Unit represents a complex of superimposed nappes, each of which usually comprises a flysch succession covered by molasse. Northeastward, it is thrust over the Sambir unit and is partially covered by the Skyba nappe in the southwest (Figs 1 and 2).

The Skyba Unit extends along the frontal part of the Carpathians (Glushko1968; Vialov *et al.* 1988; Krupsky 2001). It is the largest tectonic unit of the Outer Carpathians and is made up of a flysch succession. The Skyba Unit consists of a number of thrusts, stretching for hundreds of kilometers from northwest to southeast and overlying one another with varying amplitudes. In the Ukrainian Carpathians, the Skyba Unit is thrust over the south-western part of the Boryslav-Pikuttya Unit of the Carpathian Foredeep and covers a large part of it. The amplitude here is at least 15–25 km (Figs 1 and 2). According to the deep drill-

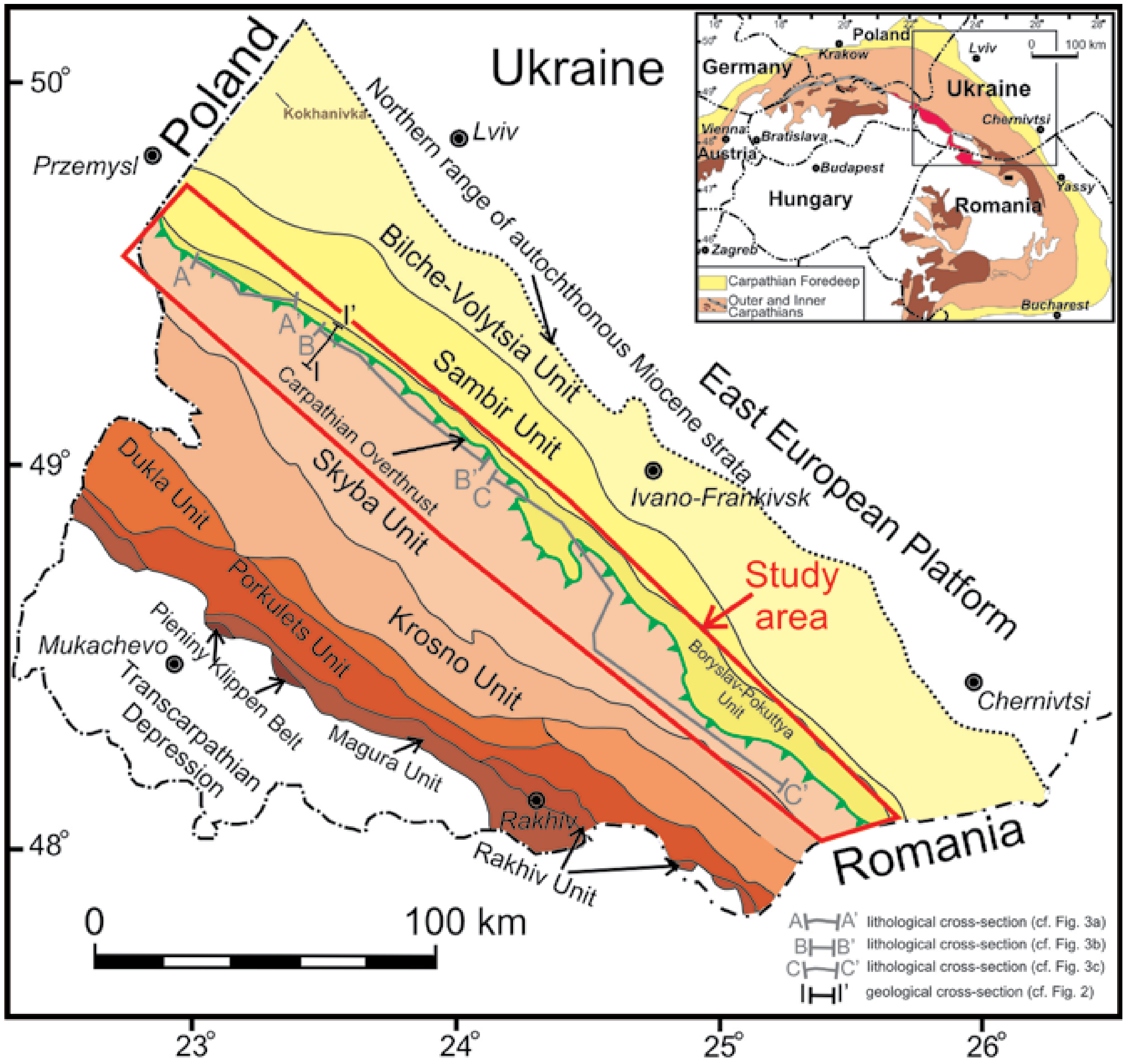

Fig. 1 Sketch geological map showing location of the main tectonic units of the Ukrainian Carpathians after Shakin *et al.* (1976), Kruglov *et al.* (1985), Krupsky (2001)

ing results (Shevchenkovo-1 borehole), the maximum thickness of the Skyba Unit exceeds 7700 m.

The flysch sequence of the Ukrainian Carpathians, which stratigraphically ranges from the Early Cretaceous to Early Miocene (Vialov *et al.* 1988), is mainly made up of intercalations of sandstone, siltstone and mudstone layers. The 200 m thick Yamna Formation is of the Paleocene age and includes Danian, Selandian and Thanetian stages (Vialov *et al.* 1988; Maslun *et al*. 2015). The representative sequence of the Yamna Formation is described at the surface outcrop in the Skyba Unit near the village Yamna (Vialov *et al*. 1988) where it is mainly represented by massive, thick-layered medium-grained light-grey sandstones with minor thin interbeds of variegated mudstones. Changes in the Yamna Formation facies are observed in the study area. In some places, the sequence is essentially composed of variegated shales. Different facies of these strata are discussed in more detail in further chapters of this article. The Yamna Formation is overlain by the Eocene Manyava Formation, which is mainly made up of variegated shales.

MATERIALS AND METHODS

Sampling and analytical procedures

Fifty-four representative rock samples of the Yamna Formation (sandstones, siltstones, mudstones) were collected for the petrographic study from eighteen surface outcrops and thirty-eight boreholes.

The contents of $CaCO_3$ and $CaMg(CO_3)_2$ in the

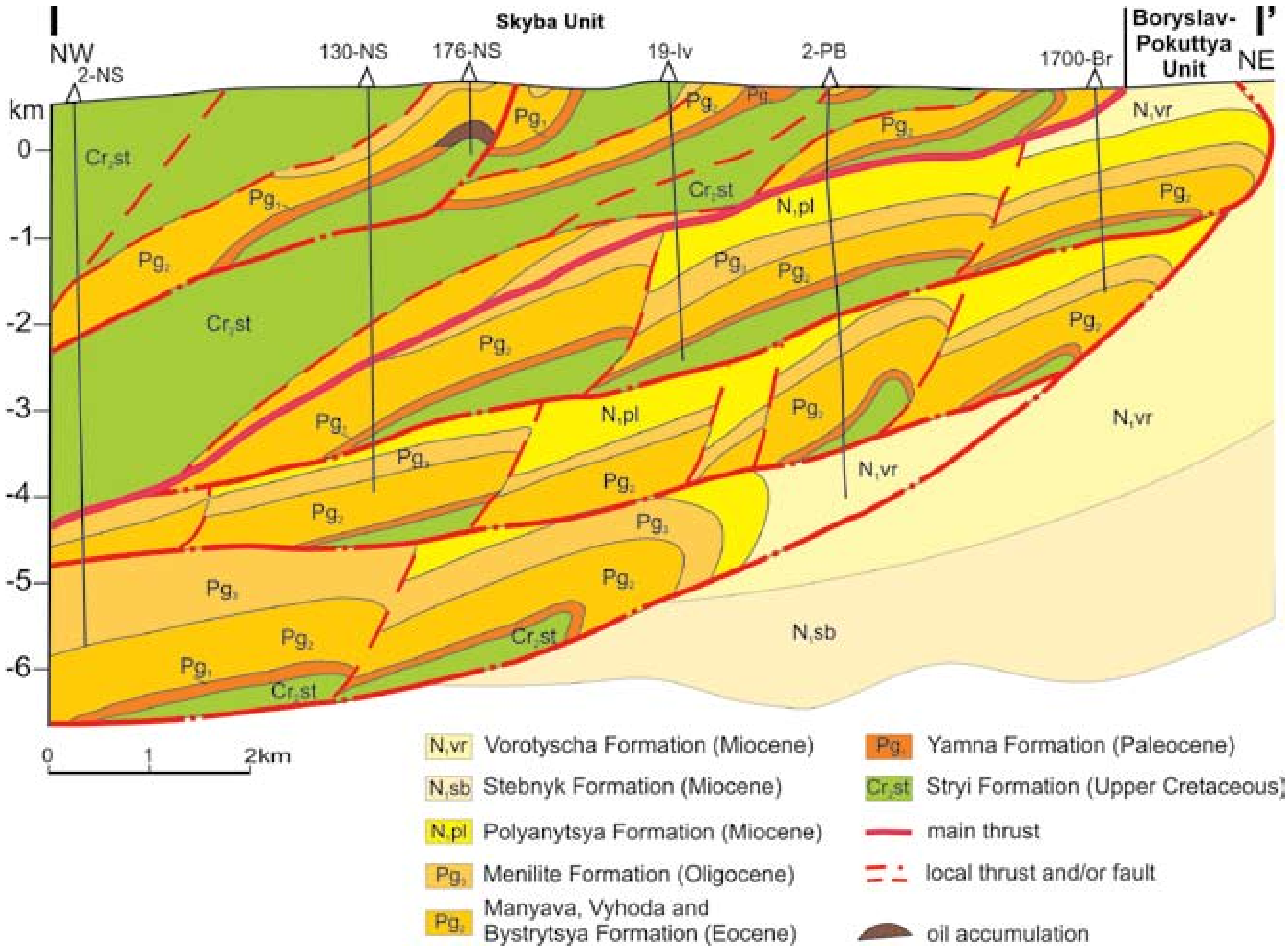

Fig. 2 Geological cross-section I – I' through the Boryslav-Pokuttya and external part of the Skyba Units (see Fig. 1 for location) (modified after Krupsky *et al.* 2014)

rocks were calculated from the results of the chemical analyses that were performed at the Institute of Geology and Geochemistry of Combustible Minerals, Lviv, Ukraine. Thin sections of rocks were examined under a polarizing microscope Carl Zeiss Jena.

Porosity and permeability of ninety-seven rock samples (Table 1) were estimated in the laboratory of the Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine.Total rock porosity was determined using Melcher's method (Nesterenko 2010) by calculating the ratio of grain density to bulk density. The analyzed samples were coated with paraffin for bulk volume measurement. The grain volume of an unconsolidated sample was determined by pycnometry. Density was measured by sample weighing and immersing it into the liquid. Effective porosity was determined using the weight method (Nesterenko *et al.* 2012). Rock samples were saturated with model reservoir water (NaCl solution with a salinity of 170 g / l) and weighted using the digital analytical balance WPS 360/C/2.

Permeability of the rocks was determined by gas filtration through core samples (Hrytsyshyn 2012). The device used for porosity measurements comprised a vessel with the compressed gas, a sample holder and the flow gauge. The washed and dried sample was placed into the sample holder within rubber casing sealing its side walls. A gas under constant pressure was pumped through the sample until the pressure at the outlet of the sample and the gas flow stabilized. The difference between the inlet and outlet pressures as well as the gas flow, which came through the sample, was recorded. Permeability of the rocks was calculated from the data obtained in accordance with the generalized Darcy's law for fluids.

The thickness of the Paleocene sequence, the variability of its facies as well as proportions of the main rock types in Yamna Formation sections were estimated by analyzing eighty-five well logs within the study area (Figs 3–6).

RESULTS

Distribution and correlation of well sections in the Yamna Formation

On the basis of our findings obtained from the well-log data analysis and mineralogical and petro-

Table 1 Reservoir properties of the Yamna Formation rocks

Well	Sample code	Area	Lithology	Depth, m	Porosity, %		Permeability, 1×10^{-3} md
					Total	Effective	
42-Blazhiv	Bl	1	sandstone	3991	11.99	9.03	1.97
42-Blazhiv	Bl	1	sandstone	3991.5	13.05	11.24	2.01
42-Blazhiv	Bl	1	sandstone	4030	12.79	11.89	7.36
42-Blazhiv	Bl	1	sandstone	4031	12.99	12.01	8.99
50-Blazhiv	Bl	1	sandstone	4092	17.07	15.43	52.21
50-Blazhiv	Bl	1	sandstone	4095	16.95	16.11	21.58
11-Monastyrets	Mn	1	sandstone	3897	12.70	11.70	7.10
11-Monastyrets	Mn	1	sandstone	3898	14.87	13.55	9.41
2-Staryi Sambir	SSm	1	sandstone	4262	15.25	12.91	9.30
2-Staryi Sambir	SSm	1	sandstone	4262.5	17.12	15.21	11.81
2-Staryi Sambir	SSm	1	sandstone	4263	17.70	14.87	16.07
2-Staryi Sambir	SSm	1	sandstone	4265	15.05	14.00	7.11
2-Staryi Sambir	SSm	1	sandstone	4270	16.30	14.89	10.01
2-Staryi Sambir	SSm	1	sandstone	4271	12.99	10.58	8.31
7-Staryi Sambir	SSm	1	sandstone	3632	14.80	13.01	4.87
7-Staryi Sambir	SSm	1	sandstone	3639.5	15.45	14.32	3.02
7-Staryi Sambir	SSm	1	sandstone	3640	13.91	10.91	5.78
20-Staryi Sambir	SSm	1	sandstone	3558	18.01	15.91	12.99
20-Staryi Sambir	SSm	1	sandstone	3958.5	17.90	14.77	11.10
20-Staryi Sambir	SSm	1	sandstone	4262	15.32	11.97	10.62
4-Semyhyniv	Sm	2	sandstone	2054	12.75	9.47	2.07
4-Semyhyniv	Sm	2	sandstone	2145	13.09	8.23	4.74
2-Skhidnytsya	Sd	2	sandstone	4456	15.98	12.04	6.82
2-Skhidnytsya	Sd	2	sandstone	4456.5	15.69	14.07	9.25
2-Skhidnytsya	Sd	2	sandstone	4457	15.86	13.73	9.91
2-Skhidnytsya	Sd	2	sandstone	4458	13.91	11.20	9.62
2-Skhidnytsya	Sd	2	sandstone	4458.5	13.75	10.93	8.05
2-Skhidnytsya	Sd	2	sandstone	4459	15.87	12.65	7.29
4-Skhidnytsya	Sd	2	sandstone	552	12.07	9.19	2.99
4-Skhidnytsya	Sd	2	sandstone	555	12.24	9.99	2.53
4-Skhidnytsya	Sd	2	sandstone	740	10.07	9.01	3.73
4-Skhidnytsya	Sd	2	sandstone	1418	11.97	8.12	5.23
10-Zavoda	Zv	2	sandstone	4203	15.50	13.18	7.7
10-Zavoda	Zv	2	sandstone	4845	14.94	13.22	10.51
15-Zavoda	Zv	2	sandstone	4851	16.05	13.24	39.11
15-Zavoda	Zv	2	sandstone	4858	15.12	12.85	15.03
81-Vyhoda Vytvytsya	VV	2	sandstone	1715	13.75	10.82	4.44
81-Vyhoda Vytvytsya	VV	2	sandstone	1515.5	12.87	11.07	3.72
6-Ulychne	Ul	2	siltstone	1400	13.05	10.84	3.39
6-Ulychne	Ul	2	siltstone	1400.2	12.59	9.36	2.94
6-Ulychne	Ul	2	siltstone	1400.5	11.34	10.27	5.61
1-Pivnichna Zavoda	PZv	2	siltstone	5310	7.59	5.71	7.71
1-Pivnichna Zavoda	PZv	2	siltstone	5312	10.01	8.77	8.02
1-Pivnichna Zavoda	PZv	2	siltstone	5315	11.23	9.91	9.64
2-Skhidnytsya	Sd	2	siltstone	1621	7.55	5.84	1.99
2-Skhidnytsya	Sd	2	siltstone	1621.5	5.99	4.88	2.07
2-Skhidnytsya	Sd	2	siltstone	1630	8.28	6.96	4.81
2-Skhidnytsya	Sd	2	siltstone	1650	9.37	8.31	6.04

Well	Sample code	Area	Lithology	Depth, m	Porosity, %		Permeability, 1×10^{-3} md
					Total	Effective	
2-Skhidnytsya	Sd	2	siltstone	1752	12.13	9.97	9.74
10-Zavoda	Zv	2	siltstone	4832	12.01	9.31	14.71
10-Zavoda	Zv	2	siltstone	4832,5	15.01	12.81	31.97
15-Zavoda	Zv	2	siltstone	4855	11.11	9.05	6.27
15-Zavoda	Zv	2	siltstone	4855.5	10.64	8.99	7.84
4-Delyatyn	Dn	3	sandstone	366	14.73	11.89	4.79
4-Delyatyn	Dn	3	sandstone	366.1	12.05	11.01	2.98
4-Delyatyn	Dn	3	sandstone	366.5	13.27	10.84	8.44
4-Delyatyn	Dn	3	sandstone	367	13.89	12.10	7.39
19-Delyatyn	Dn	3	sandstone	284	14.05	11.81	5.94
19-Delyatyn	Dn	3	sandstone	284.5	13.70	11.01	8.91
19-Delyatyn	Dn	3	sandstone	285	12.99	10.21	5.61
19-Delyatyn	Dn	3	sandstone	290	9.52	9.01	3.93
19-Delyatyn	Dn	3	sandstone	295	14.37	11.23	13.02
19-Delyatyn	Dn	3	sandstone	300	16.03	13.95	41.21
19-Delyatyn	Dn	3	sandstone	389.5	11.99	9.88	6.01
19-Delyatyn	Dn	3	sandstone	390	14.70	11.59	10.79
19-Delyatyn	Dn	3	sandstone	395.5	13.23	12.06	11.21
19-Delyatyn	Dn	3	sandstone	396	14.50	10.31	6.82
10-Kosmach-Pokuttya	KP	3	siltstone	2590	14.01	12.29	7.57
10-Kosmach-Pokuttya	KP	3	siltstone	2599	14.86	11.87	9.60
10-Kosmach-Pokuttya	KP	3	siltstone	2600	14.52	13.03	29.01
10-Kosmach-Pokuttya	KP	3	siltstone	2779.5	15.32	12.31	6.79
10-Kosmach-Pokuttya	KP	3	siltstone	2780	12.91	10.57	5.02
800-Pasichna	Ps	3	siltstone	2485	12.53	8.83	7.18
800-Pasichna	Ps	3	siltstone	2486	12.07	7.92	4.57
802-Pasichna	Ps	3	siltstone	1202	5.53	4.51	1.99
802-Pasichna	Ps	3	siltstone	1210	11.22	8.71	5.41
802-Pasichna	Ps	3	siltstone	1250	10.75	4.66	2.09
802-Pasichna	Ps	3	siltstone	1255	10.66	7.87	3.51
814-Pasichna	Ps	3	siltstone	1930	12.88	9.93	6.24
814-Pasichna	Ps	3	siltstone	1935	12.92	10.52	5.06
1-Luzhanka	Lu	4	mudstone	599	2.02	0.97	0.50
1-Luzhanka	Lu	4	mudstone	600	2.23	0.95	0.49
1-Luzhanka	Lu	4	mudstone	600,5	2.13	1.12	0.59
2-Perehinsk	Pr	4	mudstone	1680	3.71	2.09	0.73
2-Perehinsk	Pr	4	mudstone	1681	2.97	1.97	0.53
2-Perehinsk	Pr	4	mudstone	1745	2.10	1.88	0.60
2-Perehinsk	Pr	4	mudstone	1746	3.05	2.03	0.64
1-Rozhnyativ	Rn	4	mudstone	2749	5.33	4.21	1.05
1-Rozhnyativ	Rn	4	mudstone	2750	4.91	3.87	0.59
4-Rozhnyativ	Rn	4	mudstone	3880	3.41	2.31	0.63
4-Rozhnyativ	Rn	4	mudstone	3883	6.71	5.53	0.71
4-Rozhnyativ	Rn	4	mudstone	3825	2.01	1.03	0.49
4-Rozhnyativ	Rn	4	mudstone	3885	5.96	4.27	0.71
17-Rosilna	Rs	4	mudstone	3319	7.07	5.38	0.77
17-Rosilna	Rs	4	mudstone	3324	8.11	6.75	1.52
17-Rosilna	Rs	4	mudstone	3378	7.53	5.85	0.81
17-Rosilna	Rs	4	mudstone	3383	19.97	9.09	0.89

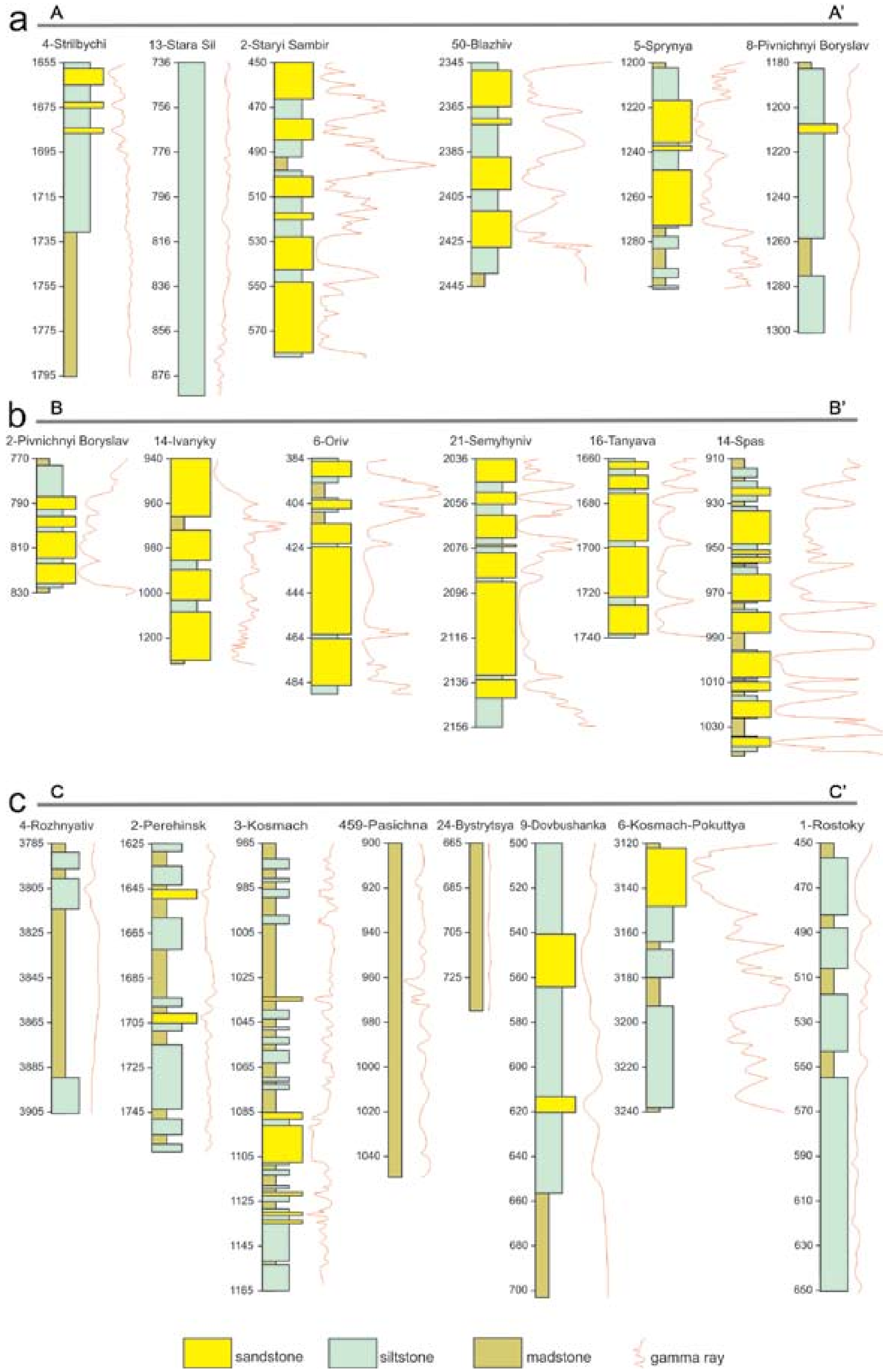

Fig. 3 Correlation of the lithological sections of the boreholes, which penetrated Yamna Formation. Sections A – A', B – B', C – C' are located from NW to SE along the Boryslav-Pokuttya and external part of Skyba Units (see Fig. 1 for location)

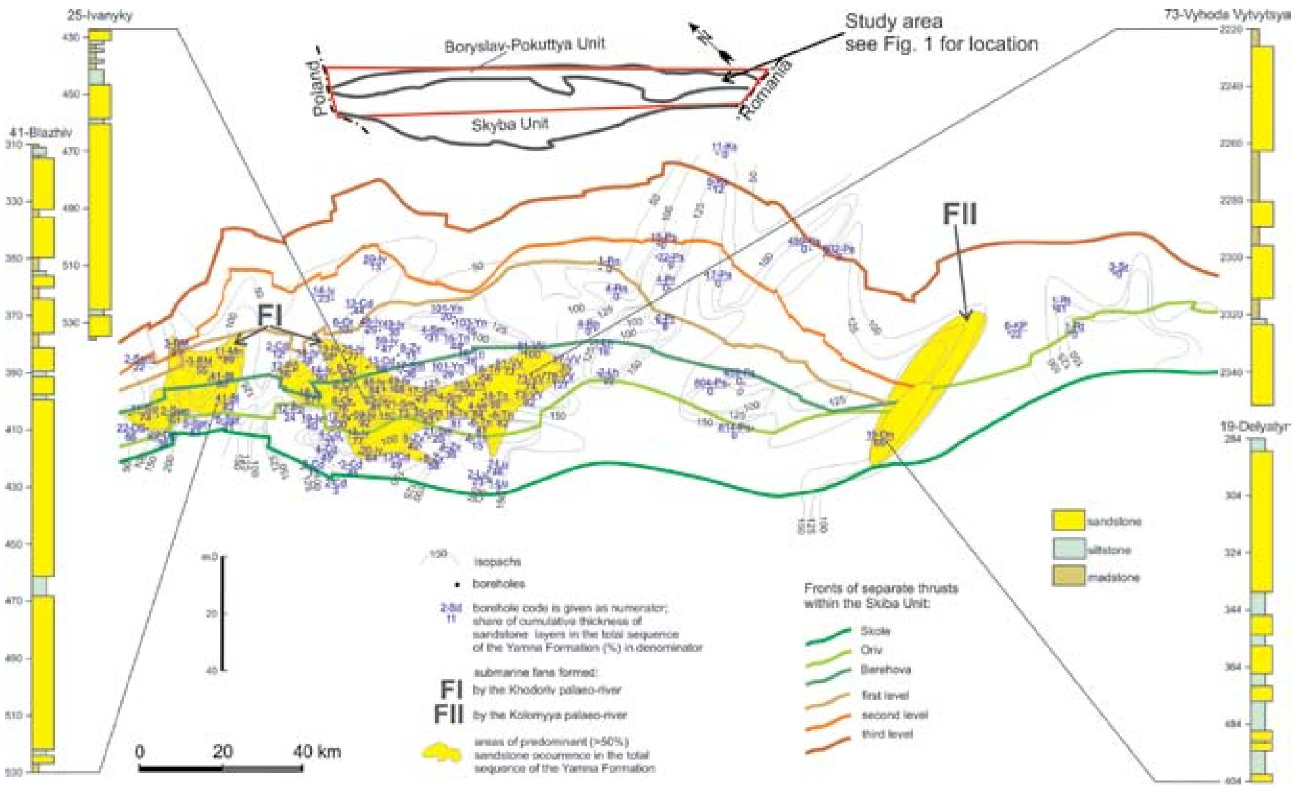

Fig. 4 Palinspastic map of thicknesses and facies of the Yamna sandy sediments of the northeastern segment of the Carpathian Basin. Palinspastic basis after Vul (2014). Boreholes: 41-Blazhiv and 50- (41-Bl and 50-), 1-Berehomet (1-Bm), 1608-Boryslav and 1609- (1608-Br and 1609-), 24-Bystrytsya (24-Bs), 3-Blazhiv-Monastyrets (3-BM), 4-Delyatyn, 19- and 22- (4-Dn,19- and 22-), 2-Dovbushanka (2-Db), 22-Dobromyl-Strilbychi (22-DS), 4-Herynya (4-Hr), 12-Ivanyky, 14-, 18-, 19-, 20-, 25-, 48-, 49-, 58- and 59- (12-Iv, 14-, 18-, 19-, 20-, 25-, 48-, 49-, 58- and 59-), 1-Komarnyky (1-Km), 6-Kosmach- Pokuttya, 10- and 11- (6-KP, 10- and 11-), 3-Kosmach and 11- (3-Ks and 11-), 1-Luhy (1-Lh), 10-Lukva and 21- (10-Lk and 21-), 1-Luzhanka and 2- (1-Lu and 2-), 11-Monastyrets (11-Mn), 1-Nova Skhidnytsya (1-NS), 2-Oriv, 6- and 9- (2-Or, 6- and 9-), 2-Pivnichnyi Boryslav, 6- and 8- (2-PB, 6- and 8-), 38-Pivnichna Dolyna, 418 and 151- (38-PD, 418 and 151-), 459-Pasichna, 800-, 801, 802-, 804 and 814- (459-Ps, 800-, 801, 802-, 804 and 814-), 1-Pivnichna Zavoda (1-Pzv), 12-Popeli (12-Pp), 2-Perehinsk and 4- (Pr-2 and 4-), 1-Rozhnyativ and 4- (1-Rn and 4-), 1-Rostoky (1-Rt), 15-Rosilna, 17- and 22- (15-Rs,17- and 22-), 2-Skhidnytsya, 3-, 4-, 7- and 13- (2-Sd, 4-, 7 and 13-), 4-Strilbychi (4-Sb), 1-Shypot (1-Sh), 4-Semyhyniv, 17-, 21- and 35- (4-Sm,17-, 21- and 35-), 11-Stara Sil and 13- (11-SSl and 13-), 2-Staryi Sambir (2-SSm), 12-Spas, 14- and 17- (12-Sp, 14- and 17-), 5-Sprynya (5-Spr), 3-Sloboda Runhurska (3-SR), 1-Serhii (1-Sr), 1-Sushytsya (1-Su), 6-Tanyava, 8-, 16- and 18- (6-Tn, 8, 16- and 18-), 2-Volya Blazhivska (2-VB), 7-Verkhovyna (7-Vn), 73-Vyhoda Vytvytsya and 81- (73-VV and 81-), 13-Ulychne and 22- (13-Ul and 22-), 15-Urych (15-Ur), 101-Yankivtsi and 103- (101-Yn and 103-), 4-Zavoda and 8- (4-Zv and 8-)

graphic investigations, we distinguished the lithological types of Yamna rocks and determined variations in the Yamna Formation thickness. The correlation between these data throughout the study area allowed determining the spatial distribution of these characteristics. The percentage of sandstones, siltstones and mudstones in the Yamna Formation section was determined in each well. The distribution features of different rock types across these strata are shown in three representative cross-sections (Fig. 3a, b, c) A–A', B–B' and C–C'. The cross-section A–A' (Fig. 3a), which is located in the northwestern part of the study area, shows that the sequence of the Yamna Formation is mainly dominated by siltstones and, to a lesser extent, by sandstones, mudstones being of secondary importance. The cross-section B–B' (Fig. 3b) goes through the oil-bearing districts of Boryslav, Ivanyky, Oriv, Semyhyniv, Tanyava and Spas. There, the sequence of the Yamna Formation is dominated by sandstones, which indicates both the existence of reservoir rocks and the potential for further oil exploration in this area. The cross-section C–C' (Fig. 3c) stretching from the Rozhnyativ oil-bearing district to the border with Romania covers the south-eastern part of the study area. The cross-sections presented in Figs 3 a, b and c show the predominance of siltstones and mudstones with a small amount of sandstones in the Yamna Formation section in central and south-eastern parts of the study territory. The central part is dominated by clay rocks and the southeastern part of this territory by siltstones and sandstones, mudstones being of less importance.

Variability in the Yamna Formation thickness was analyzed throughout the study territory based on the

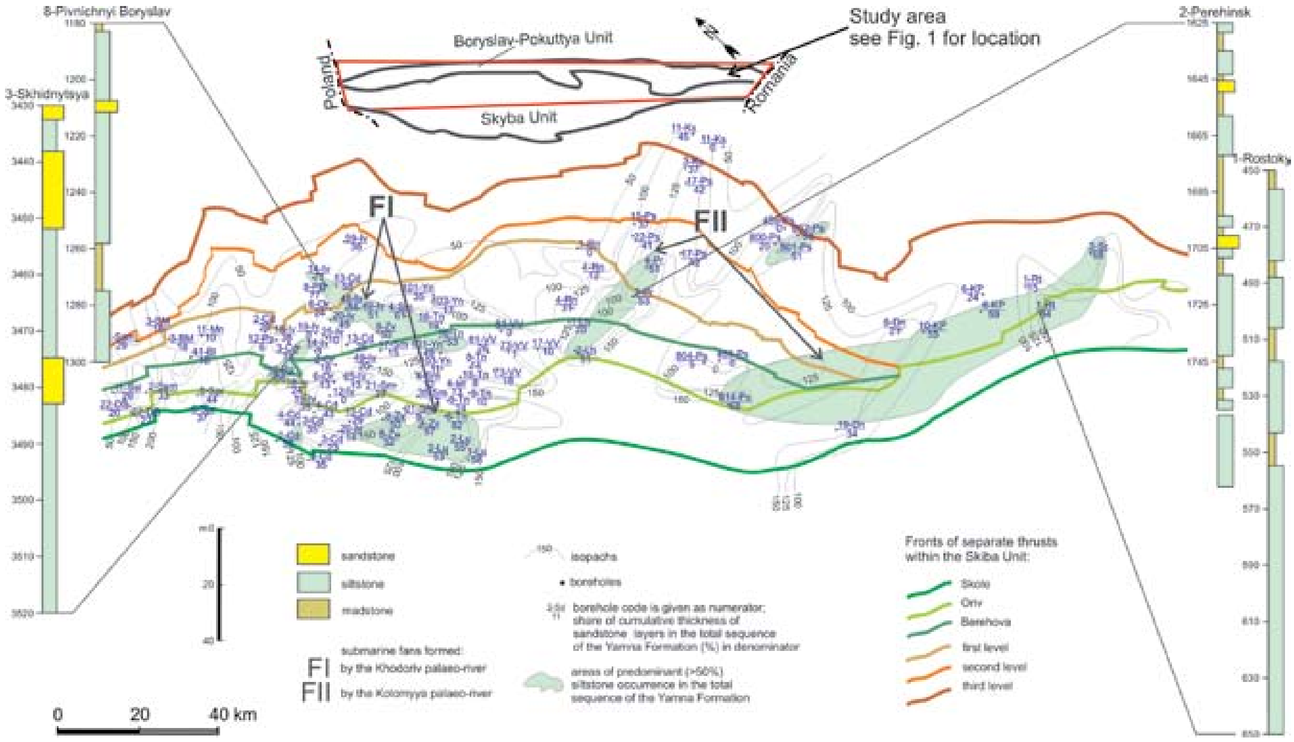

Fig. 5 Palinspastic map of thicknesses and facies of the Yamna silty sediments of the northeastern segment of the Carpathian Basin. Palinspastic basis after Vul (2014) (codes and names of studied boreholes as at Fig. 4)

well-log data. We used the palinspastic base by Vul (2014) to reconstruct the propagation of the Yamna sediments within the Carpathian basin during the Paleocene epoch. As shown in Figure 4, Yamna deposits reach the maximum thickness of 190 meters in the northwestern part of the study area. Such distribution of deposit thicknesses in the explored boreholes correlates very well with our measurements performed at surface outcrops.

We distinguished three areas with the maximum occurrence of sandstone, accounting for > 50% of the total Yamna Formation thickness (Fig. 4):

– the first area, which is located in the northwest, comprises three oil-bearing districts: Blazhiv, Monastyrets and Stary Sambir. This area is irregular in shape and has a size of 36 × 20 km. In this area, the proportion of sandstones in the sequence varies from 55 to 89%. The total thickness of the Yamna Formation ranges from 60 to 190 m.

– the second area is situated in the southeast and includes the oil-bearing districts of Popeli, Ivanyky, Smilna, Tanyava, Vyhoda and Vytvytsya. This area is larger than the first one. It covers an area of 70 × 15 km and has an amoebic shape. In this area, thick sandstone layers are interbedded with gravelstones. The percentage of sandstones in the sequence varies from 54 to 100%. The total thickness of the Yamna Formation ranges from 90 to 200 m.

– the third area is located in the south-eastern part of the study territory. It embraces the oil-bearing district of Delyatyn and is the smallest in size (43 × 11 km) of the three selected areas. It has an elliptical shape oriented SE–NW. The proportion of sandstones in the sequence reaches 66%. The total thickness of the Yamna Formation in this area varies from 100 to 150 m.

The thickness of sandstones in the study territory decreases from northwest to southeast, while the amount of siltstones and mudstones in the sequence follows an upward trend.

The localization of areas with sandstone predominance in the sequence of the Yamna Formation allows predicting the occurrence of reservoir rocks in the study territory and, consequently, the most prospective areas for hydrocarbons exploration in the Paleocene strata of the frontal tectonic units of the Ukrainian Carpathians.

Figure 5 shows the location of the areas with siltstone predominance in the Yamna Formation sequence. Siltstones constitute > 50% of the total section thickness. Seven areas with the maximum siltstone occurrence were identified, the largest of which was 105 × 16 km in size. It is located in the southeastern part of the study territory within Berehova and Oriv thrusts and includes the oil-bearing districts of Pasichna, Delyatyn, Rostoky, Sloboda Rungurska.

Three smaller approximately similar-sized areas are located almost in the central part of the study territory. The first one, which is 42 × 7 km in size, includes the oil-bearing districts of Ivanyky, Zavoda,

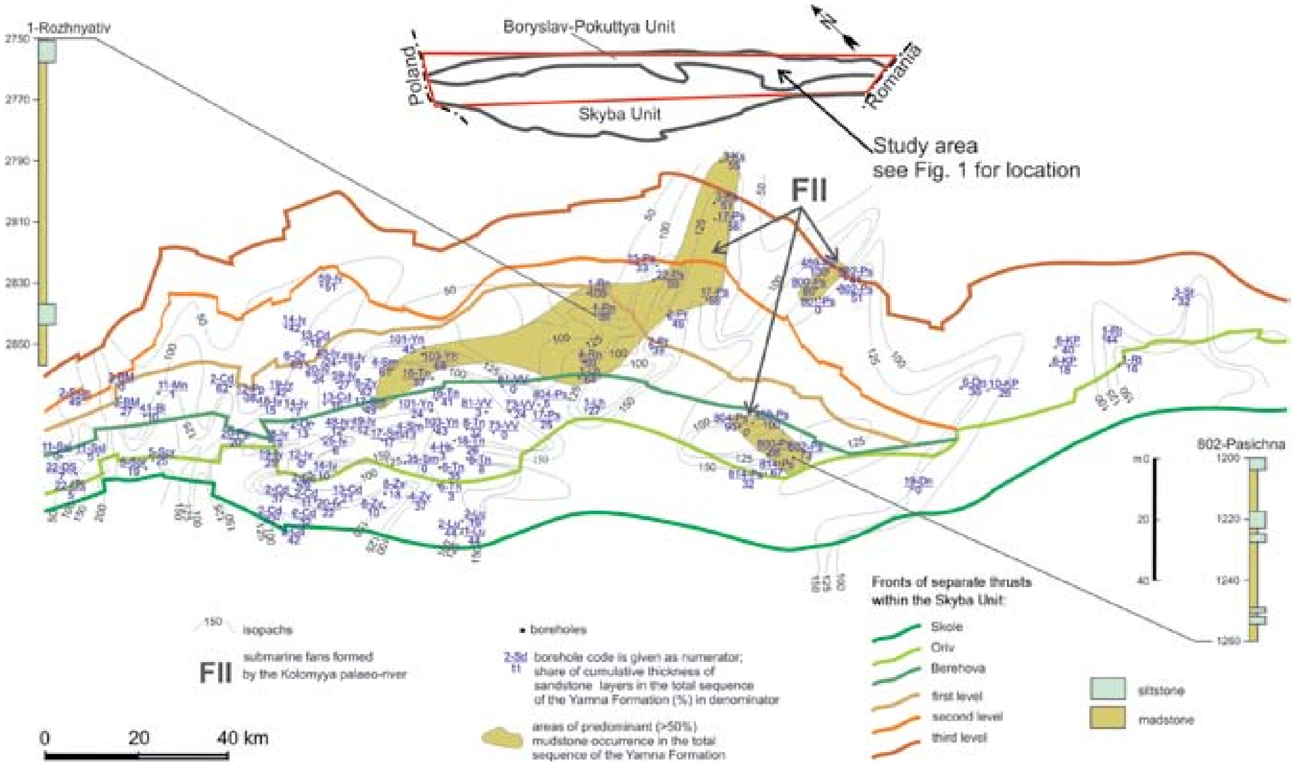

Fig. 6 Palinspastic map of thicknesses and facies of the Yamna mud sediments of the northeastern segment of the Carpathian Basin. Palinspastic basis after Vul (2014) (codes and names of studied boreholes as at Fig. 4)

Semyhyniv and Tanyava. The second one is 32 × 11 km in size and comprises the oil-bearing districts of Zavoda, Tanyava and Luzhanka. The size of the third one, which includes the oil-bearing districts of Luhy and Pereginsk, is 32 × 6 km.

In addition to the above-mentioned areas with the maximum occurrence of siltstones in the Yamna Formation section, there were three much smaller areas identified. One of them is located in the southeast of the study territory. It is 18 × 3 km in size and includes the Pasichna oil-bearing district. The other two are located in the western part of the study territory. One of them includes the Popeli-Skhidnytsia oil-bearing district and has a size of 12 × 2 km, and the other one, the smallest of the three above mentioned areas with the size of 2 × 1 km, is located within the Skhidnytsya oil-bearing district.

As is shown in Fig. 6, the predominance of mudstones in the Yamna Formation section is recorded in the central part of the study territory. There is one area of considerable size (85 × 12 km) with the proportion of mudstone in the total thickness of the Yamna Formation section exceeding 50%. This area includes the oil-bearing districts of Semyhyniv, Rozhnyativ, Rosilna and Kosmach. In the central part of the study territory, there are two more, smaller in size (18 × 3 km and 11 × 2 km) areas with mudstone predominance in the Yamna Formation sequence. Both of them are located within the Pasichna oil-bearing district at two different structural levels. It is important to localize separate areas with the predominance of mudstone in the Yamna Formation sequence because it helps identify the territories that are less promising for oil and gas exploration than the above described areas with the predominance of sandstone and siltstone.

Petrography of the Yamna Formation

The Yamna Formation is made up of the thick-layered, gray-colored quartz, glauconite-quartz with carbonate and clay-siliceous matrix, Yamna sandstones and siltstones as well as of mudstones and lenses of gravelstones and conglomerates according to the classification of Berger (1986).

Conglomerates and gravelstones. Conglomerates and gravelstones are observed in the Yamna Formation sequence throughout the study territory (Fig. 7A, B). The matrix in conglomerates is carbonate, carbonate-siliceous, carbonate-clayey and clayey-siliceous-carbonate. Gravelstones in the section occur in the form of separate lenses and interbeds with a thickness of up to 0.3–0.5 m. Gravelstones consist of fragments of coarse-crystalline limestones with a clumpy, often organogenic structure, caused by the uneven distribution of clay substance in the form of separate concretions, as well as of different-shaped micro-granular calcite inclusions. Debris of micro- and fine-grained limestones, brachiopods and red algae are observed

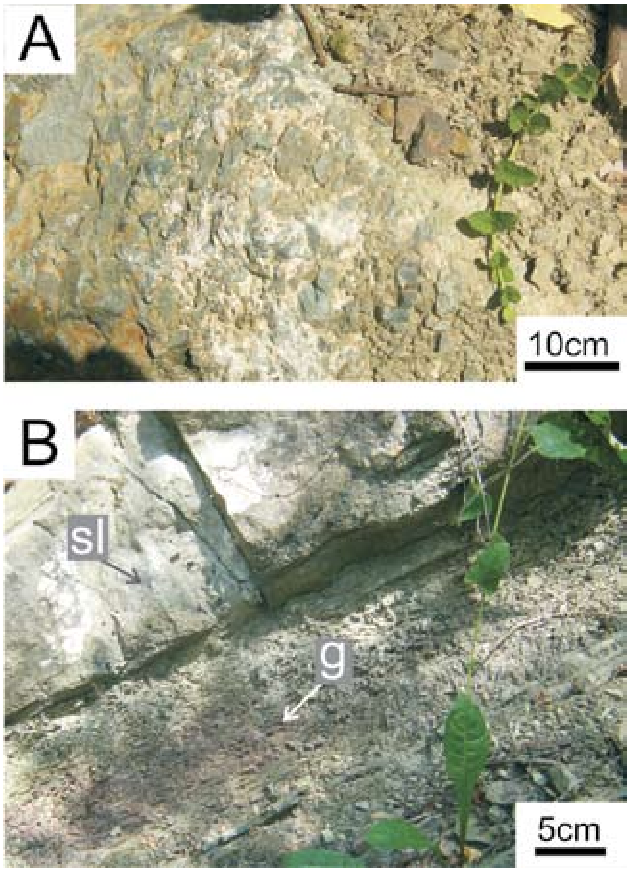

Fig. 7 Conglomerate and gravelstone of the Yamna Formation. Surface outcrop along the River Cheremosh at the northern margin of the village Tudiv, 7 km southeastward from Vyzhnytsya town: A: conglomerate; B: gravelstone interbed (g) in the lower part of the sandstone layer (sl)

more seldom. Small amounts of quartzite grains with a mosaic and toothed structure, chalcedonolites and feldspars sericitized and pelitized to a varying extent are present. The shape of debris is semi-rounded, rounded, rarely angular.

Sandstones represent the most widespread component of the Yamna Formation. Results of our investigations showed that in quantitative terms they constitute up to 75–80%, sometimes up to 90% of the sequence of these strata (Havryshkiv 2008; Havryshkiv, Radkovets 2019). Sandstones of the Yamna Formation range from coarse-grained to fine-grained, with widespread multi-grain structures (Fig. 8A–F). Grains are represented by quartz and feldspars, with a small amount of other minerals. The content of quartz in the rock varies within a wide range (from 50 to 95%) (Fig. 8A). Grains are angular and angular-rounded with a size of 0.1 to 1 mm. The content of feldspars in sandstones constitutes 2–5%, rarely – 10–15%. They are represented by 0.2–0.8 mm-sized tablet-shaped, angular and angular-rounded grains of plagioclases, rarely by those of orthoclase or microcline (Fig. 8B). Glauconite grains, 0.1–0.5 mm in size, constitute up to 2–3% of the rock (Fig. 8C). The grains are often fractured and pyritized, some of them fill in the spaces between quartz grains and play the role of a matrix (Fig. 8C–E). Scales of muscovite, biotite, chlorite and grains of carbonate occur in small quantities (up to 2%). Accessory minerals are represented by single grains of zircon, rutile, garnate, tourmaline and staurolite (Fig. 8B, D). Ore minerals are represented by irregular-shaped, up to 0.1 mm-sized grains of pyrite. In addition, fragments of quartzites, chalcedonolites, micro-granular cryptocrystalline clayey oolitic and pseudolithic limestones in the size range 0.5–0.8 to 1.5 mm occur. Shells of microorganisms (mainly of foraminifera), some of which are filled with glauconite, are also often observed. There are also fragments and aggregates of red algae, fragments of shells of pelicipods and brachiopods.

Debris of terrigenous material often have the cementless connection or form conformal and stylolite contacts. The matrix is clayey, carbonate, sometimes with siliceous matter, its content in the rock ranging from 10–15% to 40–50%.

Siltstones are observed in the form of thin (0.05–0.15 m) layers within thick sandstone layers and in rhythmic intercalations with sandstones and mudstones. They usually differ from sandstones in a higher content of mica minerals (muscovite, biotite, hydrobiotite), coalified plant detritus and heavy fraction minerals (Fig. 9A, B). Siltstones are made up of quartz, rarely of glauconite and quartz. Feldspars constitute up to 15% of the rock. Sometimes fragments of rocks occur. Accessory minerals such as zircon, tourmaline and rutile form layered concentrations in the rock constituting up to 2% of it. The matrix in siltstones is either carbonate with the admixture of clay, reaching 40% of the rock (Fig. 9A), or siliceous with the admixtures of clay, sericite, or chlorite, ranging from a few percent to 20–25% (Fig. 9B).

Mudstones are shistous, gray or greenish gray, sometimes green or cherry-red, of pelitic (Fig. 9C) or aleuritic structure (Fig. 9D). They consist of clay-sericite-carbonate-siliceous mass. Corroded quartz grains (0.02–0.04 mm) as well as similar-sized grains of carbonate, rarely those of glauconite, muscovite, biotite and chlorite are scattered throughout most of the rock (up to 15%).

Characteristics of reservoir rocks

To estimate reservoir properties (porosity and permeability) of Yamna Formation rocks in the Skyba and Boryslav-Pokuttya Units of the Ukrainian Carpathians, we analyzed 97 rock samples, which were collected from the four areas, where the maximum occurrence of sandstones, siltstones and mudstones exceeds 50% (Fig. 10). Results of the performed

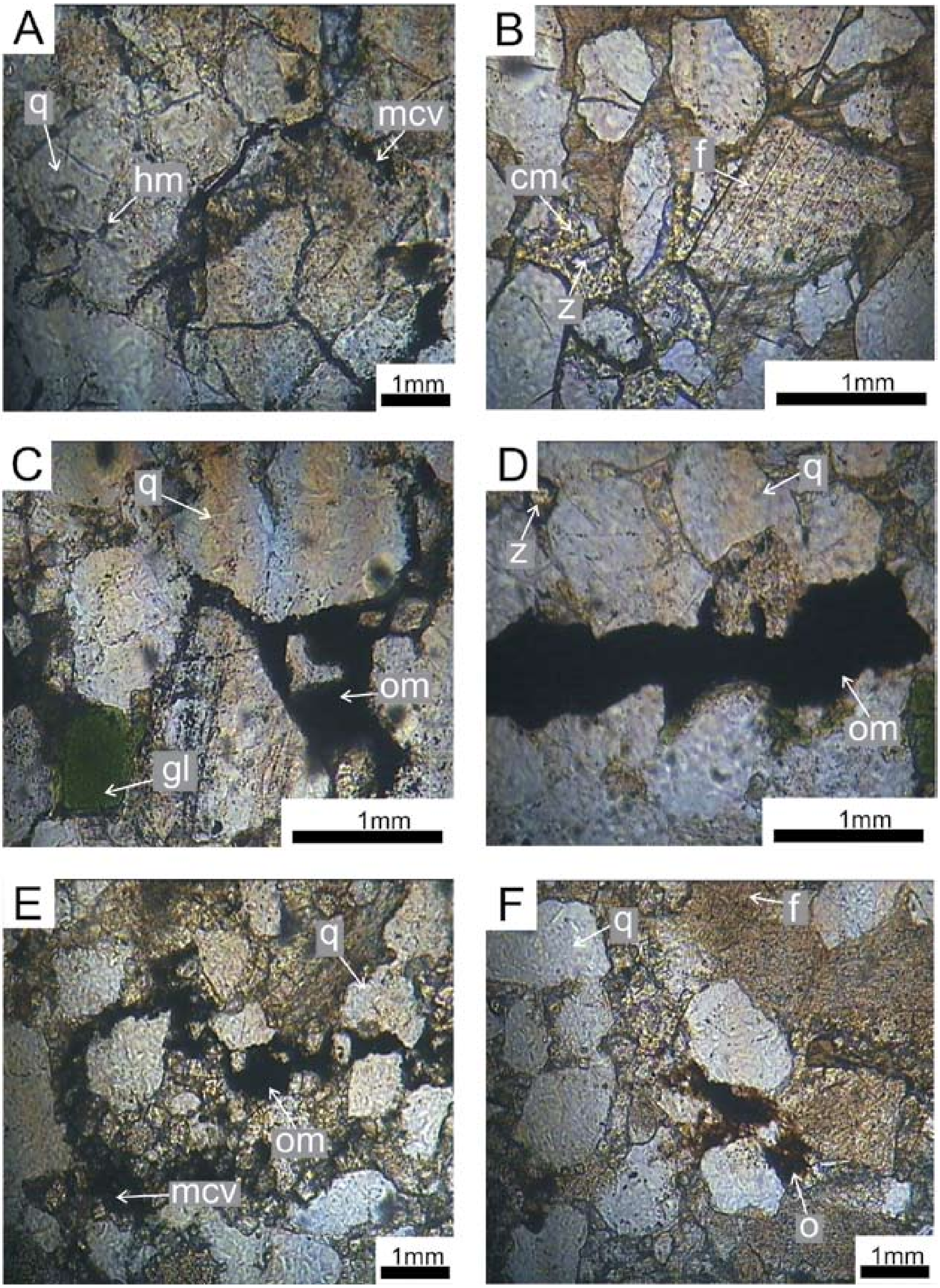

Fig. 8 Photomicrographs of the Yamna sandstones. A: medium-grained sandstone with contact hydromica matrix from borehole 1-Nyzhnya Stynava, depth 4219–4224 m; B: medium-coarse-grained sandstone with basal carbonate matrix from borehole 7-Staryi Sambir, depth 3632–3640 m; C: coarse-grained sandstone with contact carbonate-clayey matrix from borehole 15-Zavoda, depth 4851–4858 m; D: coarse-grained sandstone with contact carbonate-clay matrix from borehole 20-Staryi Sambir, depth 3958–3960 m; E, F: various-grained sandstone with carbonate matrix from borehole 2-Skhidnytsya, depth 4456–4459 m; cm – carbonate matrix, f – feldspar, gl – glauconite, hm – hydromica matrix, mcv – micro-cavities, o – oil, om – organic matter, q – quartz, z – zircon

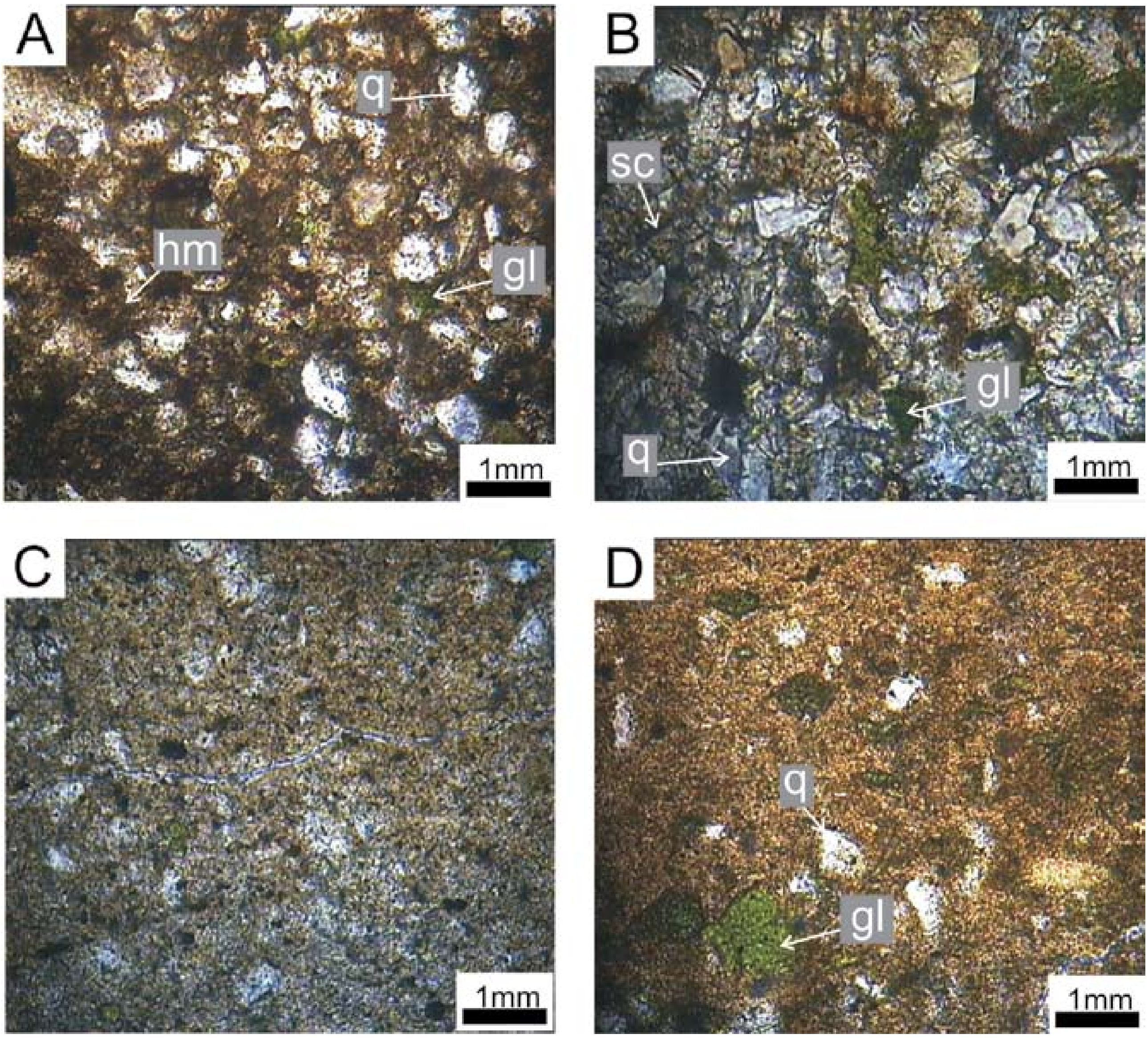

Fig. 9 Photomicrographs of the Yamna siltstones and mudstones. A: various-grained siltstone with basal-pore hydromica matrix from borehole 50-Blazhiv, depth 4092–4095 m; B: various-grained siltstone with contact siliceous-clay matrix from the surface outcrop along the River Prut in Yaremche town; C: mudstone with pelitic structure from borehole 11-Kosmach, depth 3759–3765 m; D: mudstone with aleuritic structure from the surface outcrop along the River Prut in Yaremche town; gl – glauconite, hm – hydromica matrix, q – quartz, sc – siliceous-clay matrix

analyses are presented in Table 1. Table 2 shows the generalized data of these analyses, including ranges and median values of reservoir properties of Yamna Formation rocks.

Our studies into reservoir properties of the Yamna Formation (Tables 1, 2) showed that the rocks are cemented to varying degrees and differ in the composition, porosity and permeability of the matrix.

The content of matrix in densely cemented sandstones reaches 40%. The type of cementation in most cases is basal. Its mineral composition is clayey, carbonate-clayey, and carbonate (Fig. 8A–D). Porosity of sandstones does not exceed 12%. The amount of cement in poorly cemented sandstones does not exceed 20%. The type of cement is contact (Fig. 8A). Porosity of such sandstones ranges from 10 to 18%. The most typical of the rocks under study are intergranular pores. The pore shape is irregular, angular, rounded, rarely slit-like with the size ranging from 0.03 to 6.1 mm.

Occasionally, leaching cavities are observed in the investigated thin sections. They are mainly developed in sandstones, where carbonate material acts as a matrix (Fig. 8B, E, F). Leaching cavities are also found in carbonate debris forming grains in oligomictic sandstones and gravelstones. The shape of the cavities is irregular, angular, rounded, elongated, with the size ranging from 0.06 to 1.6 mm. Individual cavities reach a length of 8.5 mm. Carbonate material occurs on the walls of the leaching cavities.

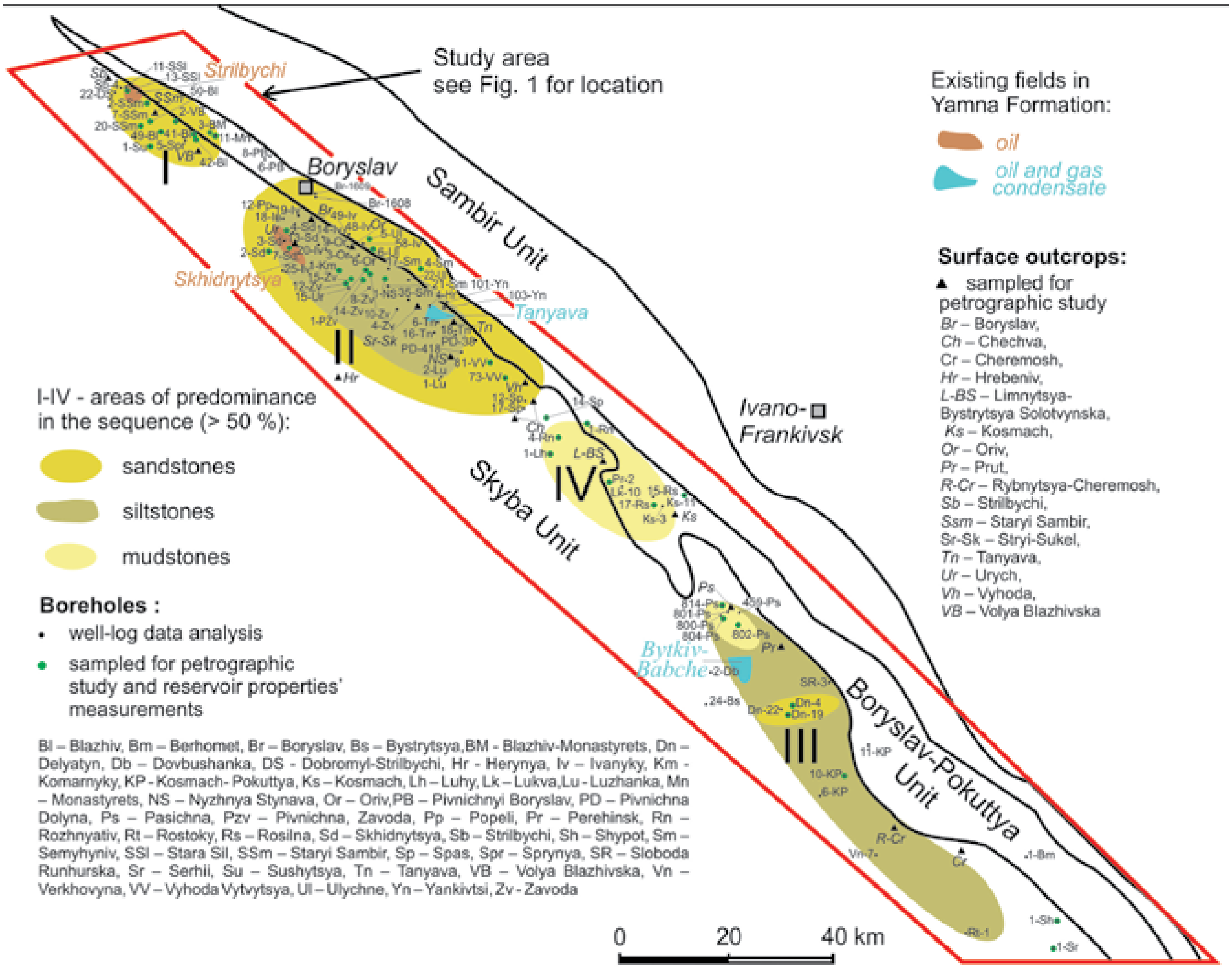

Fig. 10 Sketch map showing location of the areas prospective for hydrocarbons' occurrence in the Yamna Formation within the Boryslav-Pokuttya and external part of Skyba Units of the Ukrainian Carpathians

Table 2 Ranges and the median values of the reservoir properties of the Yamna Formation rocks

Area / Lithology	Number of samples	Porosity, %		Permeability, 1×10^{-3} md
		Total	Effective	
I / sandstone	20	12–18 / 15	9–16 / 13	2–52 / 11
II / sandstone	18	10–16 / 14	8–14 / 11	2–39 / 8.5
II / siltstone	15	6–15 / 10.5	4–12 / 9	2–32 / 8
III / sandstone	14	9.5–16 / 13.5	9–14 / 11	3–41 / 9.8
III / siltstone	13	5.5–15.5 / 12	4.5–13 / 9.5	2–29 / 7
IV / mudstone	17	2–20 / 5	1–9 / 3.5	0.5–1.5 / 0.7

Range of parameters is given as numerator; median values in denominator.

A characteristic feature of glauconite sandstones is that they have almost no leaching cavities. Single intergranular pores and leaching cavities, which have formed as a result of dissolution of the carbonate cementing substance, are observed only in individual samples.

Fracturing is typical of the fine-grained sandstones, siltstones and mudstones. Fractures are usually filled with calcite or organic matter (Fig. 8C, D), and sometimes with oil (Fig. 8 F). There are traces of bitumen on the walls of open fractures, which are winding or rectilinear in shape. The width of the fractures filled with the mineral component ranges from 0.01 to 2 mm. The total length of all fractures in individual thin sections reaches 33 mm. The volume of closed fractures varies from one hundredths of a percent to several percent. The width of open fractures, which are most typical of sandstones and siltstones, varies in the range 0.02–0.1 mm.

DISCUSSION

The above-described investigations of the Yamna Formation, which represents one of the main sequences of the flysch succession with oil/gas potential in the Ukrainian Carpathians and the Carpathian Foredeep, generated several important results. Palinspastic palaeoceanographic maps (Figs 4–6) were constructed on the basis of the performed distribution analysis of lithological complexes (sandstones, siltstones and mudstones) and the correlation of the studied boreholes, which penetrate the Yamna Formation within the Boryslav-Pokuttya and Skyba (its external part) Units. The most typical of the 85 boreholes studied are shown in Figs 3a–c. These maps (Figs 4–6) demonstrate the sedimentary features and sequence of depositional environments in the study territory in the Paleocene.

The deposition of the Carpathian flysch succession took place during the Cretaceous-Early Miocene at the continental margin of the East European Platform, where huge submarine fans, sourced by rivers, were formed (Senkovsky *et al.* 2015). The sedimentary record of this succession presents evidence of different palaeoceanographic events. Intense turbidite sedimentation resulted in the deposition of thick sandstone strata, while anoxic events caused formation of organic-rich sequences (Koltun *et al.* 1998). The presence of thick turbidite deposits in the flysch succession, Yamna sandstones being one of the main, shows their certain correlation with the eustatic sea-level drops, which might be one of the driving factors in the distribution of thick sandstone strata in the Cretaceous-Paleogene sequence. As a result, the Carpathian flysch succession contains both prolific source rocks and thick clastic reservoir rock layers. The fold-and-thrust structure of the Outer Carpathians, which formed in the Early Miocene, caused the existence of multiple structural traps. The essentially sandy Yamna Formation represents one of the main episodes of the intense gravity flow deposition in the history of the Carpathian basin.

The Paleocene Yamna Formation along with the Eocene and Early Oligocene thick sandstone successions, representing the main reservoir rocks in the Ukrainian part of the Carpathian petroleum province, is an important constituent of the Carpathian petroleum system. Besides the above-mentioned reservoir rocks, the latter contains a thick source-rock sequence of the Oligocene-Lower Miocene Menilite formation, which sourced hydrocarbons into the existing petroleum accumulations of the entire flysch succession (Koltun 1992; Koltun *et al.* 1998; Kotarba, Koltun 2006; Kotarba *et al.* 2019) as well as into the Mesozoic-Paleogene reservoirs of the East European Platform that are located under the Carpathian Overthrust (Radkovets *et al*. 2016).

Two palaeo-valleys, i.e. Khodoriv and Kolomyya valleys, representing the beds of the ancient rivers originating from the Ukrainian Shield, which had been bringing terrigenous material into the Carpathian basin from vast territories of the East-European Craton, were identified in the territory of the Carpathian Foredeep and Foreland (Utrobin 1958; Pylypchuk, Vul 1981; Havryshkiv, Hayevska 2019). The two main submarine fans of the Ukrainian segment of the Carpathian basin and their sandy facies, including the Yamna Formation, represent the continuation of these river valleys. The fans (FI and FII, Figs 4–6) were formed by the Khodoriv and Kolomyya palaeo-rivers in the northeastern and central parts of the study territory correspondingly. The areas with the increased sandstone content in the Yamna Formation correspond to the location of the most intense deposition of clastic turbidite sediments within the submarine fans.

In the northwestern fan FI, the maximum thickness and concentration of coarse-grained sediments are found in its upper part (Figs 4 and 5), while in its middle and lower parts, both the thickness and the grain size of sediments decrease. The structure of fan FII, located in the central part of the study territory (Figs 4–6), shows the prevalence of fine-grained sedimentation in its upper part, the amount of coarse-grained sediments increasing towards its lower parts.

These maps show two sources of terrigenous material within the studied part of the sedimentary basin. Coarse-grained sand dominates the sedimentary material that was transported by the river in the northwestern part of the territory, while the predominantly clayey and fine-grained psammitic material in its central part was derived from another river. Such spatial and temporal distributions of terrigenous material within the basin had a decisive influence on the Paleocene succession formation at its depositional and post-sedimentary stages and, hence, on the occurrence of reservoir rocks in the present-day section.

Based on the results obtained from the lithological analysis of the Yamna Formation rock sequence, the areas with the predominance of sandstones, siltstones and mudstones were marked (Figs 4–6) and the distribution of their thicknesses was established. The areas with the predominance of different sediment types were marked on the geological map (Fig. 10). The data obtained in combination with the petrographic study results and measurements of reservoir properties (Tables 1, 2) allow determining the preliminary location of zones with the increased petroleum potential in the Skyba and Boryslav-Pokuttya Units, where further exploration works should be carried out (Fig. 10).

The northwestern part of the study territory was found to be the most prospective from the viewpoint of reservoir rocks' occurrence. Area I is 17 × 22 km in size. This area is dominated by medium- and coarse-grained sandstones. The maximum value of total porosity of the rocks therein is 18%, that of effective porosity is 16%, and that of permeability is 52 × 10^{-3} md (Tables 1 and 2). The Strilbychi oil field is located within this area.

Area II, with the Skhidnytsya oil field and the Tanyava oil and gas condensate field located within its limits, is also prospective. This area includes the distribution ranges of both sandstones and siltstones, which are significantly more prevalent in the section above mudstones. The total porosity of the rocks therein reaches 14%, the effective one 12%, and permeability – 39 × 10^{-3} md (Tables 1 and 2). The size of area II is 29 × 64 km.

Area III stretches to the southeastern part of the study territory. It is characterized by the dominance of siltstones in the Yamna Formation sequence, with only a small part of it dominated by sandstones. The Bytkiv-Babche oil field is located in this area. Area III has an elongated ellipsoid shape and is 16 × 83 km in size. This area is generally characterized by the presence of coarse-grained siltstones and silty mudstones in the section. The maximum values of total porosity of these rocks reach 14%, values of effective porosity reach 12%, and permeability 41 × 10^{-3} md (Tables 1 and 2).

The smallest in size and the least promising is area IV. It is located in the central part of the study territory. In the Yamna Formation within this area, there are no oil or gas fields discovered. The size of area IV is 17 × 31 km. The predominant rocks in the sequence of the Yamna Formation therein are mudstones. The maximum total porosity of mudstones reaches 20%, their effective porosity is estimated at 3%, while that of sandy mudstones and siltstones at 9%. The established maximum permeability of the rocks therein is 1.5 × 10^{-3} md (Tables 1 and 2), which is significantly lower than in areas I–III.

As is known (Ahlbrandt *et al.* 2005), formation of the lithologically sealed traps for oil and gas is caused by the lateral facies substitution of clastic reservoir rocks by coeval impermeable rocks. The performed analysis of the distribution of clastic rocks and areas with sandstone and siltstone predominance in the sequence allowed determining boundaries of their occurrence in the study area. Because of the turbidite nature of sediments accumulation, their boundaries with the surrounding clayey sediments are abrupt, which manifests itself in the wedging out of sandstone layers in the present-day structure and the possible formation of lithological traps for hydrocarbons, which remained in existence after the subsequent folding tectonic processes. Though the area of the Ukrainian Carpathians and their Foredeep is a mature and densely drilled oil and gas province, the predominant majority of the existing fields are found in anticline traps. Therefore, prospecting for hydrocarbons accumulations in lithological traps holds great promise for new discoveries in the region under study.

Selection of the above-described areas within the vast territory of Skyba and Boryslav-Pokuttya Units of the Ukrainian Carpathians ranging from the Polish to the Romanian border is important since it allows concentrating further oil and gas exploration on the most prospective sites in the region.

CONCLUSIONS

The Paleocene Yamna Formation of the Ukrainian Carpathians is made up of a clay-terrigenous sequence, which is often composed basically of sandstone, with a thickness of 200 m. This Formation represents one of the principal reservoir rock sequences and an important element of the petroleum system of the Cretaceous-Paleogene flysch succession.

Areas with the maximum development (> 50% of total sequence) of sandstones (3 areas), siltstones (7 areas) and mudstones (3 areas) were established based on the investigation results of 18 outcrops and analysis of well-log data of 85 boreholes in the Yamna Formation, which are evenly distributed throughout the study territory from the Polish to the Romanian border.

The areas with the increased sandstone content, distinguished on the basis of the constructed palinspastic maps of thickness distribution and types of lithological complexes, indicate the location of two main submarine fans in the Carpathian sedimentary basin, formed as a result of discharge of the terrigenous material, which was transported by the Khodoriv palaeo-river in the northwestern part of the study territory and by the Kolomyya palaeo-river in the central part. The northwestern fan was characterized by the predominance of coarse sandy sediments, while the central one showed the predominance of clayey, silty and fine-grained psammitic material. Such distribution of terrigenous material had a significant influence on the further formation of Paleocene strata and their reservoir properties.

It has been established that material composition has influence on reservoir rock properties in the Yamna Formation. Sandstones and siltstones are represented by both densely and poorly cemented varieties, which differ in cement composition, degree of cementation, as well as in porosity and permeability. In sandstones and siltstones from the sections studied, cement is composed of clay, mixed siliceous-clay and carbonate. Sandstones with hydromica or silica-hydromica, pore and film-pore cement show distinct reservoir rock properties.

Based on the occurrence analysis of sandstones, siltstones and mudstones in the Yamna Formation section and measurements of reservoir rock properties, four priority areas were selected for further oil and gas exploration.

The most prospective of them is the northwestern part of the study territory (area I), with sandstones prevailing in the section. The rocks therein display the best reservoir properties (total porosity up to 18%, effective porosity up to 16%, permeability up to 52 × 10^{-3} md). Areas II and III, where the section is mainly made up of both sandstones and siltstones, have slightly poorer but still quite good reservoir properties (total porosity up to 14%, effective porosity up to 12%, permeability up to 41 × 10^{-3} md). Area IV is the least prospective in this respect, since it is dominated by mudstones. However, reservoir properties therein are still rather distinct (maximum values of total porosity for mudstones 20%, effective porosity for mudstones and sandy mudstones 3% and 9% correspondingly, permeability – 1.5 × 10^{-3} md), indicating that this area might have the potential for hydrocarbons exploration, too.

The areas adjacent to the boundaries between the major turbidite sandstone bodies and clayey rocks can be considered as locations of the potential wedging out of sandstone layers and, hence, as locations where new hydrocarbons accumulations in lithological traps could be discovered.

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