GEOLOGY

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DYNAMICS OF SEDIMENTATION WITHIN THE SOUTHWESTERN SLOPE OF THE EAST EUROPEAN PLATFORM IN THE SILURIAN-EARLY DEVONIAN

Purpose. The objective of this study is the investigation of the Silurian-Lower Devonian (Lochkovian) carbonate-clay sedimentary complex of the southwestern slope of the East-European platform. Its formation was the result of a single cycle of geodynamic and sedimentary events in the lithological record of the southern continental margin of Baltica. **Methodology.** The study is based on well-logs correlation, lithological and geochemical investigations of core samples, and petrographic thin sections analysis. The obtained results were used to establish patterns of changes in the material composition of the studied strata in time and space in order to determine the basin development dynamics of the continental margin of the Eastern European platform southwestern slope in the Silurian-Early Devonian. **Results.** It is established that the formation of the carbonate-clay sequence represents a single sedimentary cycle and was the result of a complex of geodynamic, depositional and paleoclimatic events that took place on the Baltica southern continental margin. The Silurian period was characterized by intensive development of benthic organisms and reef structure formation in the proximal part of the basin and clay-carbonate muds enriched with dispersed organic matter in its distal part. In the Early Devonian, carbonate biogenic sedimentation continued throughout the basin. The carbonate maximum content (80–98 %) proves the existence of the reef constructions in the basin sedimentary record. Lower values of carbonate content are characteristic of marls (40–55 %) and biodetritic limestones (56–75 %), which make up the main part of the Silurian sequence. There are no reef constructions in the section of the Lochkovian stage of Devonian, and the calcium carbonate content in the rocks varies from 45 to 83 %. The content of $CaCO_3$ in mudstones and calcareous mudstones of the Silurian varies from 5 to 15 %. Originality. The applied complex of lithological, geochemical, geological-geophysical and paleogeographic investigations allowed studying the sedimentary basin dynamics in the Silurian-Early Devonian with the assessment of the possibility of participation of these strata in oil and gas hydrocarbons generation. **Practical significance.** The obtained results show that the carbonate-clay complex of sedimentary rocks of the Silurian and Lower Devonian (Lochkovian) of the studied region can be considered as a separate petroleum system, including source rocks, reservoir rocks and possible conventional and unconventional oil and gas accumulations.

Key words: Ukraine, Silurian, Devonian, shelf of Baltica, carbonate-clay sequence, organic-rich rocks, oil and gas generation

Introduction

The Silurian period was characterized by the development of a global anoxic event, which resulted in the accumulation of thick sedimentary strata enriched in dispersed organic matter within all paleocontinents. Therefore, these deposits are of interest in terms of generation and accumulation of liquid and gaseous conventional and unconventional hydrocarbons. Paleogeographic environments in Lochkovian times of the Lower Devonian within the study area were largely inherited from the Silurian period, which led to the accumulation of clay muds with a significant content of carbonate component and contributed to the accumulation of organic matter in these sediments [Radkovets, 2015, Radkovets, 2016]. Therefore, in this paper we consider the Silurian and Lower Devonian deposits as a single facies unit, which should also be considered in view of the prospects of oil and gas exploration.

The Silurian and Devonian strata are currently the main targets of shale gas and oil exploration and development worldwide. In North America, the main unconventional hydrocarbons occur in Devonian and Lower Carboniferous (West Texas Devonian Bossier Formation, Fort Worth Basin Mississippi Barnett Formation, Appalachian Basin Devonian Ohio Formation, Michigan Basin Devonian Antrim Formation, Arkama Devonian Woodford Formation), while Silurian strata are the subject of unconventional hydrocarbons development in China (Sichuan Basin Longmaxi Formation) [Sonnenberg and Pramudito, 2009].

A number of geological and geophysical materials were analyzed and core material was investigated in this study to clarify the dynamics of the basin development at the continental margin of the southwestern slope of the East European platform during the Silurian-Early Devonian (Fig. 1).

The petrographic analysis of the Silurian and Lower Devonian (Lochkovian) rocks allowed us to trace the patterns of the material composition changes of these strata in time and space, and to outline their oil and gas generation prospects.

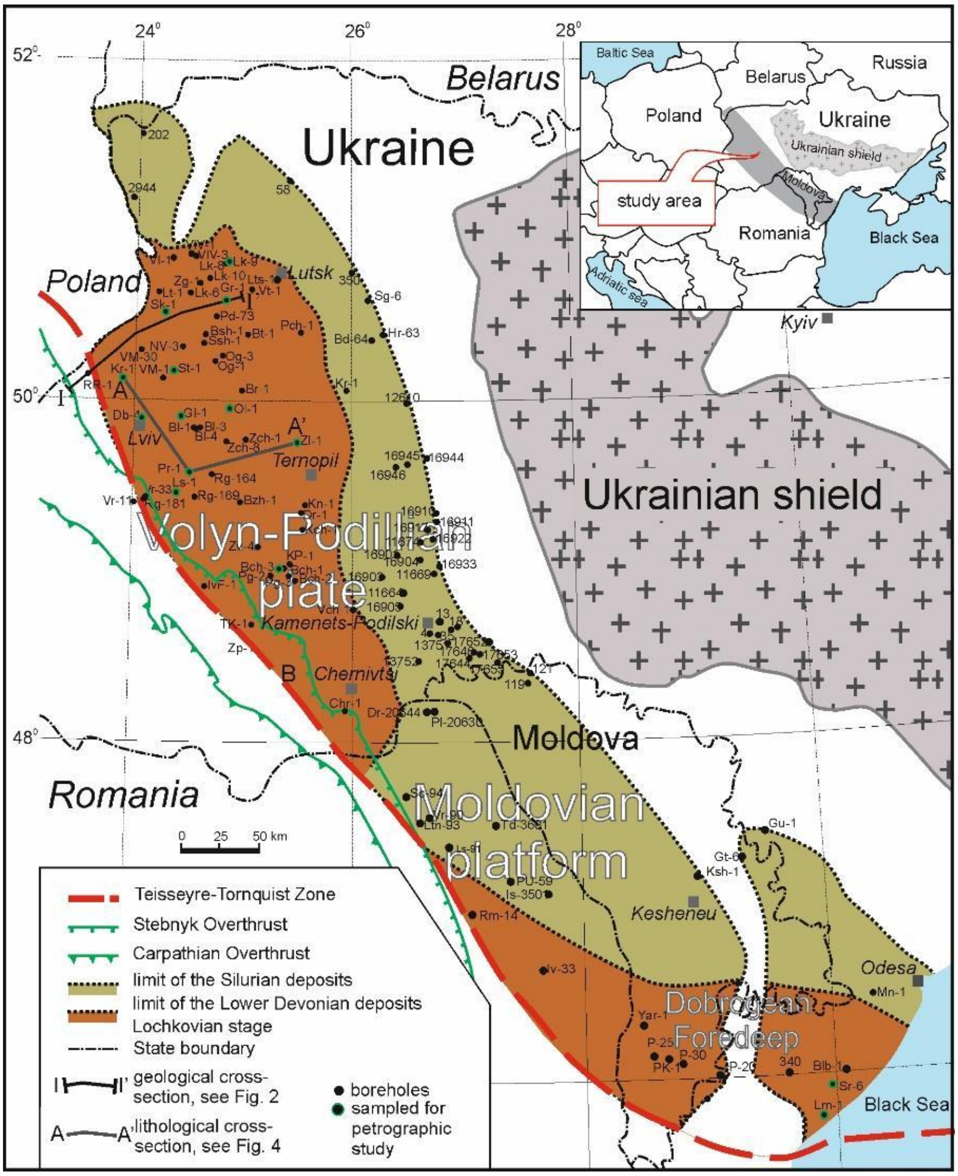

Fig. 1. Location map of the general distribution of the Silurian and Lochkovian stage of the Lower Devonian strata within the south-western margin of the East-European Platform after [Radkovets, 2015, Radkovets, 2016].

Boreholes: Bch – Buchach, Bd – Brydok, Bl – Baluchyn, Blb – Balabanivsk, Br – Brody, Bsh – Byshiv, Bt – Berestechko, Bzh – Berezhany, Chr – Chernivtsi, Db – Dublyany, Dr – Darakhiv, Drb – Darabani, Gl – Glynyany, Gr – Gorokhiv, Gt – Gyrtop, Gu – Gulanka, Hr – Horiv, IvF – Ivano-Frankivsk, Iv – Ivanesti, Is – Iasi, Khm – Khmelivka, Km – Kremenets, Kn – Konopkivka, KP– Koropets-Pyshkivtsi, Kr – Krekhiv, Ksh – Kesheneu, Lk – Lokachi, Lm – Lyman, Ls – Lishchyny, Lt – Litovezh, Ltn – Liteni, Lts – Lutsk, Mn – Myrne, NV – Novy Vytkiv, Og – Oglyadiv, Ol – Olesko, P – Valya-Perzhey, Pch – Povcha, Pd – Pidberezzya, Pg – Pidgaytsi, Pl – Paltinis, Pr – Peremyshlyany, PU – Popesti-Ungheni, Rg – Rogatyn, Rm – Roman, RR – Rava-Ruska, Sc – Suceava, Sg – Sergiyivka, Sk – Sokal, Sr – Sarata, Ssh – Sushne, St – Stremin, Td – Todireni, TK – Tlumach-Kolomya, Vch – Verchniakivtsi,Vl – Volodymyrivka, VlV – Volodymyr-Volynsky, VM – Velyki Mosty, Vr – Vorona, Vt – Voyutyn, Yr – Yargara, Zch – Zolochiv, Zg – Zagoriv, Zl – Zalozhtsi, Zp – Zagaypil, Zv – Zavadivka.

Geological background and sediments distribution

The south-western slope of the Eastern European Platform, which is the subject of this study, consists of the following geological structures: Volyn-Podillya Plate, Moldovan Platform and Dobrogean Foredeep (Fig. 1). The Archean-Proterozoic basement of this territory is represented by igneous and metamorphic rocks and is covered by a sedimentary succession composed of Neoproterozoic (Riphean, Vendian), Paleozoic (Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian occurs only in the Dobrogean Foredeep), Mesozoic (Triassic only in the Dobrogean Foredeep, Jurassic, Cretaceous) and Cenozoic (Paleogene, Neogene, Quarternary) [Gnidets et al, 2003]. The basement occurs at the surface in the area of the Ukrainian Shield, and in the direction from the Ukrainian Shield to the Teisseyre-Tornguist (TT) zone (from east to west). The top of the basement is monoclinically dipping under the sedimentary cover. Accordingly, as shown at the geological section (Fig. 2), the thickness of the sedimentary cover increases from northeast to southwest. The greatest thicknesses of the sedimentary succession is established within the Volyn-Podillya Plate and the Dobrogean Foredep. According to geophysical studies, the maximum values, reaching 10 km, are recorded in the extreme southwestern part of the Lviv Depresion [Chebanenko et al, 1990]. In the most submerged part of the Dobrogean Foredeep, the thickness of the sedimenttary cover reaches 7 km.

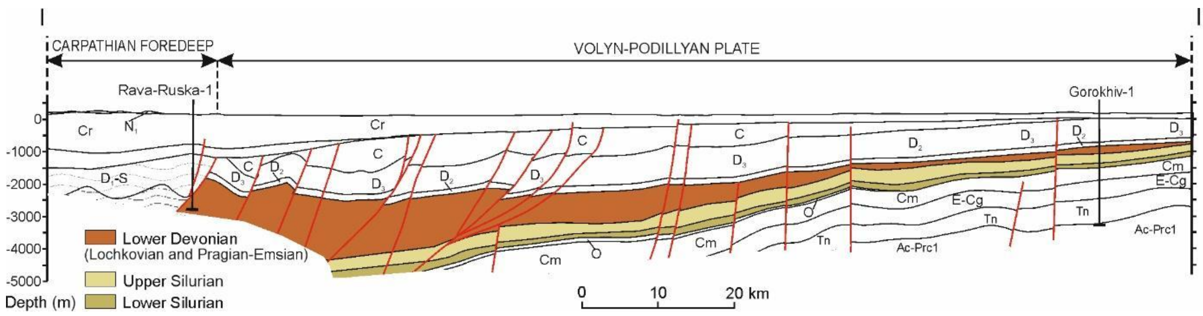

Fig. 2. Geological cross-section **I – I'** through Carpathian Foredeep and Volyn-Podillyan Plate (see Fig. 1 for location) modified after [Vashchenko et al. 2007]:

Ac – Archean, Ac-Prc$_1$ – Archean and Lower Proterozoic, Tn – Tonian, E-Cg – Cryogenian-Ediacaran, Pc-Cm – Precambrian-Cambrian, Cm – Cambrian, O – Ordovician, S-D$_1$ – Silurian and Lower Devonian undivided, D$_2$ – Middle Devonian, D$_2$ – Upper Devonian, C – Mississippian and Pennsylvanian, J – Jurassic, Cr – Cretaceous, N$_1$ – Miocene.

The Silurian and Lower Devonian (Lochkovian) deposits form a single sedimentary cycle. They are continuously distributed along the southwestern edge of the East European platform from the Baltic to the Black Sea and rest on the eroded during a long regression surface of the Ordovician, Cambrian and Vendian. The thicknesses of the Silurian and Lower Devonian (Lochkovian) regularly increase from the Ukrainian Shield to the west in the direction of the TT zone. As shown in Figure 3, the thickness of the Silurian in its deepest occurrence reaches over 1100 m. Devonian deposits within the study area are much less common than Silurian ones, however, they also reach their maximum thicknesses in the area close to the TT zone, which is 800 m in the Dobrogean Foredeep and more than 1000 m within the Volyn- Podillyan Plate.

Silurian sequence is represented by both lower and upper series [Nikiforova et al, 1972, Drygant, 2000]. The Lower Silurian, which is made up of clay-carbonate sediments, covers only the Wenlock series (Fig. 4). The Upper Silurian is composed of full age range, Ludlow and Pridoli series, which in lithological composition, in general, are represented by carbonate-clay rocks. Devonian sediments within the study region are represented by all three series: Lower, Middle, and Upper [Drygant, 2000]. The Lower Devonian is represented by two strata, different in both composition and facial features. The Lochkovian is almost indistinguishable from the Silurian sequence by its petrographic characteristics. Lochkovian deposits are made up of clay-carbonate rocks with a significant content of carbonates. The upper part of the Lower Devonian section, represented by the Pragian and Emsian stages, is composed of rocks completely different by genesis. They include reddish-brown terrigenous strata which are an age-related analogue of the Devonian continental deposits, the so-called “Old Red Sandstones”.

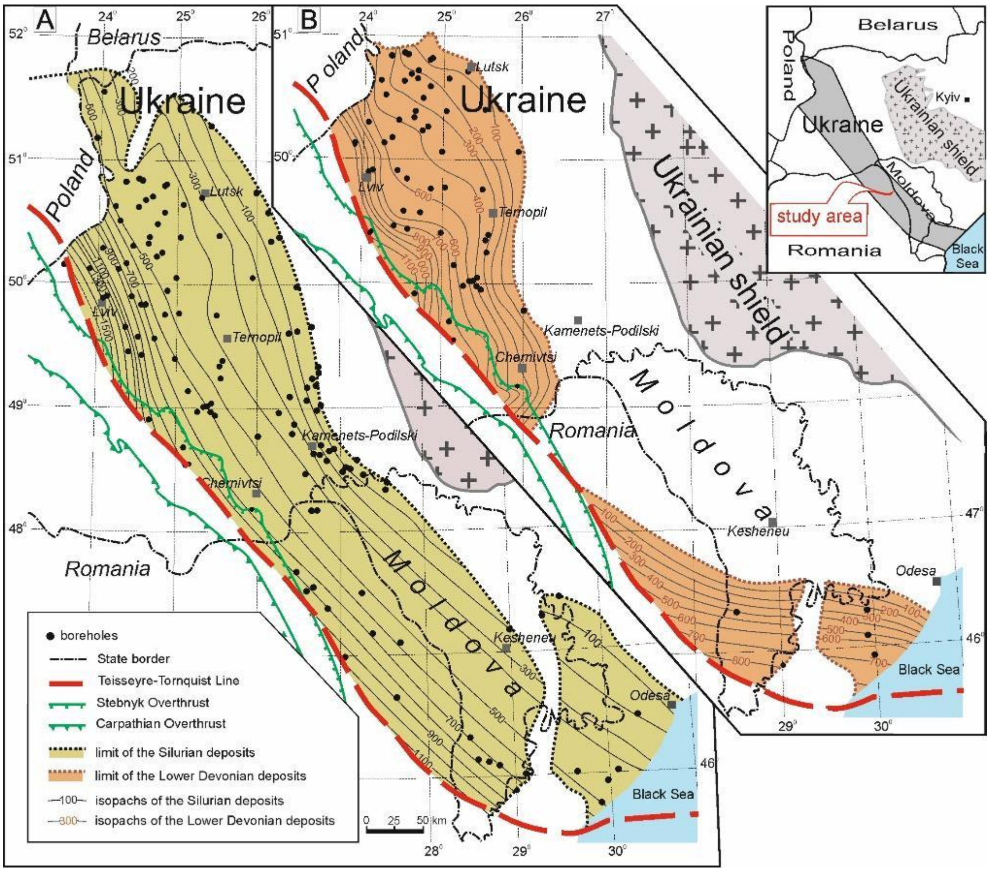

Fig. 3. Thickness maps of (A) the Silurian and (B) Lochkovian stage of the Lower Devonian within the south-western margin of the East-European Platform [Radkovets, 2015, Radkovets, 2016].

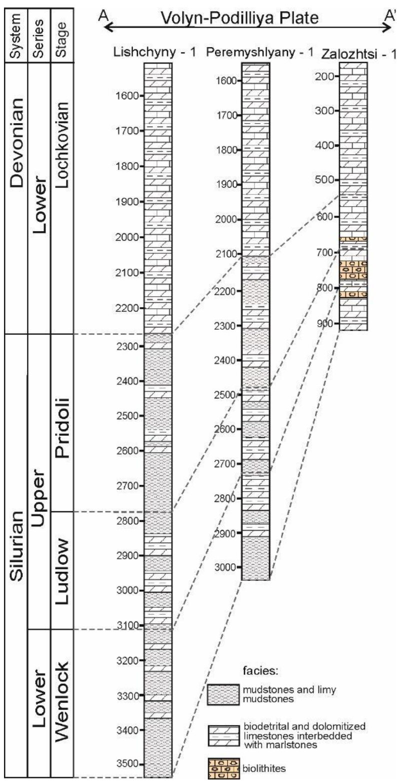

Fig. 4. Lithological section **A-A'** through the Silurian and Lochkovian stage of the Lower Devonian succession in the Volyn-Podillyan Plate (see Fig. 1 for location).

Purpose

The objective of this study is the investigation of the Silurian-Lower Devonian (Lochkovian) carbonate-clay sedimentary complex of the southwestern slope of the East-European platform, the formation of which was the result of a single cycle of geodynamic and sedimentary events in the lithological record of the southern continental margin of Baltica.

Methodology

The study is based on well-logs correlation, lithological and geochemical investigations of core samples, and petrographic thin sections analysis. The obtained results were used to establish patterns of temporal and spatial changes in the material composition of the studied strata. It aimed to determine the basin development dynamics of the continental margin of the southwestern slope of the Eastern European platform in the Silurian-Early Devonian.

Results

Lithological characteristics of rocks

Lithological sections (Fig. 4) of the Silurian strata, constructed using the well-log correlation and petrographic analysis of rocks, show a characteristic change of facies in the direction from the coastal to the deeper part of the basin. The coastal zone was dominated by biogenic sedimentation with the accumulation of carbonate muds with a slight clay component admixture, as well as intensive development of benthic organisms and the reef structure formation. The deeper part of the basin was characterized by the inflow of clay material and the formation of clay-carbonate muds. As shown at Fig. 4, intensive carbonate accumulation was characteristic of the entire study basin. However, in the deeper part against the background of carbonate muds accumulation there was a regular deposition of clay material. This resulted in the formation in the Silurian sequence of thick mudstone and calcareous mudstone strata. Due to the existence of an oxygen minimum zone in the deeper part of the basin, the mudstone layers were enriched with dispersed organic matter. Despite the fact that the Lochkovian stage of the Lower Devonian represents a single sedimentary cycle with Silurian sediments, biogenic sedimentation continued throughout the entire basin. In the deeper part there was no intensive influx of clay material. So these sediments are made up of biodetrital and dolomitized limestones, without the facial zones that existed in Silurian times [Radkovets, 2015]. Petrographic investigation of the Silurian and Lover Devonian (Lochkovian) rocks allowed selecting characteristic types of rocks from different parts of the study area (Fig. 1), which are presented in Table 1. The Silurian and Lower Devonian (Lochkovian) rocks, which represent the carbonate accumulation during this age range in the studied basin, are made up of the facies of biodetrital and dolomitized limestone interbedded with marlstones (Fig. 5A–D).

Both clayey marlstones and marlstones, which consist of a fine clay-carbonate substance, always contain quartz of a fine siltstone size which averages 43 % in clayey marlstones. Also, calcareous bioclasts debris of 0.1–0.8 mm (sometimes > 1 mm) and possibly strongly recrystallized bioclasts are present in rocks. In addition, marlstones are pyritized and a significant number of lenticular accumulations of organic matter are observed. Biodetrital and dolomitized limestones contain from 55 % to 85 % of $CaCO_3$ and $CaMg(CO_3)_2$ and are represented by rounded and non-rounded biolithites' debris with a clayey matrix. Silurian sediments, which were formed in the deeper part of the basin, due to the inflow of clay material are represented by the mudstone and lime mudstone facies (Fig. 6A, B). The matrix of rock is made up of illite, chlorite, fine scales of mica and the sub-parallel streaks of organic matter, which in these facies reaches maximum values (up to 2.16 w%). Reef structures that were characteristic of the proximal part of the basin in the Silurian period are represented by the facies of biolithites (Fig. 7A, B). The rocks contain significant amounts of skeletal fragments, including crinoids, ostracods, brachiopods and corals predominate. The highest values of $CaCO_3$ content are found in biolithites (up to 98 %). The formation of the reef facies began in Wenlock. These facies formed the boundary beyond which deep-water clay layers were deposited [Radkovets, 2015].

Thus, the distal part of the basin in the Silurian period was characterized by the accumulation of clay muds. The content of $CaCO_3$ in mudstones and calcareous mudstones varies from 5 to 15 %. Sediments of the Silurian and Lower Devonian (Lochkovian stage) accumulated in the shallower part of the basin are characterized by high calcium carbonate content in the whole section. Fig. 8 shows the $CaCO_3$ content in the sequence of the Lyman-1 borehole, which is typical for the entire proximal part of the sedimentary basin (Volyn-Podillyan Plate, Moldovian platform, Dobrogean Foredeep), in which the deposition of clay material was limited and the $CaCO_3$ content varies from 40 to 98 %. The maximum content of carbonates (80–98 %) records the existence in the sedimentary record of the reef constructions. Lower values of carbonate content are characteristic of marls (40–55 %) and biodetrite limestones (56–83 %), which make up the main part of the Silurian section. There are no reef constructions in the section of the Lochkovian stage of the Devonian, and the content of calcium carbonate in these rocks varies from 45 to 83 %.

Table 1

Petrographic composition of the Silurian and Lower Devonian (Lochkovian) rocks

Strati-graphy	Lithology	Minerals content in rock, %			
		Clay minerals	Quartz	Feldspar	Carbonate
Lower Devonian Lochkovian	marlstones	$\frac{17-21}{20.5}$	$\frac{21-28}{27}$	$\frac{0.07-3}{2.5}$	$\frac{45-52}{50}$
	biodetrital and dolomitized limestones	$\frac{8-12}{5}$	$\frac{0.7-3.5}{2.5}$	$\frac{0.7-2}{1.5}$	$\frac{63-83}{81}$
Silurian	mudstones	$\frac{24-35}{29}$	$\frac{41-64}{59}$	$\frac{3-6}{5}$	$\frac{4-6}{5}$
	limy mudstones	$\frac{22-45}{28}$	$\frac{45-60}{57}$	$\frac{3-6}{4.5}$	$\frac{5-15}{10.5}$
	clayey marlstones	$\frac{20-31}{25}$	$\frac{35-45}{43}$	$\frac{3-5.5}{4.1}$	$\frac{16-40}{31}$
	marlstones	$\frac{16-20}{17}$	$\frac{23-30}{29}$	$\frac{2-3.5}{3}$	$\frac{40-55}{51}$
	clayey biodetrital limestones	$\frac{5.5-10}{8}$	$\frac{7-15}{14.5}$	$\frac{0.5-3}{1.5}$	$\frac{56-79}{77}$
	biolithites	$\frac{1-7}{4}$	$\frac{2-11}{5.5}$	$\frac{0.5-1}{0.7}$	$\frac{80-98}{92}$

* Range of minerals content is given as numerator; median values in denominator.

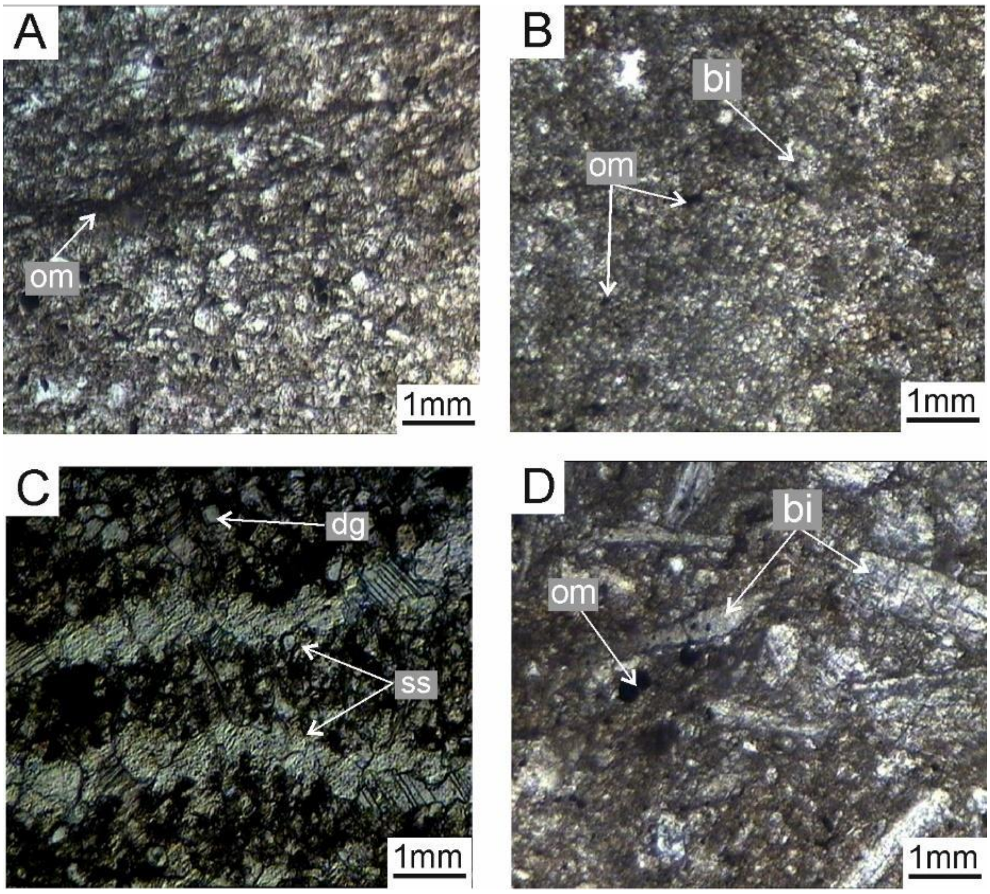

Fig. 5. Photomicrographs:
(A) of the Lower Devonian (Lochkovian) marlstones from borehole Krekkhiv-1, depth interval 3405.1–3414.7; (B) of the Silurian marlstones from borehole Zalozhtsi-1, depth interval 808.8–813.5 m; (C) of the Lower Devonian (Lochkovian) dolomitized limestones from borehole Lyman-1, depth interval 2170–2180 m; (D) of the Silurian clayey biodetrital limestone from borehole Buchach-1, depth interval 1075–1080 m
bi – calcareous bioclasts, dg – dolomite grains, om – organic matter, ss – stylolitic sutures.

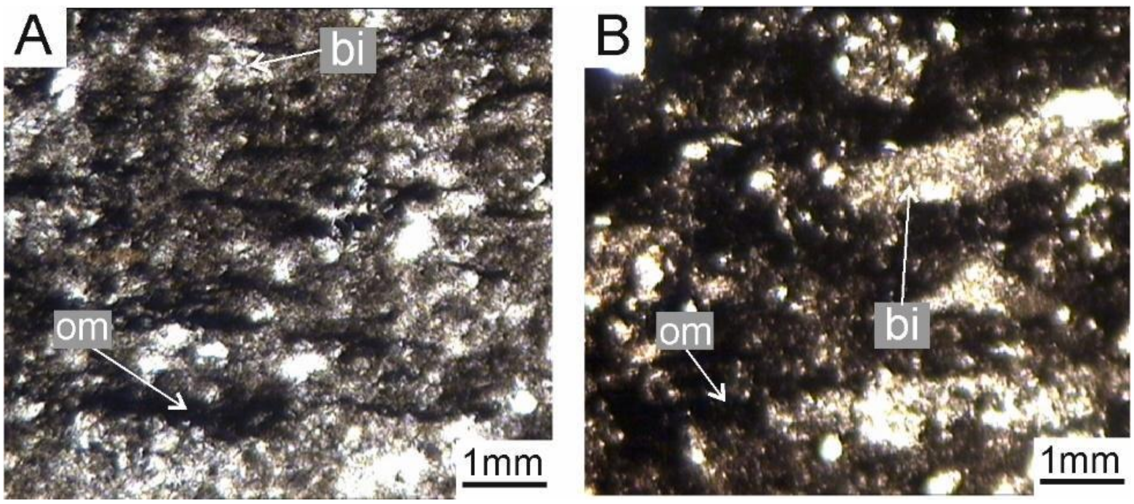

Fig. 6. Photomicrographs of the Silurian rocks: (A) mudstones from borehole Krekhiv-1, depth interval 4,560–4,565 m; (B) limy mudstones from borehole Krekhiv-1, depth interval 4,406.7–4,412.2 m
bi – calcareous bioclasts, om – organic matter.

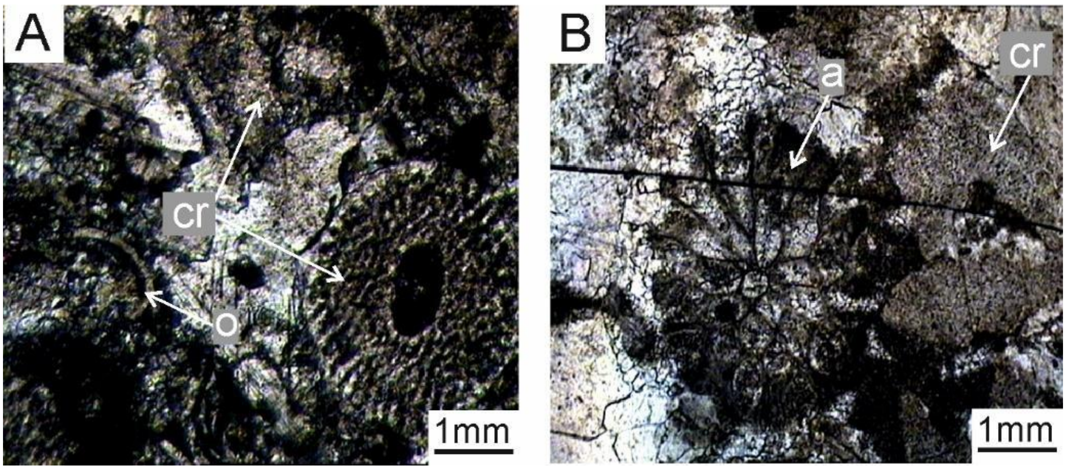

Fig. 7. Photomicrographs of the Silurian biolithites: (A) from borehole Lyman-1, depth interval 2,707–2,713m; (B) from borehole Zalozhtsi-1, depth interval 729–761 m
a – algae, cr – crinoids, o – ostracods.

Geodynamic factors and depositional environments at the southern shelf of Baltica

Geodynamic evolution

The study region is located on the southwestern slope of the East European Platform, bounded on the west by the Teisseyre-Tornquist Zone, and on the east by the Ukrainian Shield. In the Silurian (Fig. 9A) and the Early Devonian (Fig. 9B), the basin under study represents the southern shelf of the Baltica continent. Due to global tectonic events in the Ordovician [Verniers et al, 2008], the study region was elevated above the sea level. This caused a break in sedimentation in this age range in the section of the western margin of the East European platform.

In the late Ordovician there was a change in the geodynamic regime of the studied region from the stage of post-rift thermal immersion to collision. A new sedimentary basin, which represented a flexural foredeep, was associated with the Caledonian oblique collision of Avalonia and Baltica. It existed from the beginning of the Wenlock time of the Silurian to the Lochkovian time of the Early Devonian [Poprawa et al, 2018]. In the Pragian-Emsian time (Early Devonian), the Acadian-Caledonian orogeny took place and the basin entered the post-collision stage, as a result of the collision of Baltica with Laurussia [Golonka and Gawęda, 2012].

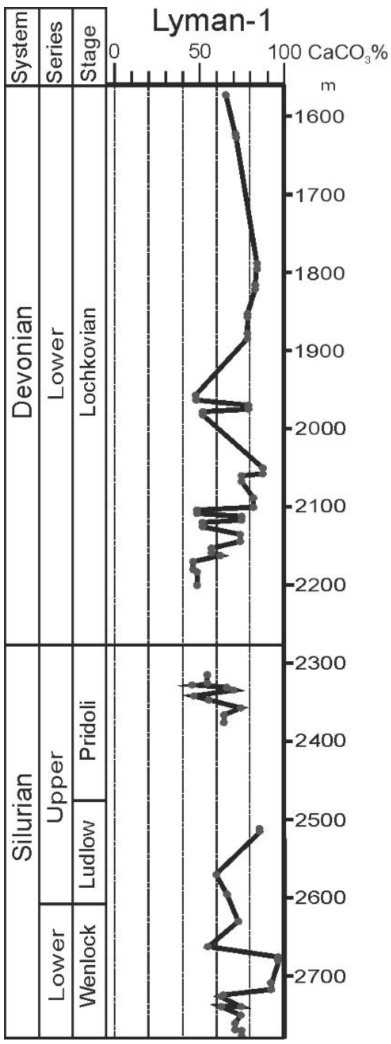

Fig. 8. $CaCO_3$ content in the Silurian and Lochkovian stage of the Lower Devonian sequence of the borehole Lyman-1 (Dobrogean Foredeep).

Depositional environments

After the Ordovician ice-house period, the climate of the study area changed abruptly to green-house. Fig. 10 shows the global changes in temperature and sea level, particularly within the southern Baltica shelf during the Silurian-Early Devonian. The surface seawater temperature in the Silurian exceeded 20 °C [Verniers et al, 2008], and in the Lochkovian time of the Early Devonian exceeded 30 °C [Kiessling, 2002, Kiessling et al, 2003]. Such climatic conditions contributed to the intensive carbonate accumulation in the shelf sediments of the studied basin (Fig. 9). The peripheral part of the basin was characterized by carbonate sedimentation formed by benthic organisms, which resulted in intense reef formation in the Silurian (Fig. 9A). In the deeper part of the shelf (at depths of over 100 m) there was an oxygen minimum zone. The carbonate muds enriched with organic matter were deposited within it, due to the effective fossilization of planktonic organisms.

The Paleocontinent Laurussia, which consisted of North America and Baltica (Fig. 9B), was a place where the deposition of muds enriched with dispersed organic matter took place during the Silurian-Early Devonian. On the modern North American continent, there are thick and extensive Devonian black shale formations. They currently represent the World's largest shale gas and oil fields, which are effectively developed in the United States [Sonnenberg and Pramudito, 2009]. The Silurian-Early Devonian sediments, which are the subject of this study, were deposited in the southern continental margin of Baltica as a result of an oxygen minimum zone that existed there.

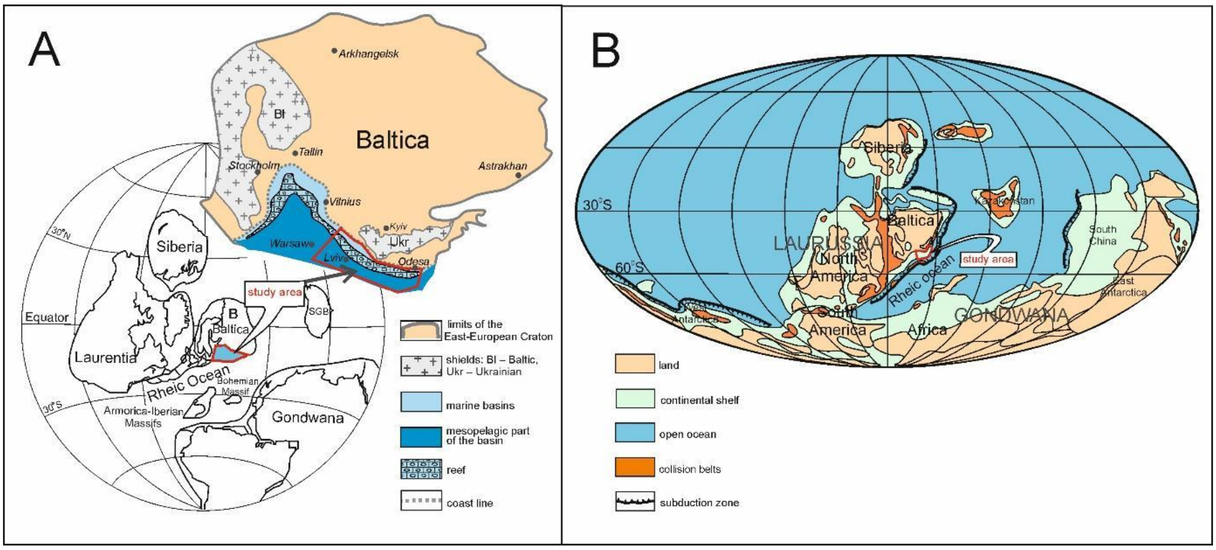

Fig. 9. Paleogeographic maps: (A) for mid-Silurian time after [Torsvik et al., 1996] and the model of southern shelf of Baltica with location of lithofacies for Ludlow time [Radkovets, 2015]; (B) for Early Devonian time after [Golonka and Gawęda, 2012].

In the Devonian period, that zone migrated to the shallow marine basin which existed within Laurussia between North America and Baltica. That led to the accumulation of the above-mentioned black shale formations.

The development of the reef constructions in the Silurian (Late Wenlock-Middle Pridoli), along the entire southern continental margin of Baltica, led to the formation of a barrier reef (Fig. 9A). The length of the reef was about 2,300 km, and the maximum width – 150 km. The Silurian Reef Range can be called the "Great Barrier Silurian Reef" by analogy with modern Australia. An interesting series of coincidences has been found between these reefs. First of all the latitudes. The reef was formed in the southern paleoshelf basin of the Baltica paleocontinent. The Great Barrier Reef exists on the present day eastern shelf of Australia. Thus, they were located in the southern latitudes (10–25°). The second similarity is the size of the reef bodies. Both the Silurian reef of Baltica and the modern Australian Great Barrier Reef have a maximum width of 150 km and length of 2,300 km. The third similarity, which is important for the carbonate accumulation, is temperature. Current temperatures within the eastern shelf of Australia are 22–27 °C. Within the studied paleobasin of the Silurian period [Verniers et al, 2008] the temperature was not less (22 °C). And the last interesting fact, the area of Australia and the Baltica paleocontinent also closely coincide (≈7,600,000 thousand km^2).

In Lochkovian time, there has been no significant change in climatic and tectonic conditions since the Late Silurian. This interval of geological history was characterized by a warm climate with a high CO_2 content in the atmosphere and in the ocean water

[Royer, 2006]. Despite the gradual rise of sea level (Fig. 10), the Lochkovian time was characterized by a favorable environment for the development of carbonate biocenosis and deposition of clay-carbonate sediments. In Lochkovian time reef formation stopped. The epicontinental basin represented a typical carbonate platform within which a diverse carbonate biocenosis existed. The abundant development of carbonate fauna contributed to the accumulation of sediments with a significant share of $CaCO_3$, the maximum content of which in the rocks reaches 83 %.

Thus, after the Ordovician glaciation in the Silurian and Lower Devonian (Lochkovian) in the conditions of the greenhouse effect (Fig. 10) there was a basin with intensive carbonate accumulation and an oxygen minimum zone. Due to the decrease in the rate of tectonic subsidence and climate change in Pragian time, the sedimentary basin decreased in size, the accumulation of carbonates stopped, and terrigenous sedimentation began.

Prospects for oil and gas

The carbonate-clay complex of the Silurian and Lower Devonian (Lochkovian) sedimentary rocks of the Eastern European platform is of certain interest from the point of view of oil and gas prospects and can be considered as a separate petroleum system, which comprises source rocks, reservoir rocks and possible conventional and unconventional oil and gas accumulations. Silurian sediments, which include thick sequences of carbonate mudstones enriched with a dispersed organic matter, distributed over a vast area from the Baltic to the Black Sea, have been considered as a shale gas exploration target during the past decade [Poprawa, 2020, Sachsenhofer and Koltun, 2011].

To date, the commercial viability of developing unconventional hydrocarbons in the Silurian sequence has not been confirmed, although further research in this direction is ongoing. The average TOC content in the Silurian mudstones is 0.8 wt%, but locally the values are reaching 2.16 wt% [Radkovets et al, 2017a]. Taking into account the significant thickness of this black shale sequence reaching over 1300 m, further investigations may show the prospects of the Silurian succession for unconventional hydrocarbons. In the north-eastern part of the study region, where Silurian deposits occur at shallow depths and have a lower thermal maturity, shale oil can be expected. Further south-west these strata reach greater depth and higher thermal maturity, thus being prospective for shale gas. Silurian reef constructions are prospective for conventional oil. Numerous oil deposits have been recorded in a number of wells, in particular in the Lokachi field [Chyzh, 1977, Rizun et al, 2007].

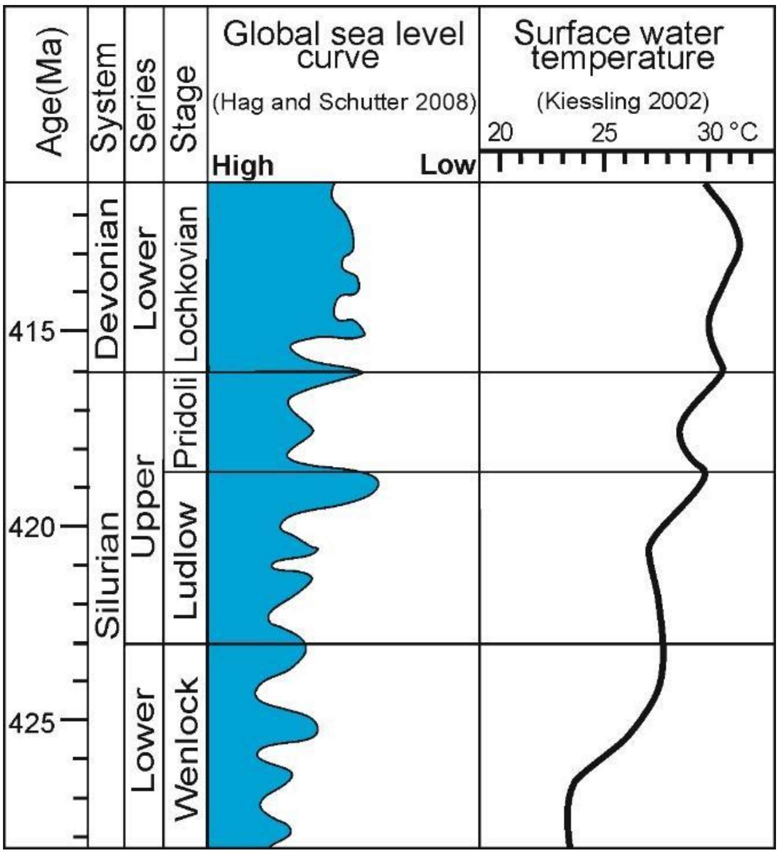

Fig. 10. Global sea level curve and surface water paleotemperatures for the Silurian and Lochkovian time of the Lower Devonian.

Carbonate-clay deposits of the Lochkovian stage of the Lower Devonian of the Volyn-Podillyan Plate, as shown by single measurements, have a low TOC content, which is 0.2 wt% [Radkovets et al, 2017b]. However, studies of sediments of this age of the Lublin Depression, accumulated in the same sedimentary basin and representing the same facies, showed the TOC content in rocks up to 1.8 wt%. This suggests the possibility of local participation of these rocks together with the Silurian black shale deposits in the processes of generation of hydrocarbons, which accumulated in the overlying terrigenous variegated strata of the Pragian-Emsian stages of the Lower Devonian. In particular, such a productive horizon was found at Lokachi field [Krupsky et al, 2014].

Originality

The applied complex of lithological, geochemical, geological-geophysical and paleoceanographic investigations allowed studying the dynamics of the sedimentary basin in the Silurian-Early Devonian with the assessment of the possibility of participation of these strata in the generation of oil and gas hydrocarbons.

Practical significance

The obtained results show that the carbonate-clay complex of sedimentary rocks of the Silurian and Lower Devonian (Lochkovian) of the studied region can be considered as a separate petroleum system, including source rocks, reservoir rocks and possible conventional and unconventional oil and gas accumulations.

Conclusions

The formation of the Silurian-Lower Devonian (Lochkovian) sedimentary succession was the result of a complex of geodynamic, sedimentary and paleoclimatic events that took place on the southern continental margin of Baltica. The studied carbonate-clay sequence represents a single sedimentary cycle, which contains thick black shale strata and biogenic carbonate layers. The change of the geodynamic regime in the Silurian from the stage of post-rift thermal immersion to the collision led to the formation of a new sedimentary basin, which existed from the beginning of the Wenlock time of Silurian to Lochkovian time of Early Devonian and represented a flexural foredeep.

In the Silurian in the proximal part of the basin an intensive development of benthic organisms and the formation of reef structures took place. In the distal part of the basin, against the background of intensive carbonate accumulation, there was an influx of clay material and the formation of clay-carbonate muds. As a result of the global greenhouse effect in the deeper part of the basin developed zone of oxygen minimum. Clay-carbonate muds were enriched with dispersed organic matter, forming the thick black shale strata. Carbonate biogenic sedimentation continued throughout the entire basin also in the Lower Devonian (Lochkovian) but in the distal part there was no intensive influx of clay material, so the deposits of this age are made up of exclusively biodetrital and dolomitized limestones interbedded with marlstones.

The carbonate-clay complex of the Silurian and Lower Devonian (Lochkovian) sedimentary rocks of the studied region can be considered as a separate petroleum system, which comprises source rocks, reservoir rocks and possible conventional and unconventional oil and gas accumulations. To date, the commercial viability of developing unconventional hydrocarbons in the Silurian sequence has not been confirmed due to the low average TOC content in rocks. However, taking into account a significant thickness of this black shale sequence, the Silurian black shale strata still can be considered as prospective for shale oil in the northeastern part of the study region, where Silurian deposits lie at shallow depths and therefore have reached less thermal maturity and are prospective for shale gas in the more subsided part of the Platform. The carbonate-clay deposits of the Lochkovian stage of the Lower Devonian could locally participate together with the Silurian black shale deposits in generation of hydrocarbons that accumulated in the overlying terrigenous variegated strata of the Pragian-Emsian stages of the Lower Devonian.

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ДИНАМІКА СЕДИМЕНТАЦІЇ В МЕЖАХ ПІВДЕННО-ЗАХІДНОГО СХИЛУ СХІДНОЄВРОПЕЙСЬКОЇ ПЛАТФОРМИ У СИЛУРІ – РАННЬОМУ ДЕВОНІ

Мета роботи – вивчення карбонатно-глинистого комплексу осадових порід силуру та нижнього девону (лохківський ярус) південно-західного схилу Східноєвропейської платформи, формування якого стало результатом єдиного циклу геодинамічних та седиментаційних подій у літологічному літописі південної континентальної окраїни Балтики. Методика передбачає кореляцію геофізичних досліджень свердловин, літологічне та геохімічне вивчення кернового матеріалу та петрографічний аналіз порід. Одержані результати використано для встановлення закономірностей зміни речовинного складу досліджених нашарувань у часі й просторі з метою з'ясування динаміки розвитку басейну континентальної окраїни південно-західного схилу Східноєвропейської платформи у силурі-ранньому девоні. **Результати.** Встановлено, що формування карбонатно-глинистої товщі являє собою єдиний седиментаційний цикл і стало результатом комплексу геодинамічних, седиментаційних та палеокліматичних подій, які відбувалися на південній континентальній окраїні Балтики. Для силурійського часу був характерний інтенсивний розвиток бентосних організмів та формування рифових побудов у проксимальній частині басейну і глинисто-карбонатних мулів, збагачених розсіяною органічною речовиною, в його дистальній частині. У ранньому девоні карбонатна біогенна седиментація продовжувалась у межах всього басейну. Максимальний вміст карбонатів (80–98 %) фіксує існування в седиментаційному літописі басейну рифових побудов. Нижчі значення вмісту карбонатів характерні для мергелів (40–55 %) та біодетритових вапняків (56–75 %), які становлять основну частину розрізу силуру. У розрізі локхівського ярусу девону рифові побудови відсутні, а вміст карбонату кальцію у породах змінюється від 45 до 83 %. Вміст $CaCO_3$ в аргілітах та вапнистих аргілітах силуру – від 5 до 15 %. **Наукова новизна.** Застосований комплекс літологічних, геохімічних, геолого-геофізичних та палеогеографічних досліджень дав змогу вивчити динаміку розвитку дослідженого осадового басейну у силурі-ранньому девоні з оцінкою можливості участі цих нашарувань у генерації нафтових і газових вуглеводнів. **Практична значущість.** Одержані результати показують, що карбонатно-глинистий комплекс осадових порід силуру та нижнього девону (локхівський ярус) дослідженого регіону може розглядатися, як окрема нафтогазова система, що містить материнські породи, породи-колектори і можливі традиційні й нетрадиційні поклади нафти і газу.

Ключові слова: Україна; силур; девон; шельф Балтики; глинисто-карбонатні нашарування; породи, збагачені органічною речовиною; генерація нафти і газу.

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