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The Silurian of southwestern margin of the East European Platform (Ukraine, Moldova and Romania): lithofacies and palaeoenvironments

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Silurian strata, stretching along the western margin of the East European Platform from the Baltic to the Black Sea, represent a potential target for both conventional and unconventional hydrocarbon exploration. Distribution of the black shale facies, prospective for shale gas, and the reef facies, prospective for oil, has been studied in respect of palaeoenvironments. The Silurian sequence has been investigated in the territory of Ukraine (Volyn-Podillyan Plate, Dobrogean Foredeep) and correlated with the data on Moldova and Romania (Moldovian Platform). The occurrence of Silurian strata, their thickness, and petrographic and lithological characteristics allowed reconstructing the distribution of open-shelf, reef and lagoonal facies. The reef facies migrated during the Wenlock–Middle Pridoli, shifting towards the open sea and back towards the shore, and therefore has been termed a migrating reef facies. Correspondingly, the boundary between the open-shelf and reef facies was shifting. The facies distribution was controlled by the transgressive-regressive cycles, which caused the fluctuations of the shelf water depth in different time intervals of the Silurian. The shelf water depth of about 100 m, where the top of the oxygen-minimum layer impinged on the sea bottom, was the boundary between the open-shelf facies, represented by organic-rich sediments, and the reef buildups.

Key words: East European Platform, Silurian, lithofacies, reef, Baltica shelf, palaeoenvironments.

INTRODUCTION

Silurian sequence of the East European Platform currently attracts much interest, being one of the main European potential targets for shale gas exploration. It covers a great area, stretching from the Baltic to the Black Sea. The Silurian within the Ukrainian territory, which is the principal subject of this study, is the continuation of the Polish part of the sedimentary basin, whose shale gas potential has been widely discussed (e.g., Poprawa, 2010; Sachsenhofer and Koltun, 2011). Facies distribution within the Silurian sequence of the East European Platform is of great importance for oil and gas prospecting. Location of the reef and open-shelf facies in the study area allows delineating the occurrence of two separate potential plays. The external border of the reef, which, as it is shown below, was migrating during the Silurian, marked the occurrence of organic-rich facies of graptolitic shales. The latter occupied the extensive area in the deeper part of the basin. These shales are prospective for shale gas all over the territory of their occurrence (Poprawa, 2010; Sachsenhofer and Koltun, 2012). Therefore, it is important to understand the nature and to delineate the boundary between these facies. The limestones, forming the reefal buildups, are the potential oil-reservoir rocks. Numerous oil shows have been observed in boreholes at Lokachi, Gorokhiv and Oglyadiv prospects within the Ukrainian part of the East European Platform (Rizun et al., 2007).

Investigations of the Silurian strata in Ukraine were based on the analysis of data from existing boreholes, in particular well-log data, core samples, and thin sections. The content of $CaCO_3$ in rocks was calculated from chemical analyses performed at the Institute of Geology and Geochemistry of Combustible Minerals. Thin sections were examined under a polarizing microscope. Well-log data along with the data of analytical and petrographic analyses of rocks were used for lithostratigraphical correlation of the examined sections. Lithological sections allowed composing a map of Silurian occurrence with isopachs and facies distribution. Correlation of the data on western Ukraine with adjacent areas of Silurian occurrence, involving those from Moldova and Romania (Lodan, 1999; Olaru et al., 2006; Olaru and Ţabără, 2011; Tari et al., 2014) as well as Poland, Lithuania, Latvia and Estonia (Nestor and Einasto, 1977; Einasto et al., 1986; Lazauskiene, 2003; Porębska et al., 2004; Zdanaviciute and Lazauskiene, 2007; Verniers et al., 2008; Poprawa and Kiersnowski, 2008; Skompski et al., 2008; Łuczyński et al., 2009; Poprawa, 2010; Kaljo et al., 2012; Tari et al., 2012; Podhalańska, 2013; Porębski et al., 2013; Jarochowska and Kozłowski, 2014) allowed elucidating the occurrence of these strata, their thickness and petrographic composition over the vast territory within the southwestern margin of the East European Platform, and obtaining the integral characteristics of depositional environments in the Silurian of the study area. This was a base for palaeoceanographic reconstruction and elucidation of different types of sediments and facies distribution within the southern palaeoshelf of Baltica.

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The objective of this study is to show the occurrence of the main Silurian lithofacies in the study area, describe the palaeoenvironments and the nature of these deposits prospective for oil and gas, which explain the regularities of their distribution both in time and space.

GEOLOGICAL BACKGROUND

The study area is the southwestern margin of the East European Platform. It includes the following tectonic units: Volyn-Podillyan Plate, Moldovian Platform and Dobrogean Foredeep (Fig. 1). The sedimentary cover of this territory rests on an Archean-Proterozoic basement made up of magmatic and metamorphic rocks. The basement crops out at the surface within the Ukrainian Shield and monoclinally dips westward towards the Teisseyre-Tornquist Zone. The maximum thickness of sedimentary cover reaches 10 km in the Volyn-Podillyan Plate and 7 km in the Dobrogean Foredeep (Kruglov and Tsypko, 1988; Chebanenko et al., 1990). The sedimentary succession is represented by Neo-Proterozoic (Riphean and Vendian strata), Paleozoic (Cambrian, Ordovician, Silurian, Devonian and Carboniferous deposits in the Volyn-Podillyan Plate, Moldovian Platform and Dobrogean Foredeep; Permian deposits in the Dobrogean Foredeep), Mesozoic (Triassic deposits in the Dobrogean Foredeep, Jurassic and Cretaceous deposits in the Volyn-Podillyan Plate, Moldovian Platform and Dobrogean Foredeep) and Cenozoic (Paleogene, Neogene and Quaternary deposits).

At the beginning of the Silurian, the entire southwestern margin of the East European Platform was uplifted and underwent intense denudation. As a result, the Silurian deposits rest upon the eroded surface made up of Ordovician, Cambrian and Vendian rocks (Chebanenko et al., 1990; Gerasimov et al., 2006).

Silurian strata stretch along the southwestern margin of the East European Platform from the Baltic to the Black Sea. Thickness of the Silurian regularly increases from the Ukrainian Shield westwards towards the Teisseyre-Tornquist Zone, reaching the maximum values of over 1400 m. Cross-sections I–I1 (Fig. 2) and II–II1 (Fig. 3) (see Fig. 1 for location) show the entire sedimentary cover of the study area, in particular the occurrence of the Silurian.

Within the southwestern margin of the East European Platform the Silurian system is represented by the Lower and Upper Silurian. It was established that the Lower Silurian platform strata of Poland and Lithuania comprise Llandovery and Wenlock (Verniers et al., 2008). As to completeness of the Lower Silurian stratigraphic succession at the territory of Ukraine there are different opinions. Krandiyevsky et al. (1968), Tsegelnyuk et al. (1983) and Drygant (2000) stated that the Lower Silurian is represented here with both Llandovery and Wenlock. Nikiforova et al. (1972) expressed doubts as to the presence of Llandovery in the Silurian sequence and assumed that these Lower Silurian strata should be considered as Wenlock. Rizun et al. (2007) concluded that within the territory of Ukraine the Lower Silurian platform strata are represented only by Wenlock (Kytayhorod and Bagovytsya stages). Upper Silurian covers the entire time range and includes Malynivtsy stage of Ludlow and Skala stage of Pridoli (Fig. 4).

LITHOFACIES OF THE SILURIAN

Silurian strata of the study area consist of carbonate, clay-carbonate and clay deposits. In the Volyn-Podillyan Plate, they are subdivided into three facies: lagoonal, reef, and open shelf, occurring west of the Ukrainian Shield towards the Teisseyre-Tornquist Zone. The previous studies (Chyzh, 1977; Yushkevych et al., 1982; Drygant, 2000; Rizun et al., 2007; Kurovets et al., 2012) showed the boundaries of the reef facies in the Volyn-Podillyan Plate in the Wenlock (Bagovytsya stage), Ludlow (Malynivtsi stage) and Pridoli (Skala stage) in a different way.

The Silurian lithofacies map (Fig. 5) was constructed on the basis of our investigations from the Volyn-Podillyan Plate and Dobrogean Foredeep using the information contained in the above mentioned publications, which were compared with the data from Romania and Moldova (Kruglov and Tsypko, 1988; Lodan, 1999; Olaru et al., 2006; Olaru and Ţabără, 2011; Tari et al., 2014). The map shows the occurrence of Silurian strata, their thickness and facies within the area from the border of Ukraine with Poland and Belarus to the Black Sea. Silurian sediments continuously cover the entire area, apart from separating bands where they are lacking. At monoclinal dipping, the thickness of Silurian strata increases gradually up to 700 m and then more sharply from 800 to over 1400 m. The growth of thickness shows a clear dependence on the Silurian facies zoning. The quick thickness increase (800–1400 m) correlates well with the deeper-water open-shelf facies, while the thinner sequence reflects the shallow water reef and lagoonal facies.

PETROGRAPHIC CHARACTERISTICS

Lagoonal facies is represented (Nikiforova et al., 1972) by marlstones (39–60% of biodetrital calcite, 34–48% of clay material and 4–11% of dolomite), biodetrital dolomitized limestones (50–60% of calcite, 25–40% of dolomite and 10–15% of insoluble residue, mostly clay material) and gypsum and anhydrite-bearing dolomites, which occur in the eastern littoral part of the area. Gypsum and anhydrite in dolomites occur as veins and streaks of variable thickness (from 1 mm to 1 m). Fossils are lacking. Westward, gypsum- and anhydrite-bearing dolomites pass laterally into dolomites, marls and dolomitized biodetrital limestones. Dolomites contain 69–75% of dolomite and 10–25% of clay material, admixture of dispersed calcite and small amount of silt (Fig. 6). The rock comprises the clay-carbonate matrix. Dolomite crystals (0.1–0.5 mm) are usually rhombohedral in shape. Small solitary calcite crystals are observed too.

Rhombohedral dolomite grains in clay-carbonate matrix of dolomite from the Sarata-6 borehole, depth interval 4467–4470 m.

Reef facies, which represents the reef buildups between the two facies zones – lagoonal and open sea, is made up of limestones (biolithites according to Folk, 1962) as well as by biodetrital limestones and dolomites. Biolithites form the reef core surrounded from both sides by biodetrital limestones and dolomites. Biolithites are light grey, cream-grey and grey and consist of corals, crinoids, stromatoporoids and algae along with ostracods, gastropods and brachiopods. Chemical analysis shows that the $CaCO_3$ content in the limestones mainly ranges between 80 and 90%, reaching 98%. Biodetrital limestones are represented by rounded and non-rounded biolithite debris with clay matrix. Biodetrital dolomites are fine-grained, macro- and micro-cavernous, fractured, completely recrystallized, full of debris of corals, crinoids, stromatoporoids, and contain stylolitic sutures.

Open shelf facies is represented by clay-carbonate-siliceous rocks often enriched with dispersed organic matter. Argillites are dark grey to black, unevenly limy, pyritized, and with solitary graptolites. Marlstones are grey to black, clayey, mainly detrital and granular. Fabric is cryptocrystalline, con-

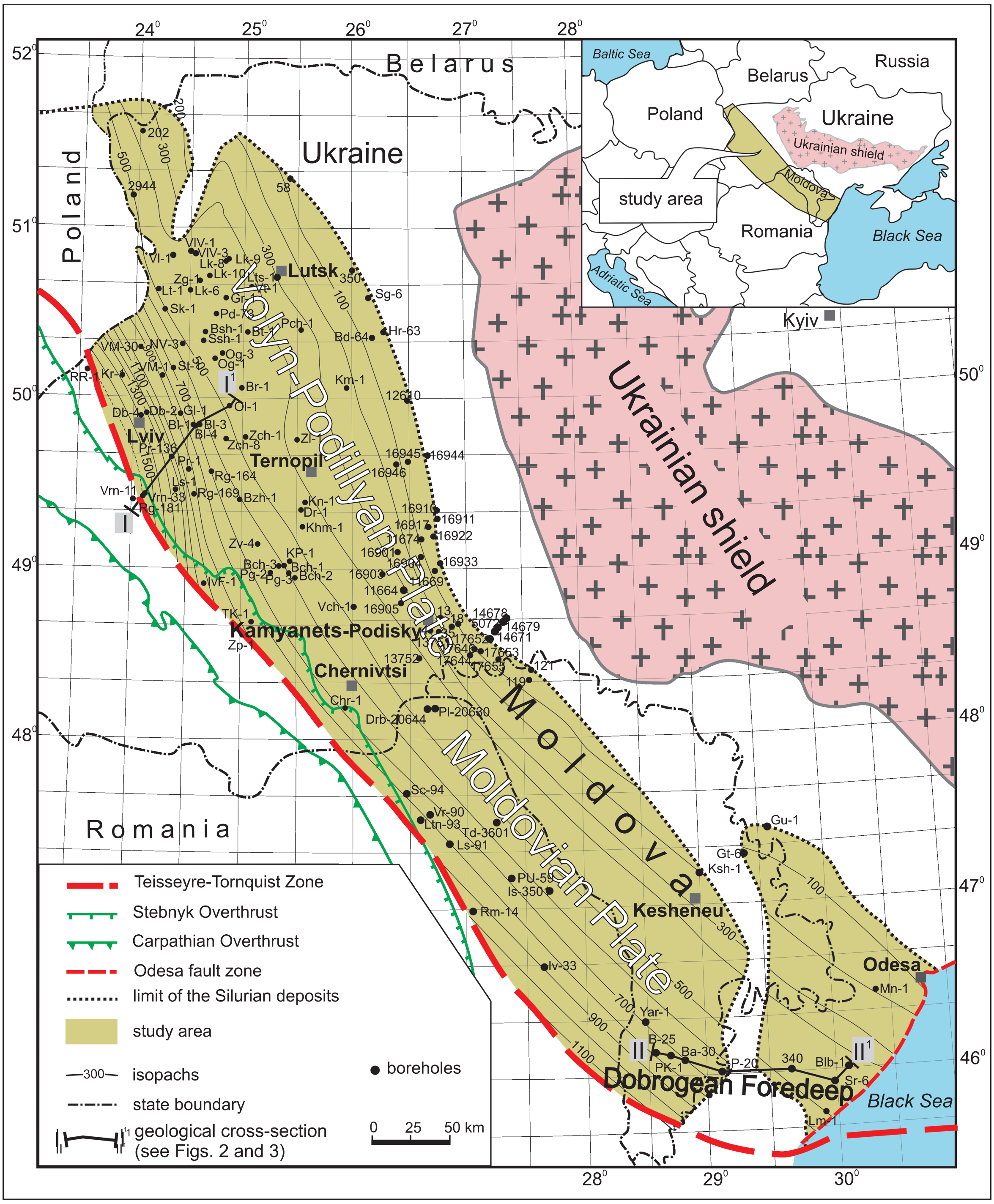


Fig. 1. Location map of the general distribution and thickness of the Silurian in the southwestern margin of the East European Platform

Boreholes: B – Baymaklia, Ba – Baurchi, Bch – Buchach, Bd – Brydok, Bl – Baluchyn, Blb – Balabanivka, 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, PK – Kangaz, 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 – Verkhniakivtsi, Vl – Volodymyrivka, VlV – Volodymyr-Volynsky, VM – Velyki Mosty, Vr – Vorona, Vt – Voyutyn, Yar – Yargara, Zch – Zolochiv, Zg – Zagoriv, Zl – Zalozhtsi, Zp – Zagaypil, Zv – Zavadivka

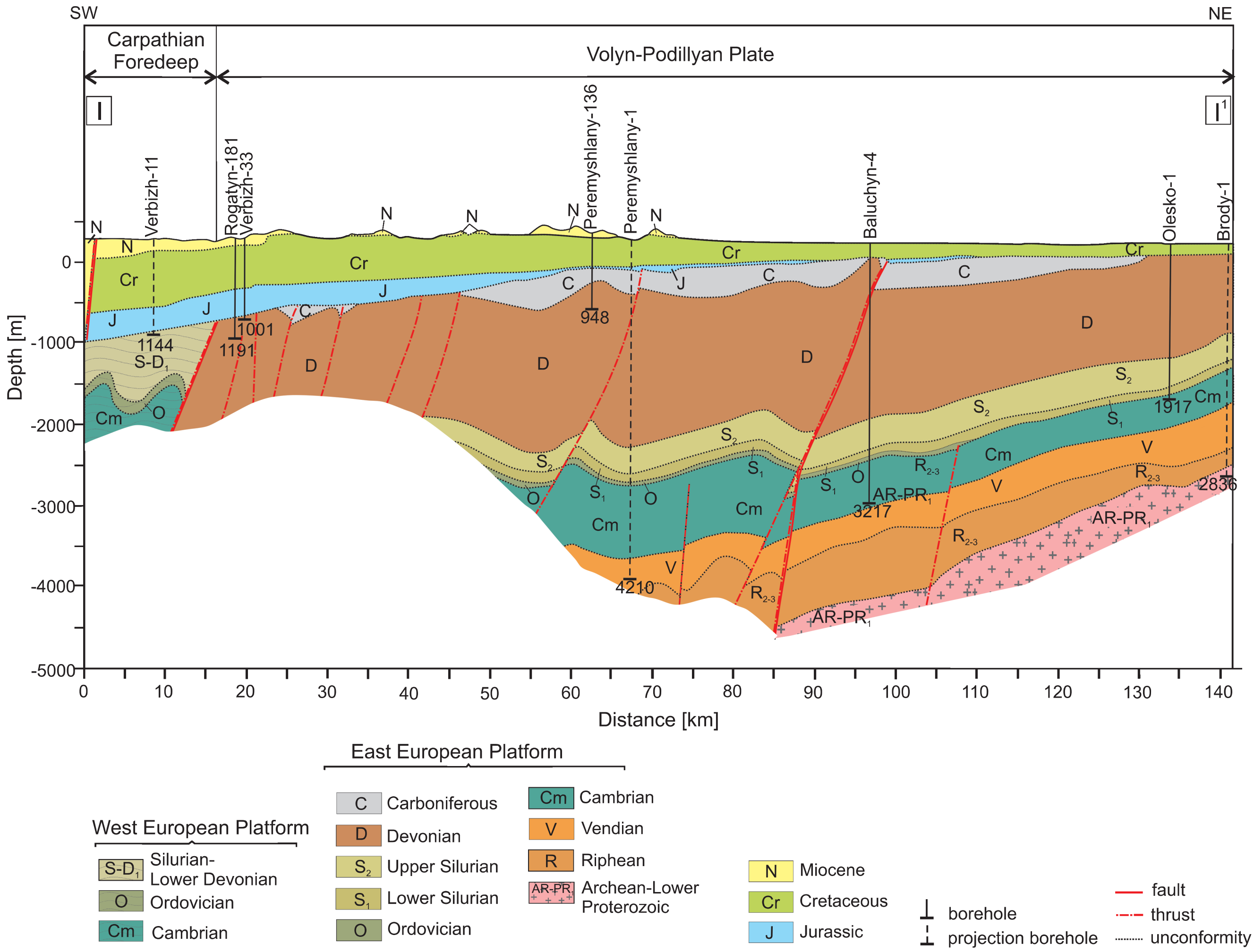


Fig. 2. Geological cross-section I–I[1] through the Carpathian Foredeep and Volyn-Podillyan Plate (modified after Vashchenko et al., 2007)

See Figure 1 for location

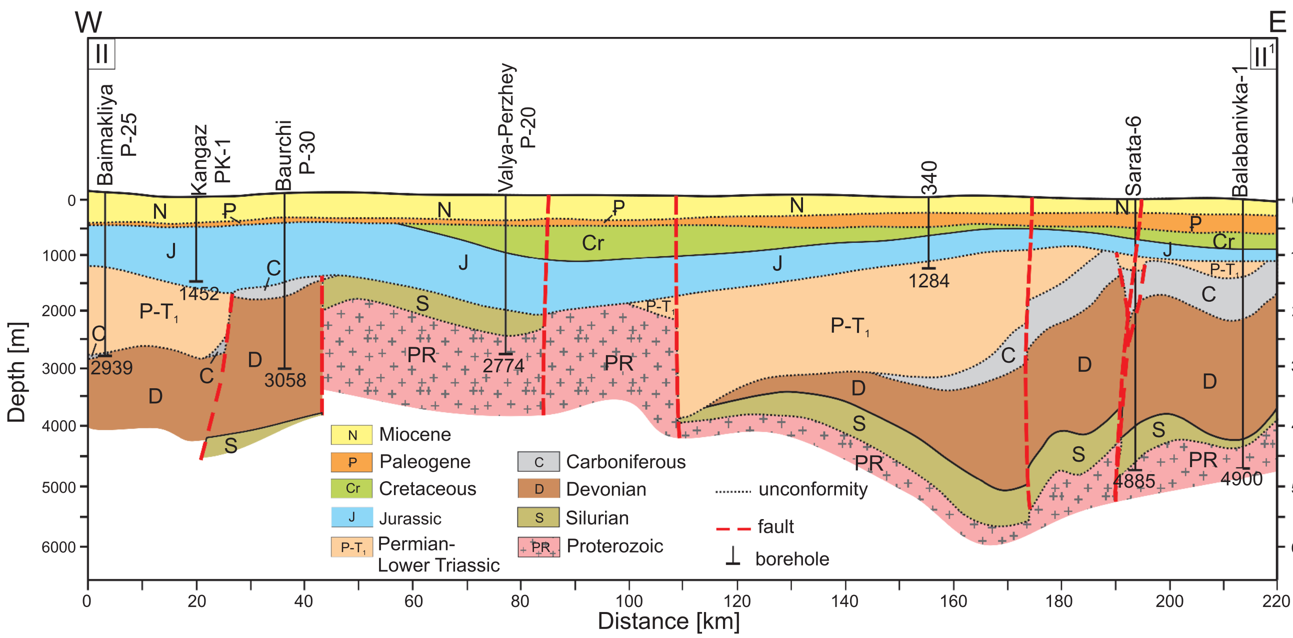


Fig. 3. Geological cross-section II–II[1] through the Dobrogean Foredeep (modified after Gnidets et al., 2007)

See Figure 1 for location

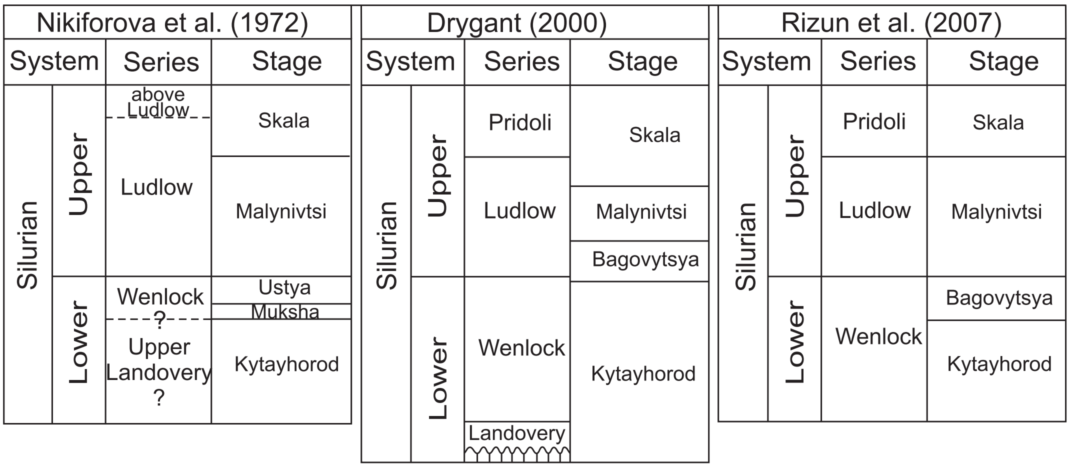


Fig. 4. Stratigraphic scheme of the Silurian deposits of the Volyn-Podillyan Plate (modified after Nikiforova et al., 1972; Drygant, 2000; Rizun et al., 2007)

glomerate-like and clumpy (Kurovets et al., 2010). The thickness of argillites significantly exceeds the thickness of coeval clay-carbonate rocks.

It has been established that the reef facies was changing its extent in various time intervals of the Silurian (Wenlock–Middle Pridoli), moving towards the continent or towards the open sea depending on transgressive-regressive cycles. Therefore, we term it as a migrating reef facies. Figure 6 shows the change of reef facies extent in time. In the Wenlock (Bagovytsya stage) the reef facies occupied a small area, in the Ludlow (Malynivtsi stage) the extent of this facies reached its maximum, while in the Pridoli (Skala stage) the area of the reef facies somewhat reduced comparing to the Ludlow. Correspondingly, the open shelf facies in these time intervals changed its external boundary. It occupied the maximum area in the Wenlock (Bagovytsya stage), the minimum one in the Ludlow (Malynivtsi stage) and an intermediate in the Pridoli (Skala stage).

Argillites are calcareous (carbonate content 10–40%), siliceous (silica content 10–20%), locally silty (up to 15–35% of silt), pyritized, laminated, dense and hard. The rocks are black in colour due to dispersed organic matter. Total organic carbon content usually ranges from 0.2 to 1%, locally exceeding 2%. Great thickness and type II kerogen allow considering these rocks to be a potential target for shale gas exploration. Figure 7A and B show the photomicrographs of limy argillite. Matrix of the rock is made up of fine mica scales and sub-parallel streaks of organic matter. Small amount of silt-size quartz grains, carbonates (calcite, dolomite) as well as muscovite scales is observed. Locally, there occur lenticular accumulations of silt-size quartz grains and relicts of calcareous bioclasts.

Marlstones (Fig. 7C, D) are dark grey, clayey, pyritized and dolomitized. The carbonate content is 43–54%. The rock is finely and micro-laminated due to distribution of small pyrite grains, lenticular accumulations of organic matter and problematic calcareous bioclast debris. Marlstones consist of dispersed fine-scaly clay-carbonate particles, which form the matrix. Admixture of 0.01–0.08 mm size quartz grains is present in small amount. Abundant fine pyrite, often forming wavy microstreaks, is observed. Problematic calcareous bioclast debris, 0.1–0.8 mm, occasionally >1 mm in size, and possibly strongly recrystallised bioclasts are locally present.

Throughout the Silurian sequence there are numerous 0.05–3.0 m thick intercalations of K-bentonites (tuffites) (Fig. 8). 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-logs analysis and correlation with the basic section of Podillya. The SEM, X-ray and thermal analyses (Nikiforova et al., 1972) show that the clay material of these rocks is represented by glauconite-type hydromica, and their fibers envelop the relicts of volcanic ash particles. Along with the clay minerals, occurs mainly pyroclastic material represented by idiomorphic quartz grains, replaced by feldspars and ore minerals, and numerous biotite scales with diffused edges. K-bentonites are typical of the Upper Silurian. In particular, they are most abundant in the Malynivtsi stage (Ludlow), less in the Skala stage (Pridoli). In the Lower Silurian (Wenlock) two K-bentonite horizons are identified in the Peremyshlyany-1 and Lyman-1 boreholes, and only one in other boreholes.

Huff et al. (2000) have interpreted the Ludlow and Pridoli K-bentonites of the Dnister Basin in Podillya as representing active volcanic arcs along the margin of the Rheic Ocean. Histon et al. (2007) showed that the ancient explosive volcanism in the form of altered airfall volcanic ash beds (K-bentonites) has the global occurrence in the Silurian succession, being reported in Europe, North America and Argentina. K-bentonite beds have been recognized in the Ordovician-Silurian transition (Ashgill–Early Llandovery) in the Yangtze Block, South China (Su et al., 2004).

DISTRIBUTION OF LITHOFACIES

Figure 8 shows the location of Silurian lithological sections, which give the best insight into the lithological features of these strata and spatial distribution of lithofacies. Separation of stages at lithological sections is based on the analysis of well-log data, K-bentonite beds occurrence, and petrographic investigations. The Podillya section (Nikiforova et al., 1972) was used for correlation of these boreholes, as it was constructed on the basis of investigation of 40 Silurian outcrops along the Dnister River and its tributaries. The data on these outcrops are especially valuable because presently most of them are submerged as a result of the Dnister hydroelectric power station construction 40 years ago.

Among the existing schemes of sea level reconstruction for the Silurian (e.g., Johnson, 1996, 2010; Azmy et al., 1998; Haq and Schutter, 2008; Olaru and Ţabără, 2011; Fig. 9), we have

Fig. 5. Lithofacies map of the Silurian deposits in the southwestern margin of the East European Platform

used the regional scheme by Olaru and Ţabără (2011) as the most appropriate one, as it has been constructed for the Volyn--Podillyan Plate. Lithological sections of the Volyn-Podillyan Plate and Dobrogean Foredeep (Fig. 8) reflect the influence of transgressive-regressive cycles on formation of petrographic composition of rocks. Lithological sections of the Krekhiv-1, Lishchyny -1 and Peremyshlyany-1 boreholes (Volyn-Podillyan Plate) consist of clay and clay-carbonate organic-rich rocks typical for open shelf facies. From the Krekhiv-1 borehole westwards to Peremyshlyany-1, some changes in lithology are observed. Along with argillites and limy argillites, more marlstones and clayey limestones appear, showing the transition from

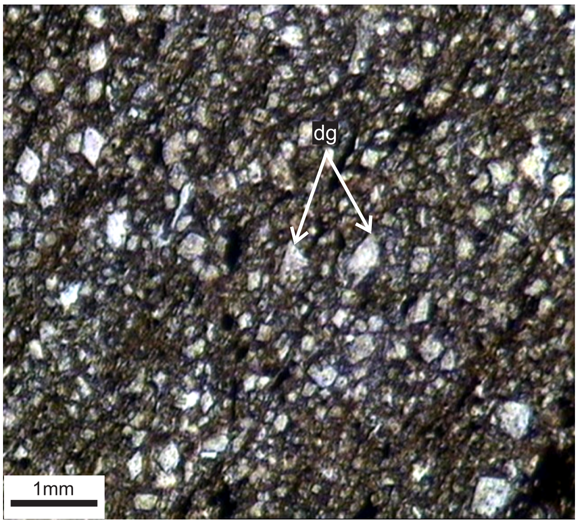


Fig. 6. Photomicrograph of a Silurian rock of lagoonal facies (Dobrogean Foredeep)

dg – dolomite grains

more deep-water clay to shallower carbonate facies. The sections of Baluchyn-1, Buchach-3, Khmelivka-1 and Zalozhtsi-1 boreholes, and the key outcrop sections of Podillya are made up of clay-carbonate and carbonate rocks (marlstones, dolomites, biodetrital limestones). All the studied sections include thick (up to 60 m) reef limestones of various age (Wenlock, Ludlow, Pridoli). Lithological observations and well-log data on Silurian strata in a number of boreholes from the Dobrogean Foredeep indicate similar clay-carbonate and carbonate rocks, in particular reef limestones containing up to 98% $CaCO_3$ (Fig. 10). Silurian lithological sections in the Lyman-1 and Sarata-6 boreholes, typical of the Dobrogean Foredeep, show their good correlation with the Zalozhtsi-1 borehole and the base outcrop sections in the Volyn-Podillyan Plate. Analysis of the lithological sections from the Dobrogean Foredeep shows that the spatial and temporal extent of all types of Silurian rocks perfectly correlates with the rocks from the Volyn-Podillyan Plate.

The formation of Silurian reefs in the southern shelf of Baltica started in the Wenlock (Nikiforova et al., 1972; Mõtusa and Grytsenko, 2007; Verniers et al., 2008; Olaru and Țabără, 2011). Figure 8 shows that a significant transgression took place during the Wenlock (Bagovytsya stage), which caused the shift of coastline further onto the continent towards the Ukrainian Shield. This palaeoceanographic event correlates well with the trend of reef construction. The Bagovytsya stage reef limestones are observed close to the palaeoshore (Fig. 8) in the basic section of Podillya. In the Ludlow, a significant regression took place. Lithological sections between the Baluchyn-1 and Zalozhtsi-1 boreholes (Fig. 8) show thick reef limestones (25–60 m) whose seaward boundary was located at the maximum distance from the shore. The Ludlow and Pridoli reef limestones of significant thickness (25–50 m) are also encountered in the Lyman-1 and Sarata-6 boreholes in the Dobrogean Foredeep (Fig. 8). A considerable transgression with short-term regression cycles took place in the study area in the Pridoli. Lithological sections (Fig. 8) of the Buchach-1, Khmelivka-1

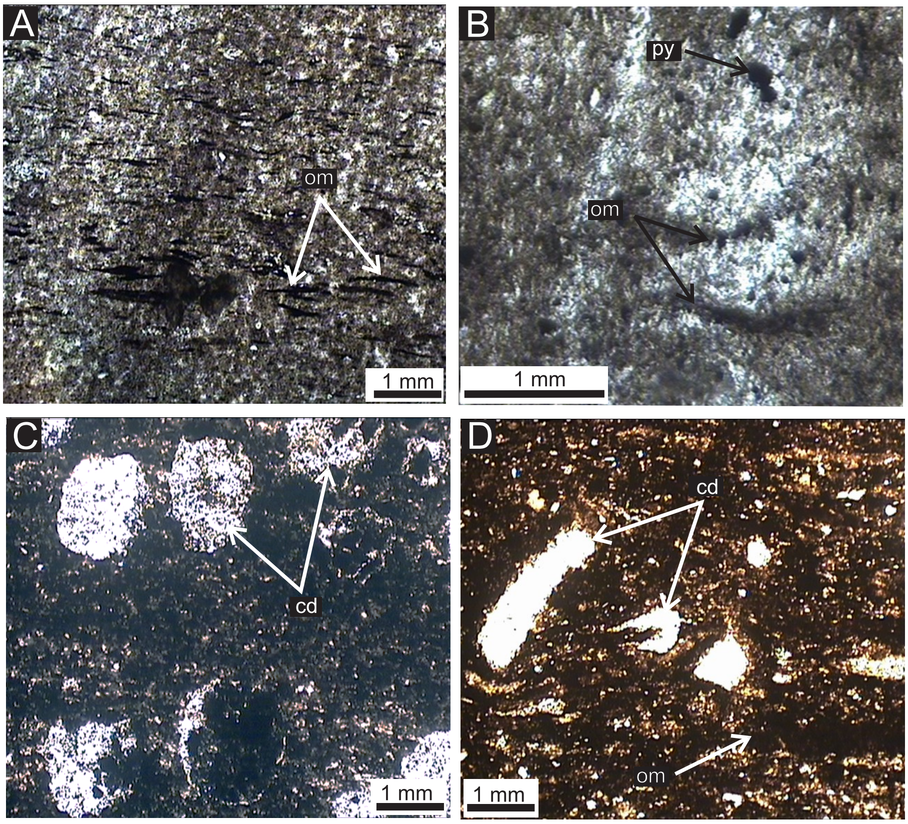


Fig. 7. Photomicrographs of a Silurian rock of open shelf facies (Volyn-Podillyan Plate)

A, **B** – limy argillite with sub-parallel streaks of organic matter (om) and small pyrite grains (py) from the Krekhiv-1 borehole, depth interval 4 146–4 151 m; **C**, **D** – dark grey marlstones, clayey, pyritized, dolomitized, with organic matter (om) and problematic bioclasts (cd)

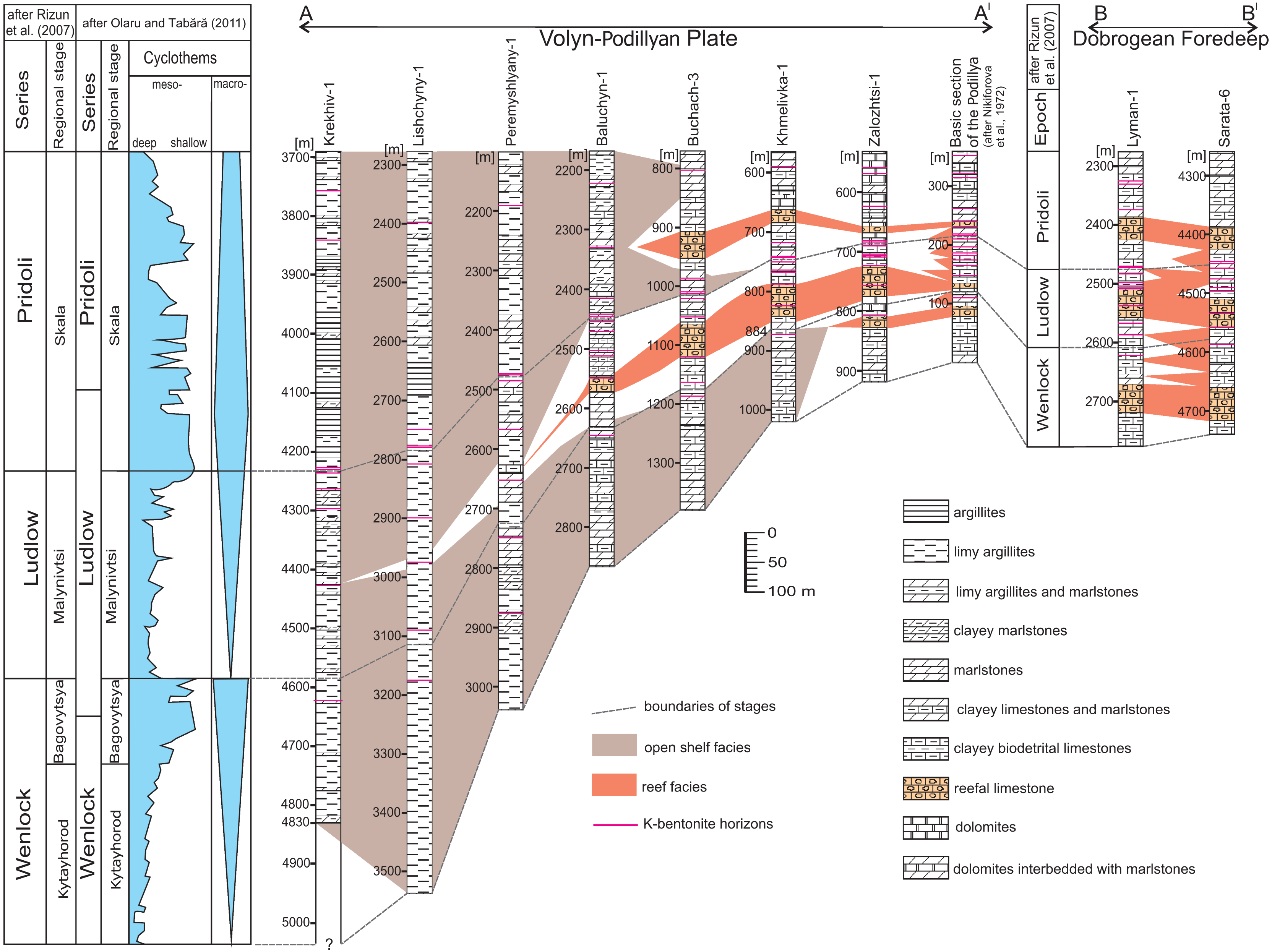


Fig. 8. Lithological sections through the Volyn-Podillian Plate (A–A[1]) and Dobrogean Foredeep (B–B[1]) (see Fig. 5 for location) and their correlation with the regional scheme (modified after Olaru and Țabără, 2011) of Silurian transgressive-regressive cycles

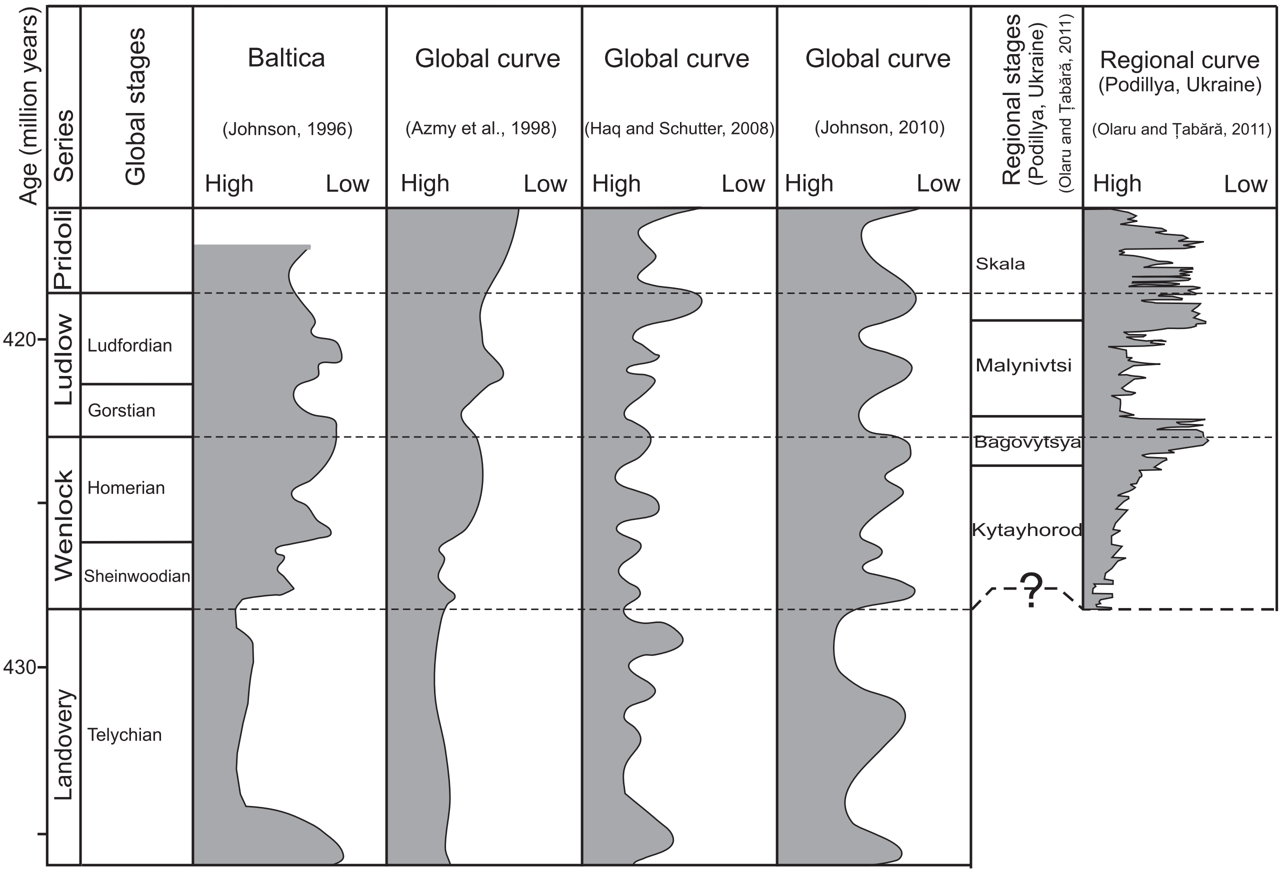


Fig. 9. Compilation of sea level reconstructions for the Silurian

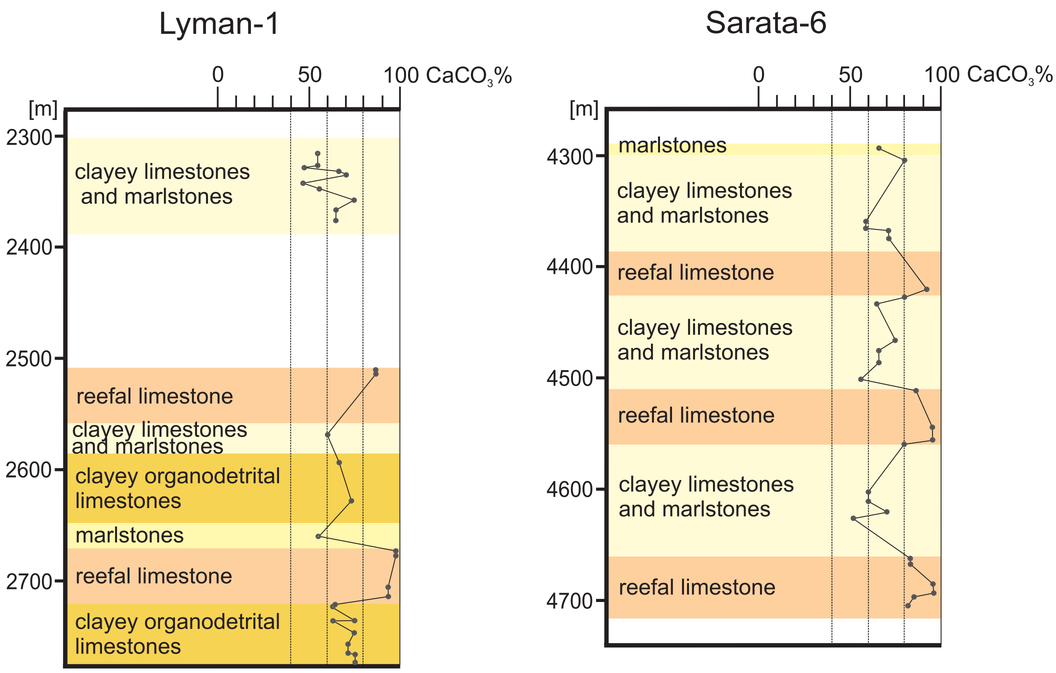


Fig. 10. $CaCO_3$ content in the Silurian sequence of the Lyman-1 and Sarata-6 boreholes (Dobrogean Foredeep)

and Zalozhtsi-1 boreholes show the occurrence of reef limestones in the Lower and Middle Pridolian strata, the extent of which correlates with short-term regression cycles. There are no reef limestones in the Upper Pridoli strata, which reflects the cessation of reef building (cf. Verniers et al., 2008).

Based on the typical lithological sections (Fig. 8) and sequences in a number of boreholes from the Volyn-Podillyan Plate and Dobrogean Foredeep as well as from Moldova and Romania (Lodan, 1999; Olaru et al., 2006; Olaru and Ţabără, 2011), it can be concluded that the reef limestones developed from the Wenlock to Middle Pridoli. This stratigraphic interval is a time of continual reef formation. As to the spatial extent of reef constructions, their limits during the above-mentioned time interval were shifting, depending on the shoreline fluctuations caused by transgressive-regressive cycles. Consequently, a migrating reef facies was formed during the Silurian (Wenlock–Middle Pridoli).

FACIES PATTERN IN RELATION TO SILURIAN OCEANOGRAPHY AND SEA LEVEL CHANGES

GLOBAL AND REGIONAL EVENTS

At the end of Ordovician time, a global regression took place due to a significant fall of temperature and glaciation in the southern hemisphere, when the ice cap covered the central part of Gondwana. As a result, the southern shelf of the Baltica sedimentary basin (southwestern margin of the East European Platform) emerged above the sea level (Verniers et al., 2008) and the area underwent intense erosion.

As it was shown by Royer (2006) and Verniers et al. (2008), the Silurian was an environmentally and faunally stable period in the Earth history – a greenhouse period with a moderate latitudinal climate gradient and impoverished marine faunas slowly recovering from the end-Ordovician mass extinction. However, according to Bickert et al. (1997), Page et al. (2007), Cramer and Saltzman (2007) and Calner (2008), the Silurian period was a time interval of repeated global changes. Marine biodiversity crises took place, affecting e.g., graptolites, conodonts, chitinozoans, acritarchs, brachiopods and reefs, and these turnovers were closely linked to abrupt and significant changes in oceanography and the global carbon cycle. Based on observed temporal changes in lithology and conodont faunas in the carbonate platform rocks of Gotland, three main events – the Early Silurian Ireviken Event, the Middle Silurian Mulde Event, and the Late Silurian Lau Event – have been identified (Jeppsson, 1990) with regard to biodiversity changes and relation to carbon and oxygen stable isotope evolution and sea level change. For the sedimentary succession of Podillya, Ukraine, temporal changes in isotope composition ($\delta^{13}C$, $\delta^{18}O$) and faunas have been established (Racki et al., 2012), which are related to the regional carbonate crisis and cooling episodes, corresponding to the Ireviken and Klonk events.

A significant transgression started at the beginning of the Silurian (Early Llandovery) advancing from the west and northwest (the present-day territory of Estonia, Latvia and Lithuania). A sedimentary basin developed, in which organic-rich muds accumulated (Nestor and Einasto, 1977; Einasto et al., 1986). Further transgression eastwards (Late Llandovery–Early Wenlock) resulted in submerging of significant territories of the western margin of Baltica and the sedimentary basin had reached the shape and size, which it had during the Ordovician (Verniers et al., 2008). The Silurian southern shelf basin of Baltica was located in low southern latitudes (15–20°S) (Fig. 11A; Torsvik et al., 1996). In the Early Wenlock, a stable sedimentary basin was formed and the facies zoning was ultimately established there from the shoreline towards the shelf break: lagoonal, reef and open-shelf facies.

Figure 11B shows the model of southern shelf of Baltica for mid-Silurian times. Location of the three above-mentioned facies is indicated in the map for Ludlow time. In this epoch, the reef formation reached its maximum development and the reef constructions occupied the greatest area. As it is shown in the map, the lagoonal facies was separated from the open sea by a barrier reef belt that stretched along the entire shelf. Beyond the reef belt in the deeper part of the basin, organic-rich sediments of the open-shelf facies were deposited.

The results of my lithological investigations of the Ukrainian part of the Silurian area are consistent with the oceanic-climatic model by Bickert et al. (1997), showing the expansion of the oxygen minimum zone towards the shore during transgressions and its significant retreat towards the shelf break during regressions. Transgressive-regressive cycles could correlate with the climatic changes (Page et al., 2007; Cramer and Saltzman, 2007; Calner, 2008) and the latter could represent the important factor of biodiversity crises. However, our data show that the impact of these climatic changes on carbonate sedimentation was not that considerable and the reef building, though changing its spatial extent, might have not been interrupted during the Wenlock–Middle Pridoli. Nikiforova et al. (1972) described reef-building organisms as well as bioherms within the entire succession in numerous outcrops of Silurian shallow-water shelf deposits of Podillya. Another evidence of favourable climatic environments is a permanent existence of reefs in sections of Western Lithuania (Lazauskiene et al., 2003; Zdanaviciute and Lazauskiene, 2007) in the time range from Late Wenlock to Early Pridoli.

The existing data allow assuming that, though the climatic changes during the Silurian had a significant control on distribution of carbonate fauna within the southern shelf of Baltica, the environments in these subequatorial latitudes still remained favourable for persistent existence of reefal buildups.

DEPOSITIONAL ENVIRONMENTS

Figure 12 shows the scheme of depositional environments at the southern shelf of Baltica. Within the shallow part of the water column within depths of up to 100 m, where water was oxygenated, the calcareous plankton evolved over the entire area.

The realm of calcareous benthos was restricted by bottom depths of up to 100 m. Shelf calcareous biocenosis was represented by large amount and diversity of fauna including: crinoids, stromatoporoids, rugose corals, tabulate corals, algae, ostracods, gastropods, brachiopods, trilobites and graptolites (Nikiforova et al., 1972). At favourable bathymetric environments, the abundant benthic organisms created numerous submarine overgrowths and banks which formed the reef. The deeper part of the shelf with water depth exceeding 100 m was occupied by the oxygen minimum zone, which caused the phyto- and zooplankton extinction, and partial dissolution of the calcareous skeletal debris, and facilitated the efficient organic matter fossilization and accumulation of organic-rich sediments. Anoxic environment in this deeper part of the basin became a determinant factor for the formation of organic-rich (with the total organic carbon content reaching >2%) so-called graptolitic shales. Deposition of organic-rich sediments of this age was a global phenomenon and resulted from the Silurian oceanic anoxic event (Verniers et al., 2008).

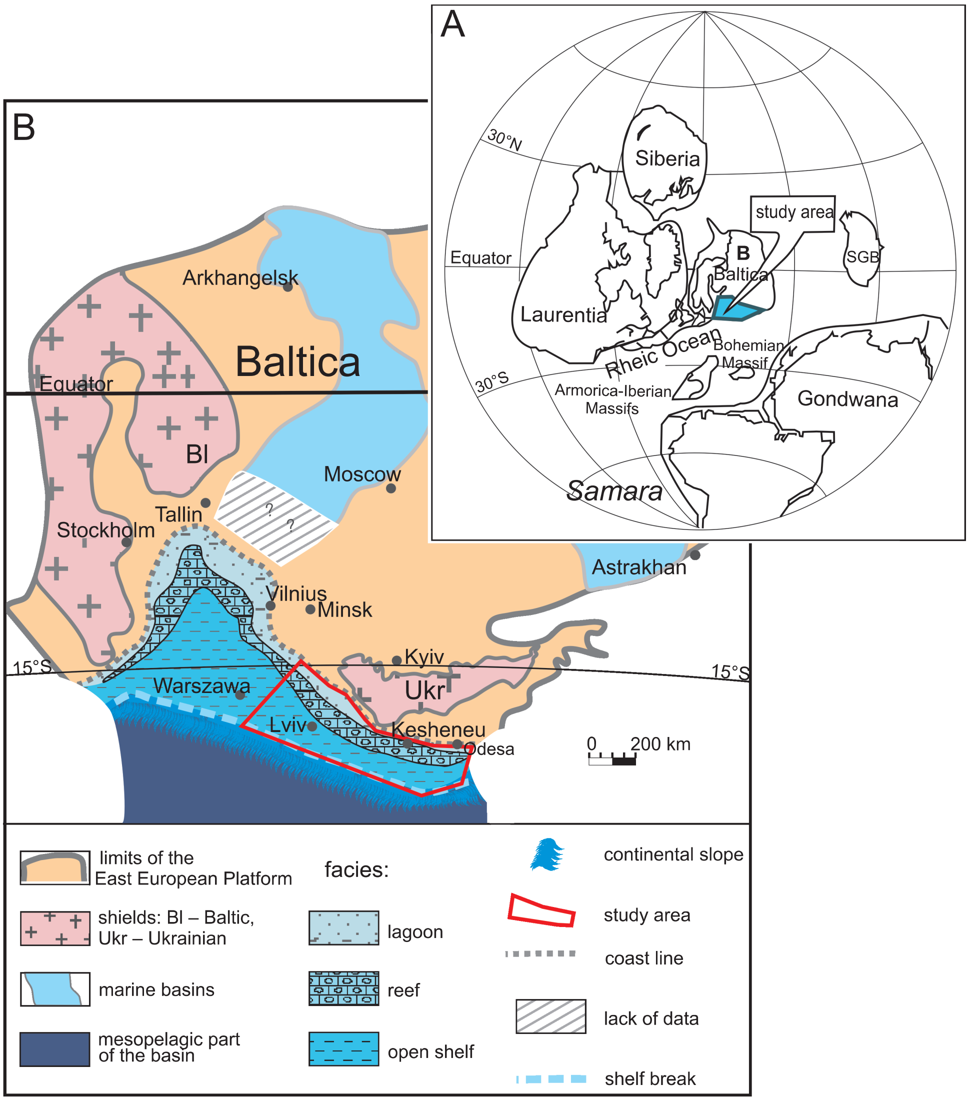


Fig. 11A – palaeogeographic map for mid-Silurian times, showing the position of the study area within Baltica (after Torsvik et al., 1996); B – sketch map showing the model of southern shelf

Figure 8 shows that during the Silurian the regression and transgression cycles controlled the shifts of boundaries of facies, especially of open-shelf and reef ones. During transgressions (Fig. 13A), in this instance in the Wenlock, the open-shelf facies significantly advanced towards the shore. The area of oxygen-minimum zone and, consequently, of organic-rich sediments deposition expanded. The reef formation zone had a minimum width and occurred in the most proximal part of the shelf within the water depth of 100 m. In the periods of regressions, as it was in the Ludlow (Fig. 13B), the reef formation zone extended towards the open sea.

The facies change, in particular the spatial and temporal evolution of reef formation is illustrated in Figure 14. During the regression (Ludlow) the newly formed reefs shifted towards the deeper part of the basin and accumulated upon the fore-reef facies, while the old reefs were covered by the shallow-water back-reef lagoonal sediments. During the transgression (Pridoli) the opposite processes took place. The newly formed reefs covered the back-reef sediments, while the old reefs were overlain by the deeper-water fore-reef deposits. Hence, during the Silurian, the reef-formation zone was shifting towards the shore and back towards the shelf break depending on sea level changes, remaining a continuous phenomenon for the shallow part of the entire southern shelf of Baltica (Fig. 11B).

Analysis of lithological sections on Ukraine and Moldova and the data on the adjacent territories show that the reef belt extended over approximately 2300 km and its maximum width was about 150 km.

SUMMARY AND CONCLUSIONS

Study of well-log data, lithological and petrographic investigations of Silurian strata in the Volyn-Podillyan Plate and the Dobrogean Foredeep and their correlation with coeval deposits in the adjacent territories of Moldova and Romania (Moldovian Platform), Poland, Lithuania, Latvia and Estonia allowed us de-

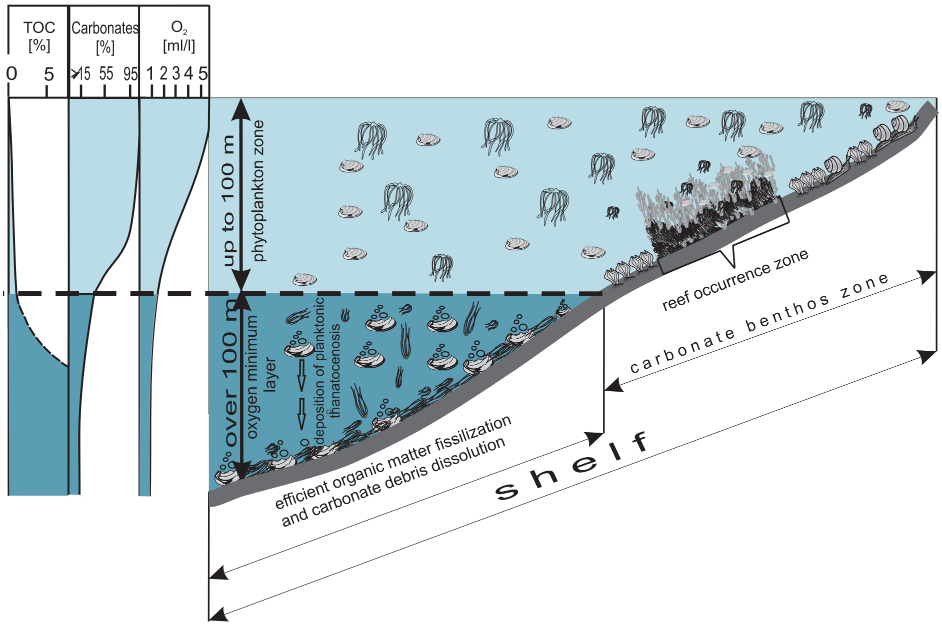
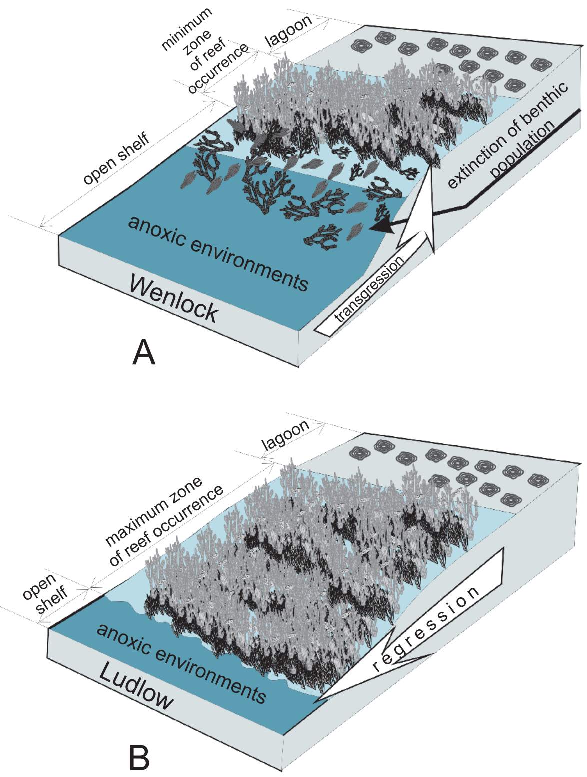


Fig. 12. Scheme of depositional environments in the Silurian within the southern shelf of Baltica

O_2 concentration in water column after Demaison and Moore (1980); TOC – Total organic carbon



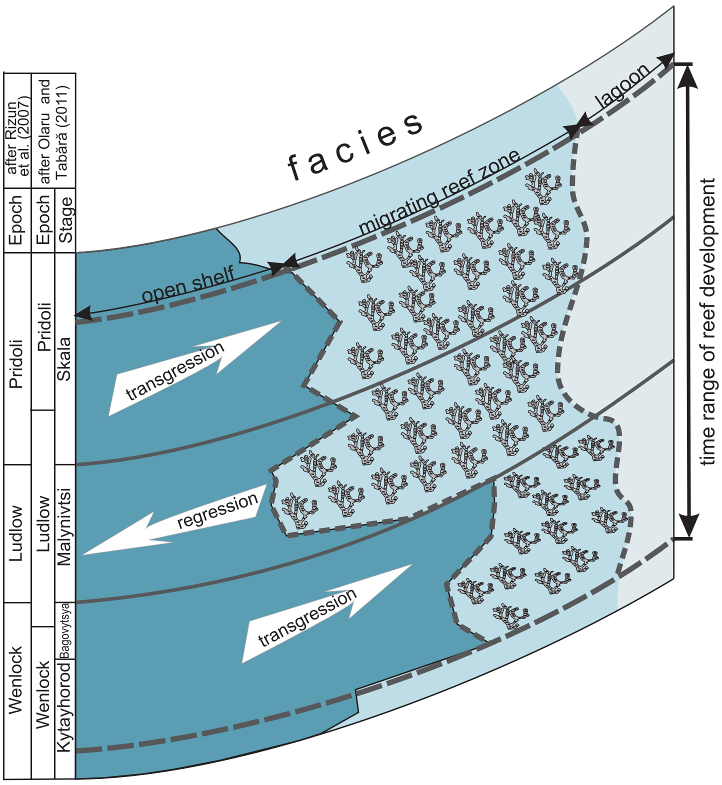


Fig. 13. Models of the southern shelf of Baltica in the Silurian for the periods of transgression (A) and regression (B), which controlled the shifts of the boundary between open-shelf and reef facies

Fig. 14. Spatial and temporal evolution of migrating reef facies in the Silurian within the southern shelf of Baltica

veloping an integral concept of the extent of Silurian deposits, regularities of thickness changes, petrographic composition of rocks and distribution of lagoonal, reef and open shelf facies within the southwestern margin of the East European Platform. The reef facies, which represented a barrier between the lagoonal and open shelf facies, was a subject of a number of earlier investigations, which considered separate Silurian reef constructions in different parts of the south-western margin of the East European Platform. In this study, reconstruction of sedimentary environments during the Silurian within the southern shelf of Baltica integrates my results and the data from the publications of earlier authors. It shows that there was a continuous reef belt stretching along the entire shelf within the time range from Wenlock to Middle Pridoli. The reef facies was shifting within the shelf and changing its width depending on sea level changes. Analysis of palaeoceanographic environments of the reef formation shows that the oxygen minimum layer, which in Silurian marine basins occupied the water column below a depth of 100 m, and the transgressive-regressive cycles were the decisive factors of spatial and temporal distribution of facies in the sedimentary basin of the southern shelf of Baltica. Organic-rich anoxic sediments were being deposited in the deeper part of the basin, while the shallower part was the area of reef buildups and back-reef lagoonal sediments. The boundary between the open-shelf and the reef facies was controlled by the top of the oxygen minimum layer, which was shifting towards the open sea or back towards the shore depending on changing depth of the shelf in different time intervals of the Silurian. Both the reef and the open-shelf facies are prospective for hydrocarbons and hence the delineation of the areas of their occurrence in different time ranges of the Silurian is important for exploration purposes.

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