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UNCONVENTIONAL SHALE GAS POTENTIAL OF LOWER VISEAN ORGANIC-RICH FORMATIONS IN GLYNSKO-SOLOHIVSKYI PETROLEUM REGION

Exploration of unconventional gas resources in Ukraine is highly relevant and important for achievement energy independence of Ukraine and Europe. Production of current oil & gas fields and alternative energy resources are not able to cover our needs nowadays. Now we can not fully fill these gaps by energy resources. In this article geological environments, age, mineralogy composition and maturity of unconventional shale and carbonate gas reservoirs of Lower Visean in one of the biggest field of Dnipro-Donets Basin (DDB) were studied. The hydrocarbon potential of two main target horizons V-23 and V-24-25 by using integrated approach of analyzing available core analysis data were performed. The results of the geochemical analysis show that the maturity level of shale of the Rudov beds (V-23) appear in oil window (Ro~0.8 %) which can generate oil in the early mature phase. Visean carbonates (V-24-25) have the similar level of maturity - (Ro~0.77 %). Target rocks are characterized by high total organic content (TOC): average values vary from 2% for organic-rich carbonates to 5.6 % for shales which indicates relatively good to excellent source rock generative potential. According to X-ray diffraction analyses (XRD) of black shale formation domination of silica minerals (54.6 %), calcite and clays (25.6%) with minor amounts of albite, feldspar and pyrite were observed. Carbonate platform V-24-25 logically is characterized by much higher calcite content of 52.2 % with low amount of dolomite – 5.5 %. Quite high quartz content is also observed – average value is of about 30.7 %. Clay minerals are not identified in every sample, but average values are of about 18.9 %, pyrite content – 6.8 %. It shows that Visean target formation of Glynsko-Solohivsky Petroleum region is characterized by anoxic environment. This data verified that V-23 and V-24-25 horizons are the brittle formations and favorable for multistage fracking. Thin section analysis confirms our results from mineralogical point of view. The presence of fractures in core samples is additional indicator for hydraulic fracturing and producing gas from such unconventional reservoirs. As a conclusion, the Lower Visean organic-rich formations V-23 and V-24-25 from Glynsko-Solohivsky Petroleum region are mature, are characterized by a high content of organic carbon, have enough thickness (30–120 m) and large areal extent. They should be regarded as a potential shale gas target.

Key words: Source rock, unconventional reservoirs, total organic carbon, XRD, rudov beds, Lower Visean, thermal maturity, brittleness

Introduction

The Dnipro-Donets Basin (DDB) is a major Paleozoic rift basin located in the Sarmatian craton in Eastern Ukraine of more than 15 km depth [Tectonics…, 2015; Starostenko et.al., 2017]. It is considered that DDB is a Super Basin with multiple prolific gas fields. In its area, the Shebelynka field is located as one of the Europe’s largest gas deposit, currently producing 22 Tcf. The main gas/oil formations refer to Permian and Carboniferous rock deposits. They are conventional reservoirs (sandstones, siltstones) are characterized by quite high porosity and permeability. However it needs to focus on unconventional types of reservoirs for purpose of significant increasing of gas & oil production in Ukraine. As it well-known the major of unconventional types of reservoirs are as following [Lukin et.al., 2020]:

- Shale gas;
- Tight gas (Cent ral Basin Gas);
- Coalbed Methane gas (CBM).

The unconventional shale reservoirs affect huge impact on oil & gas production in such countries as the USA, Canada, Argentina, China, Thailand etc. We hope it will be one of the main ways to increase production in Ukraine, especially by using advanced technologies of horizontal drilling and multi-stage fracturing. As it well-known unconventional shale gas formations are acting as the source, reservoir and the trap for the natural gas [Vyzhva, et.al., 2019; Orlyuk et.al., 2018]. These kinds of natural gas formations are characterized by very low porosity and permeability values in the Nano-Darcy range. There are three main organic-rich source rocks in the DDB. 1) The Upper Visean Rudov Beds contain very high indexes of total organic carbon (TOC) content (average 5.5 %); 2) oil-prone Lower Serpukhovian deposits and 3) gas-condensate prone Middle Carboniferous formations in the southern and southeastern part of the basin. In addition, Devonian rocks are the most important source rocks in the Pripyat Trough [Misch, et al., 2015; Misch, et al., 2016 (b); Vakarchuk, et al., 2013].

As it known the Lower Visean formation is one of the major source rock intervals, which consists of marine limestone, silica and organic shale. Due to the intense exploration and field development activities all over the DDB, the Lower Visean source sequence can be thoroughly investigated by new modern approaches and technologies. It gives the possibility for better understanding the hydrocarbon potential of this formation.

The main aim of this paper was to determine and describe the key properties of organic-rich rocks (mineralogy, total organic carbon, thermal maturity) and shale gas potential of Lower Visean source rocks - Rudov Beds (V-23) and Visean carbonate platform (V-24-25). Northwestern part of DDB were studied, depth of zone interests was 4-4.5 km. In addition, we answered the question about the Visean carbonate platform possibility acts as unconventional reservoir target. The special core analysis methods (SCAL) and modern log data (elemental-spectroscopy, spectral gamma ray, NMR etc.) were integrated to solve this problem.

Geological settings

The study area is located northwest of Dnipro-Donets Basin, which is bounded by the Ukrainian Shield and Voronezh Massif (Fig. 1).

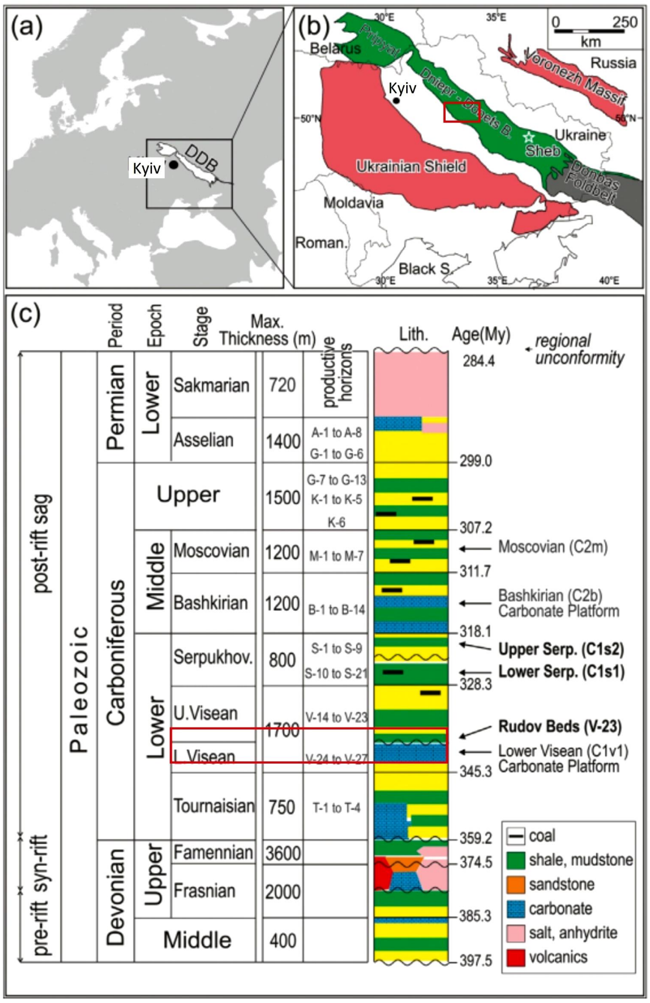


Fig. 1. Regional setting of the Dnipro-Donets-Basin (DDB) in Eastern Europe (a, b; c – Age data follow [Misch, et al., 2018].

In this study we focused on the Glynsko-Solohivsky Petroleum region and oil/gas unconventional shale reservoirs. The target area structure is a brachianticline fold of northwest trend. It is located in the northwestern part of the DDB within the southern slope of the Zhdaniv depression. Gas and oil exploration in this area are connected with intervals from Bashkirian deposits (C2b) to Devonian (D3f) ones. However, a lot of previously studies (Lukin O., Makogon, V., Sachsenhofer R., Shymanovskyy V. A., Mish D, Karpenko O., Karpenko I., Prigarina, T., Ulmishek G. Goncharov G., etc.) described that the Lower Visean high-organic formations (Rudov Beds, Carbonate Platform V-24-25) have hydrocarbon potential in the territory of DDB and in field A in particular (Fig. 2) [Lazaruk,2012; Mihailov, 2014; Misch, et al.; 2016 (a); Ogar, 2012; Sachsenhofer, et al., 2010]. During the last years in several wells, a number of modern logs acquiring and coring analysis were applied. It gives new results and answers about shale gas potential of this area. The core and tin sections description give the information about depositional environments and ages of V-23 and Carbonate platform V-24-25. It mostly confirms by previously studies of Lukin O., Karpenko O., Karpenko I., Ogar V. etc. The horizon V-23 (hot shale) corresponds to marine environment, probably – to shallow water shelf. The similar environment is observed in theV-24 carbonate platform [Karpenko, et al., 2021; Mihailov, 2014; Misch et.al., 2018].

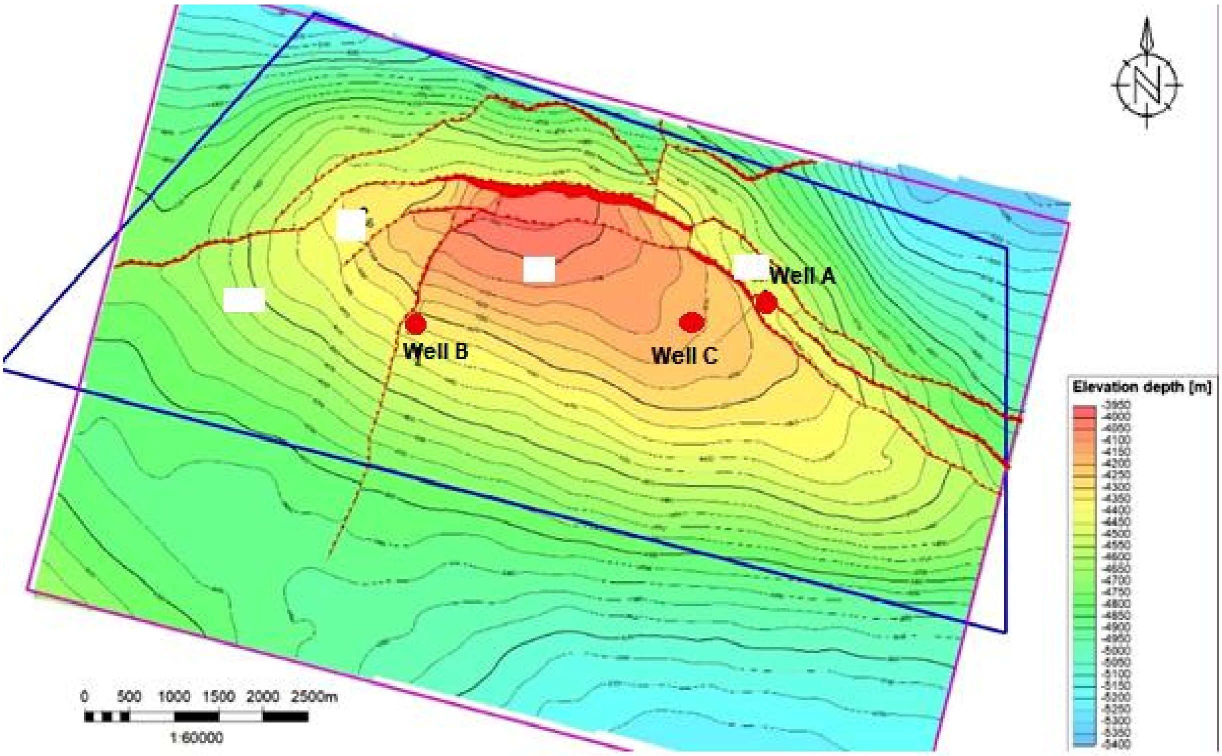


Fig. 2. Structural map of field A (Top V-23). Well A, B, C – cored wells.

Samples and Methods

The unconventional shale reservoirs are much complicated than conventional target formations. It is because of more complex mineral composition, very low porosity and permeability values (<0.1 mD) of this deposits. As usual this rock consists of silica, clay, calcite, pyrite and kerogen. Due to proportion of these main rock components we can make assumptions about hydrocarbon and fracturing potential of these formations. According to international experience more than 40 % of the clay content of this rock makes it is not possible to frac it and get good economical results. It is due to very soft rock geomechanical properties and respectively poor brittleness index (BI) [Jarvie, et al., 2007]. Usually high calcite content does not have positive impact on the hydrocarbon potential of unconventional source rock reservoirs because it reduces porosity, but it is not make the rock more ductile. Silica is useful mineral for both reservoir quality (RQ) and mechanical quality (MQ) of formation. Pyrite and kerogen are not so important because of their low content proportion of total unconventional reservoir content.

For our investigation 75 core samples from wells (A, B, C) were studied, which represent horizons V-23 and carbonates V-24-25 (Figs. 1, 2). Table 1 shows the coring depth, amount of removed core in meters and in %. According to this data, it was received a lot of useful information about our target formations from wells (Figs. 3, 4).

It is important to note that all core samples where accurately shifted to log data. It was possible due to laboratory measurements of all core samples by Gamma Ray, Spectral Gamma Ray and Density tools (Fig. 5) [Lyzanets, et al., 2021]. It makes our studies more precise than if we use quite old core data which were shifted only by using drilling pipe measurements.

Routine core analysis (RCAL) of samples from well C, A and special core analysis from well A showed highly heterogeneity of rocks. Most of the samples from well B were divided into three pieces for such investigations as XRD, TOC, Rock-Eval for excluding heterogeneity impact on laboratory measurements. Mean values of the three measurements were further used for correct estimation of reservoir petrophysical properties. Finally, more than 200 measurements were performed, which made our investigations more precise (Fig. 6).

Table 1

Coring length in wells of the area of study

Well	Hor	Depth, m	Coring, m	Removed core, m	Removed core, %
A	V-24	4.400–4.500	33.5	32.18	96.63
B	V-23-24	4.400–4.500	27	23.42	86.74
C	V-24	4.500	18.2	18.2	100

Fig. 3. Core well B (Hor-V-23-V-24-25).

Fig. 4. Core well B (Hor. V-24-25).

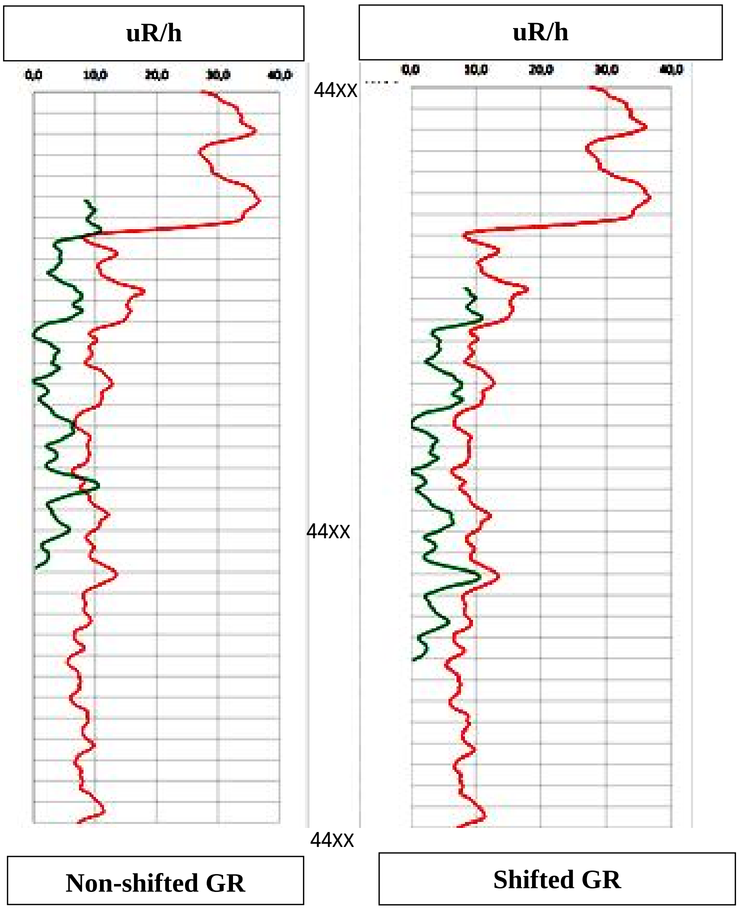


Fig. 5. Well A example – how core data can be depth-shifted. Red curve is Gamma ray from logs, green is core gamma ray.

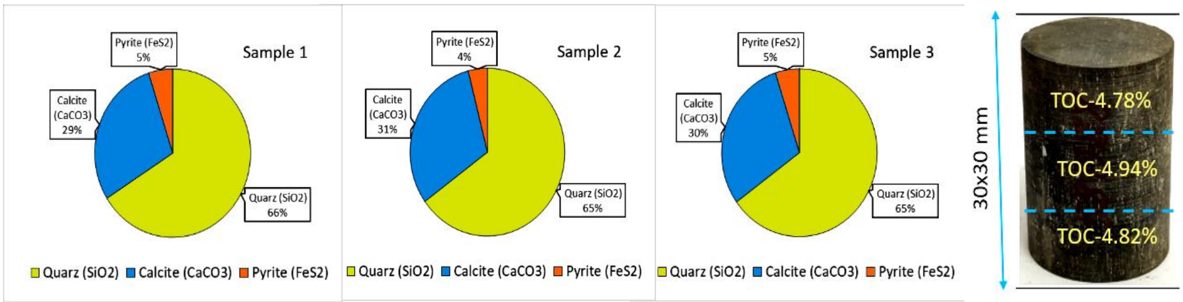


Fig. 6. An example of core sample and received values of TOC, mineralogy (XRD).

Mineral composition and determination by XRD

For determination of rock fabric, XRD analysis was performed in two wells from study area and covered mostly horizon V-24 and partially horizon V-23. Of about 200 samples were prepared for applying a Panalytical diffractometer. All the tests have been completed at the Ukrnaukageocentre, Poltava, Ukraine.

Geochemical analysis

Geochemical studies on a Rock-Eval 6 Classic S3 pyrolysis unit by using Rock Six software were carried out. For conducting pyrolysis, the Bulk Rock Basic method was chosen. It allows to determing the main geochemical parameters of the parent strata. The initial temperature of pyrolysis was 300 °C, the final temperature was 650 °C. Carbonates & shale core samples were crushed and selected for LECO TOC analysis. Carbonates were extracted from every sample (100 mg) by using 5 % HCL solvent.

Petrographic analysis

To get the results of petrography analysis, the thin sections were prepared at the complex laboratory of core research by using the standard method. The core samples were boiled in rosin, and then pasted on Canadian balsam. The thickness of the sections (≈ 0.03 mm) was determined with a microscope by the color of the quartz grains. Finally, a cover glass was glued to the Canadian balsam.

Results and discussion

Mineral content

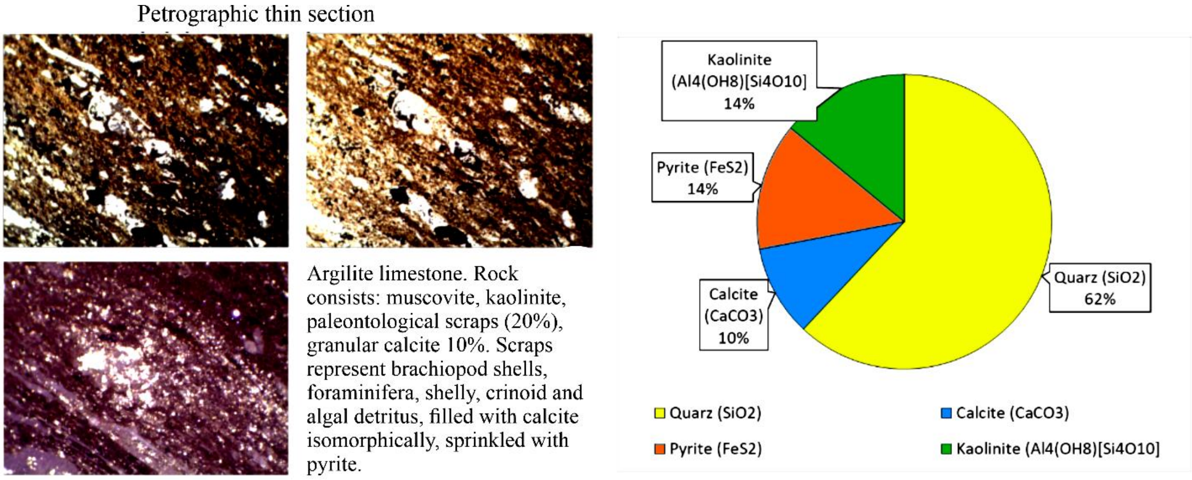
Bulk mineralogical composition (quartz, feldspars, pyrite, apatite, calcite, dolomite, clay minerals etc.) of 200 selected samples was determined by using XRD analysis and applying a Panalytical diffractometer. It gives detailed information about mineralogy composition which helps to estimate reservoir (porosity, saturation) and geomechanical properties. Those properties are very important for unconventional reservoir. Core samples for XRD covered V-23 and V-24-25 shales, limestones and partially sandstones.

16 of 73 investigated samples represent the high organic (>5 %) of Lower Visean source rocks (V-23 Rudov Beds). We can observe predomination of silica minerals in all samples – from 8.6 to 95.3 %, which mostly consist of quartz. On the average, we observe 54.6 % of silica which is very positive indicator in case of brittleness of formations. There are some samples with albite content (5 samples). Carbonate minerals content vary from 1 to 34 %, one sample are characterized by high value – 83.4 %. Perhaps it hasn’t been shifted correctly. Mostly, carbonates are represented by calcite and several samples are represented by dolomite and ankerite. Dolomite is present in seven samples, the same number of samples have ankerite. Clay minerals are mainly represented by kaolinite, illite and dikkite of varying amounts. Muscovite is also present in some samples from horizon V-23. Kaolinite and illite are the major clay minerals, which is present in most samples. The total clay content in black shale rock in average consists of 25.6 %. All high organic shales core samples contain pyrite which confirms anoxic geological environments of Lower Visean source rocks. Amount of pyrite varies from 1 to 15 % with average values of 5.9 % (Fig. 10).

The Carbonate platform (V-24) is also covered by our investigation, mineralogical characterization of rocks were researched. Laboratory analysis showed that carbonates as main rocks in such formations varies between 8 to 94.3 %. Carbonates are represented by calcite, dolomite and rarely ankerite. The content of calcite, which is present in 55 samples, varies between 8 and 94.3 % with average content of 52.2 %. The content of dolomite which is present in only eight samples is from 1 to 11 % with average value of 5.5 %. The ankerite content varies between about 2 and 4.4 % in only five samples. In second unconventional formation there are several high organic shales between layers. There is nine samples from total number, with lower carbonate content, but it still consists up to 77.7 %. We can observe quite high silica content in horizon V-24, which makes rocks much ductile. The content of quartz, which is present in 55 samples, is ranges from 5.7 to 66.3 % with average content of 30.7 %. In 17 samples we can see albite present with a range between 3.9 to 26 %. According to XRD analysis, several samples have anorthite in their content (only 5 samples). Clay minerals are not represented in every sample, but in 16 samples they are observed. The average values of total clay minerals in V-24 reach 18.9 %. They are mainly represented by kaolinite, dikkite, illite and few samples with muscovite or smectite minerals. Kaolinite is the main clay mineral with average content 10.6 %, and range between 5 and 17 %. Other clay minerals are represented in less than ten samples, which is shown in the histogram (Fig.11). The content of pyrite, which is detected in most core samples, varies between 2 and 17 % with average content of 6.8 %. This mineral is present in 42 samples of all 55 samples of horizon V-24.

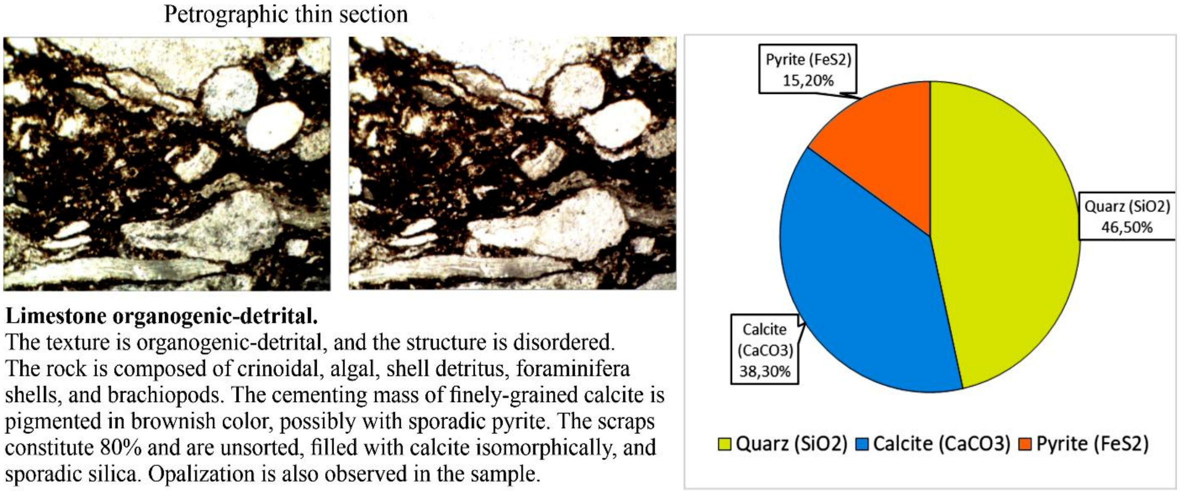
The Petrographic thin section analysis including mineralogical content was conducted for better characterization of our target rocks. Based on the received results the most minerals which are present in the target formation confirm XRD analysis results (Figs. 7–9).

According to XRD and petrographic thin section analysis we can assume that horizon V-23 is characterized by low amount of high clay content minerals (av. 25.6 %). Much lower content is observed in carbonate platform V-24 – av. 5.3 % that makes target formations acceptable for multistage fracking and producing hydrocarbons. Also it shows the possible potential of higher porosity values in target zones.


Petrographic thin section

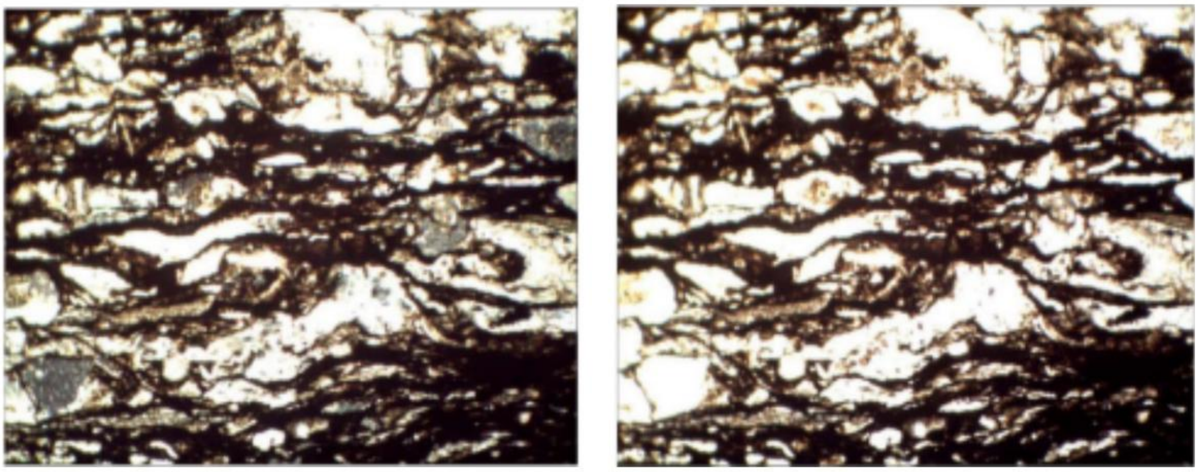
Argilite limestone. Rock consists: muscovite, kaolinite, paleontological scraps (20%), granular calcite 10%. Scraps represent brachiopod shells, foraminifera, shelly, crinoid and algal detritus, filled with calcite isomorphically, sprinkled with pyrite.

Fig. 7. The thin section photo from microscope and XRD data from hor. V-23 (argilite).


Petrographic thin section

Limestone organogenic-detrital.
The texture is organogenic-detrital, and the structure is disordered. The rock is composed of crinoidal, algal, shell detritus, foraminifera shells, and brachiopods. The cementing mass of finely-grained calcite is pigmented in brownish color, possibly with sporadic pyrite. The scraps constitute 80% and are unsorted, filled with calcite isomorphically, and sporadic silica. Opalization is also observed in the sample.

Fig. 8. The thin section photo from microscope and XRD data from hor. V-23 (limestone)



Limestone organogenic-detrital.
The texture is organogenic-detrital, and the stucture is subtly layered, influenced by the arrangement of the detritus.
The rock is composed of crinoidal, algal, shell, and coral detritus, permeated by veinlets filled with carbonaceous-bituminous material, densely speckled with pyrite. The scraps constitute 80%, are unsorted, filled with calcite isomorphically, some sprinkled with pyrite, and partially opalized. Small grains of quartz and feldspar, corroded by carbonate, constitute 3%. Opalization is also noticeable in the interstices.

Fig. 9. The thin section photo from microscope and from hor. V-24 (limestone).

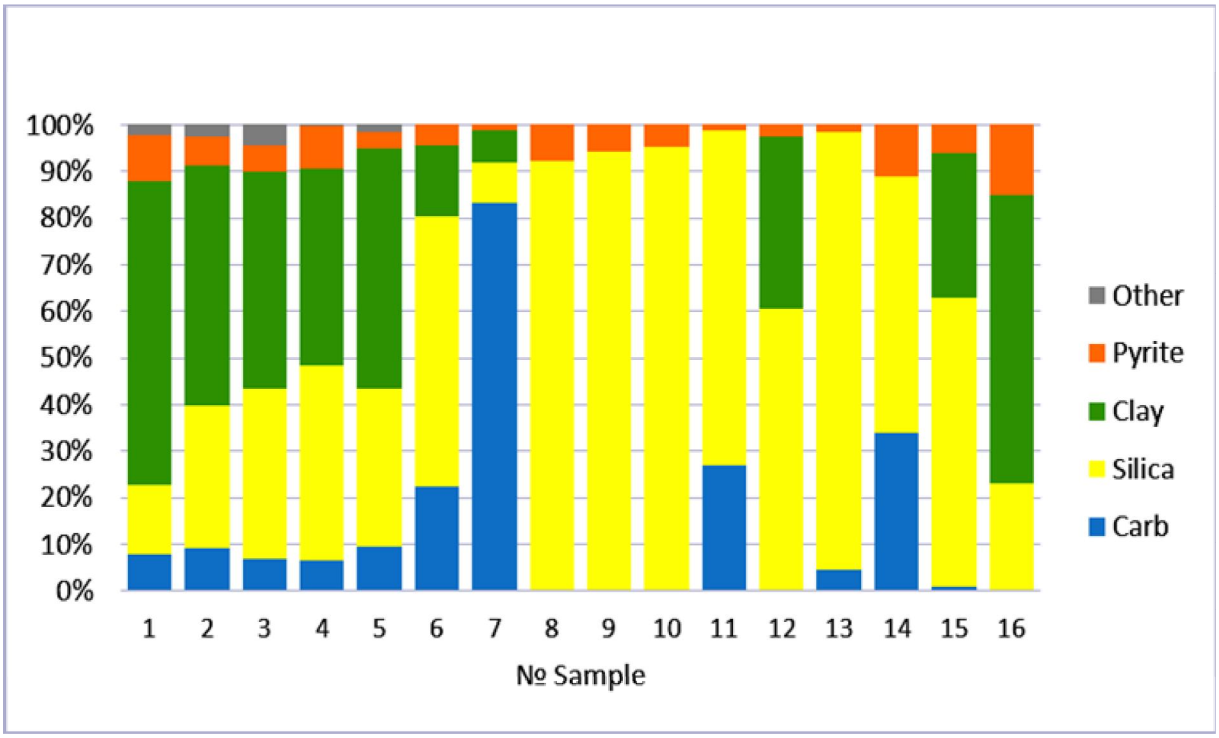


Fig. 10. XRD results. Mineral composition of selected V-23 organic-rich shale samples, %.

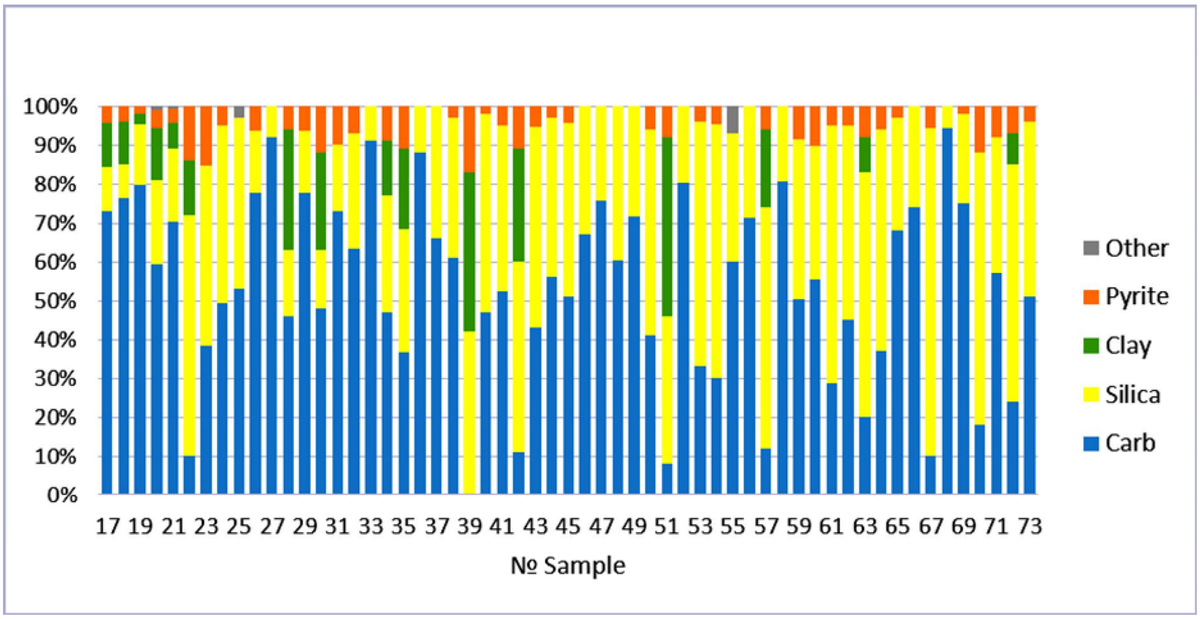


Fig. 11. XRD results. Mineral composition of selected V-24 organic-rich carbonate samples, %.

The Rock fabrics research is very important for unconventional reservoir. As a result, special mineralogy triangle plot are computed as usual. Mineralogy data from North America analogs of shale gas reservoirs are added to our plot investigations (Fig.12). According to this plot, horizon V-24 consists of 60–90 % of carbonates, 5–20 % of clay and 5–30 % of silica. In V-23 (hot shale) formation, more silica content in rock composition are observed: silica – 45–70 %, carbonates – 4–27 % and clay 20–50 %. As a conclusion the best matches in the our field are observed: for horizon V-23 – with Barnett shale and for V-24 – with Eagle Ford as USA analogues. In our further studies, petrophysical investigations of other rocks properties (TOC, porosity, elastic properties etc.) and their comparative analysis will be conducted.

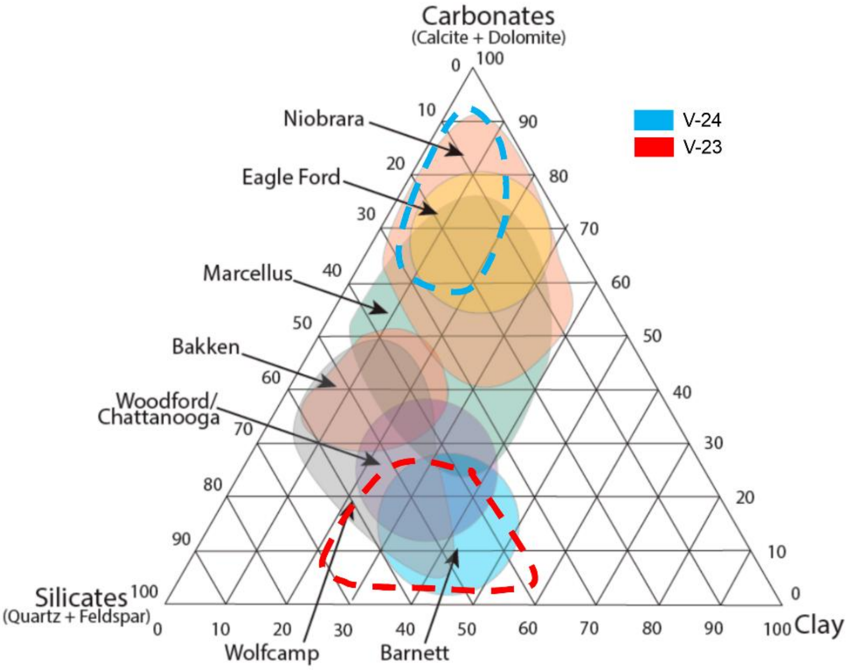


Fig. 12. Compearing ternary diagram showing the average mineral content in the some formations in USA [Mews, 2019]. Blue circle is data from V-24 (carbonate platform), red – V-23 (Rudov beds).

TOC and Rock-Eval pyrolysis. Thermal maturity of source rock

In our study, geochemical analysis of core was carried out to determine TOC, thermal maturity and kerogen type. For determination of organic matter and evaluating the generative hydrocarbon potential of shales and organic-rich carbonates (V-24-25) measuring of content of total organic carbon (TOC, wt %) were investigated. Definition of TOC was carried out by the AN-7529M express analyzer, which is designed for the express determination of the mass fraction of carbon, by burning the rock in a furnace to carbon dioxide (CO2) with its subsequent coulometric titration in a coulometric cell by the value of pH. The value of the organic carbon content is obtained by the method of direct combustion at a temperature of 1200°C in a stream of oxygen. The content of organic carbon in the studied samples of V-23 is from 1.4 % by weight up to 7.6 % by weight in samples No. 1–16. The average value is 5.6 % which suggests relatively good to excellent source rock generative potential [Karpenko, et al., 2021]. For black carbonates platform it is from 0.4 % up to 5.2 % by weight in samples No. 17–73. Average value of about 2 % confirms high potential for hydrocarbon generation in such thick target (>100 m). The results of determining the content of organic carbon are showed in Table 2. Correlation plot of TOC and depth in this area of study are presented in Fig.13 a. In previous studies, the authors made an attempt to estimate TOC values by using logging data from several wells in the area of study, but unfortunately, core analysis wasn't available for confirming results of interpretation [Karpenko, et al., 2021]. The methodology ΔRLog was performed [Passey, et al., 1990].

According to pyrolysis analysis, main parameters of generative potential of source rocks and hydrocarbon presence – S1, S2, Tmax, HI, PI etc. were received. The amount of hydrocarbon (S2) generated during pyrolysis is a useful parameter for evaluating the generative potential of source rocks. The average value of the residual hydrocarbon potential, expressed by the S2 indicator, for organic-rich shales (V-23) is 9.83 mg HC/g, the lowest values is 0.84 mg HC/g, the highest corresponds to 23.72 mg HC/g. Due to heterogeneity of rocks wide ranges of S2 are observed, but mostly they vary from 8 to 15 mg HC/g. It shows good and very good generation potential of source rock. The residual hydrocarbon potential S2 of limestone (V-24-25) ranges from 0.3 to 12.59 mgBB/g of rock, average value is 2.33 mg HC/g of rock. The main values for both formations are 1.5 to 4.5 mg HC/g. Therefore studied samples have good generation properties (Table 2). Hydrogen and production indices of the samples were calculated.

Table 2

Bulk geochemical results for Rudov beds (V-23) organic-rich shale and V-24-25 carbonate samples from TOC/Rock-Eval analysis using calculated parameters and vitrinite reflectance (%Ro)

Wells A & B			TOC	S1	S2	Tmax	Ro	HI	OI	PI
No.	Hor	Litho	wt %	(mg HC/g)	(mg HC/g)	(°C)	%			
1	V-23	Shale	5.0	2.03	7.61	444	0.83	151.0		0.2
2	V-23	Shale	6.6	4.41	18.2	442	0.80	275.8		0.2
3	V-23	Shale	6.5	2.31	15.11	444	0.83	232.5		0.1
4	V-23	Shale	6.9	3.51	15.67	443	0.81	227.1		0.2
5	V-23	Shale	1.9	0.31	2.27	434	0.65	119.5		0.1
6	V-23	Shale	1.4	0.71	0.99	434	0.65	70.7		0.4
7	V-24	Limestone	0.5	0.39	0.31	439	0.74	62.0		0.6
8	V-24	Limestone	2.1	1.90	4.3	434	0.65	204.8		0.3
9	V-24	Limestone	1.1	1.52	2.17	419	0.38	197.3		0.4
10	V-24	Limestone	0.9	1.01	1.69	412	0.26	187.8		0.4
11	V-24	Limestone	1.4	1.22	1.49	419	0.38	106.4		0.5
12	V-24	Shale	4.3	1.12	2.46	444	0.83	57.0	1.0	0.3
13	V-24	Shale	1.7							
14	V-24	Limestone	2.2	1.09	3.84	446	0.87	174.0	5.0	0.2
15	V-24	Shale	2.3	2.31	6.82	450	0.94	302.0	5.0	0.3

Continuation of Table 2

Wells A & B			TOC	S1	S2	Tmax	Ro	HI	OI	PI
No.	Hor	Litho	wt %	(mg HC/g)	(mg HC/g)	(°C)	%			
16	V-24	Shale	1.5							
17	V-24	Limestone	1.6							
18	V-24	Shale	3.7	2.52	12.59	451	0.96	340.0	1.0	0.2
19	V-24	Limestone	1.7							
20	V-24	Shale	4.2	1.56	4.42	451	0.96	106.0	1.0	0.3
21	V-24	Shale	3.5	3.22	8.74	452	0.98	250.0	2.0	0.3
22	V-24	Shale	3.0	2.97	7.16	454	1.01	236.0	1.0	0.3
23	V-24	Limestone	0.8							
24	V-24	Shale	3.7	1.65	4.12	447	0.89	112.0	1.0	0.3
25	V-24	Limestone	3.3	0.78	2.48	445	0.85	74.0	1.0	0.2
26	V-24	Limestone	0.9							
27	V-23	Shale	7.3	2.515	7.795	440	0.76	106.0	1.2	0.2
28	V-23	Shale	7.0	2.17	12.56	446	0.87	177.0	1.0	0.1
29	V-23	Shale	7.6	2.71	11.89	445	0.85	157.0	0.7	0.2
30	V-23	Shale	5.8	1.97	13.33	443	0.81	226.0	2.5	0.1
31	V-23	Shale	6.0	2.46	9.32	449	0.92	148.0	0.4	0.2
32	V-23	Shale	14.3	3.2	23.72	443	0.81	165.0	0.7	0.1
33	V-23	Shale	2.2	0.85	2.37	439	0.74	102.0	0.6	0.3
34	V-23	Shale	2.7	0.37	0.84	439	0.74	31.0	0.9	0.3
35	V-23	Shale	8.5	0.73	5.88	446	0.87	62.0	0.4	0.1
36	V-24	Limestone	0.9	0.9	1.8	443	0.81	187.0	6.8	0.3
37	V-24	Limestone	1.1	0.38	0.89	435	0.67	79.0	0.6	0.3
38	V-24	Limestone	4.4	0.29	1.81	448	0.90	41.0	2.1	0.1
39	V-24	Limestone	1.3	0.6	1.13	443	0.81	84.0	2.5	0.3
40	V-24	Limestone	2.1	0.49	1.31	440	0.76	55.0	1.5	0.3
41	V-24	Limestone	3.6	0.2	1.01	439	0.74	28.5	0.8	0.2
42	V-24	Limestone	2.2	0.7	1.32	441	0.78	60.0	2.9	0.3
43	V-24	Limestone	1.1	0.84	1.2	436	0.69	110.0	2.8	0.4
44	V-24	Limestone	1.6	0.87	1.88	448	0.90	114.0	2.7	0.3
45	V-24	Limestone	0.7	0.73	1.08	437	0.71	155.0	14.0	0.4
46	V-24	Limestone	0.8	2.3	3	444	0.83	317.0	5.2	0.4
47	V-24	Limestone	0.9	1.21	2.18	446	0.87	246.0	4.5	0.4
48	V-24	Limestone	0.5	0.87	1.93	446	0.87	370.0	18.4	0.3
49	V-24	Limestone	1.6	0.46	1.15	437	0.71	74.0	3.6	0.3
50	V-24	Limestone	4.8	0.64	2.25	447	0.89	46.0	1.2	0.2
51	V-24	Limestone	0.4	0.91	1.43	436	0.69	315.0	25.0	0.4
52	V-24	Limestone	2.0	0.67	1.43	442	0.80	67.0	0.5	0.3
53	V-24	Limestone	2.3	0.79	2.11	447	0.89	90.0	2.0	0.3
54	V-24	Limestone	0.6	0.75	1.33	443	0.81	202.0	9.3	0.4

Continuation of Table 2

Wells A & B			TOC	S1	S2	Tmax	Ro	HI	OI	PI
No.	Hor	Litho	wt %	(mg HC/g)	(mg HC/g)	(°C)	%			
55	V-24	Limestone	0.6	0.76	1.45	446	0.87	244.0	9.3	0.3
56	V-24	Limestone	3.2	0.31	0.297	438	0.72	30.0	0.7	0.5
57	V-24	Limestone	0.6	0.38	1.04	437	0.71	152.0	17.0	0.3
58	V-24	Limestone	1.9	0.53	1.52	437	0.71	80.0	1.9	0.3
59	V-24	Limestone	2.4	0.39	1.34	445	0.85	57.0	0.5	0.2
60	V-24	Limestone	1.1							
61	V-24	Limestone	1.6	0.39	1.29	436	0.69	83.0	1.6	0.2
62	V-24	Limestone	3.0	0.37	1.04	435.5	0.68	32.0	3.1	0.3
63	V-24	Limestone	1.9							
64	V-24	Limestone	1.1	1.04	1.71	441	0.78	155.0	6.5	0.4
65	V-24	Limestone	0.6	0.5	1.1	430	0.58	187.0	7.0	0.3
66	V-24	Limestone	5.2	0.33	1.21	438	0.72	23.0	0.5	0.2
67	V-24	Limestone	0.4	0.92	1.84	436	0.69	451.0	28.6	0.3
68	V-24	Limestone	1.0							
69	V-24	Limestone	4.0	0.47	1.46	438	0.72	35.0	0.4	0.2
70	V-24	Limestone	2.6	0.45	1.35	435	0.67	53.0	1.5	0.3
71	V-24	Limestone	3.0	0.46	1.11	440	0.76	37.0	7.4	0.3
72	V-24	Limestone	1.5	0.55	1.64	446	0.87	106.0	0.8	0.3

The content of free hydrocarbons (C1-C33), which is reflected by indicator S1, ranges from 0.31 to 4.41 mg HC/g of rock for all studied samples from horizon V-23. For carbonates values of S1 vary from very low – 0.2 up to 3.22 mg HC/g of rock. It indicates the saturation of the studied samples with hydrocarbons not only in black shales, but either in Lower Visean carbonates formation.

Thermal maturity is one of the main parameters of source rock and unconventional reservoirs for understanding their potential to generate hydrocarbons in petroleum system. Tmax and Ro data analysis for the thermal maturity determination of V-23 and carbonates V-24-25 were used.

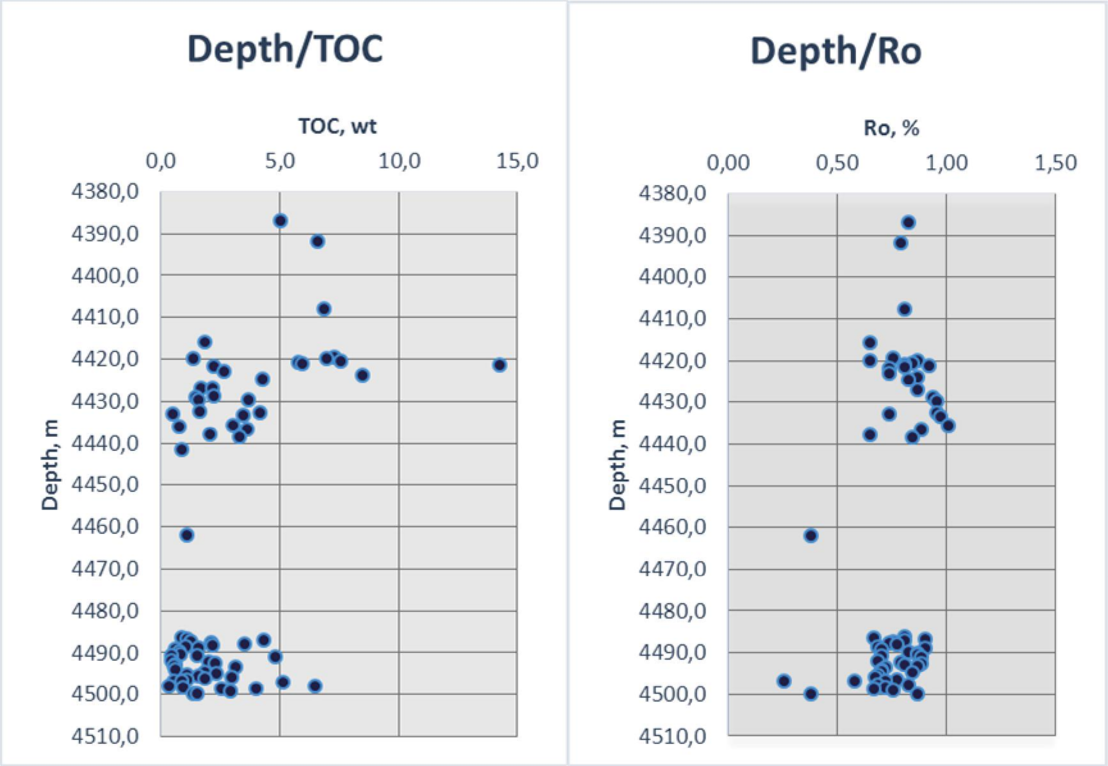
The maximum temperature of the release of hydrocarbons (Tmax) for the studied samples of “Rudov beds” is 434–449 ºC. Such values indicate that the deposits are located in the middle-late “oil window” and correspond to the stage of catagenesis of the MK3 gradation (according to M.B. Vassoevich).

For carbonate formations Tmax is 430–454 ºC, but vast majority of the samples show >435 ºC which corresponds for late “oil window” as in shale samples of V-23. There are three samples from carbonate formation with quite low Tmax values – 412–419 ºC, which are not typical according to full available numbers of samples (63 samples). Those specimen were taken from cuttings, therefore, it could affect the quality of the measurements.

According to [Jarvie et al., 2001] the Vitrinite Reflectance equation is the following: Ro = = 0.018*Tmax-7.16. The results of the evaluation of the Ro average values for black shale formations is 0.8 % and for carbonates (V-24) is 0.77 %. Our studies on diagram Ro vs. depth show that the sample data are mostly located in oil window, therefore it could be concluded that Rudov beds (V-23) and organic-rich carbonate formations can potentially generate oil or perhaps condensate (Fig. 13, *b*). It has also been confirmed by the results of cross-plot of Hydrogen Index (HI) and Tmax (Fig. 14, *a*). As it shown in Fig. 14, *a*, unconventional target formations of Lower Visean entered phase early to peak maturity, which means they could generate oil and have kerogen of type II and III. It was also confirmed by logging data in some sandstone intervals with good porosity which are located above carbonate platform V-24-25 in Well B. This borehole has oil signs on logs (Triple Combo, NMR and elemental spectroscopy logs data). Thin section analysis also demonstrated the presence of organic and bitumen includes (Fig. 15, *a*). It correlates with other pyrolysis analysis data.

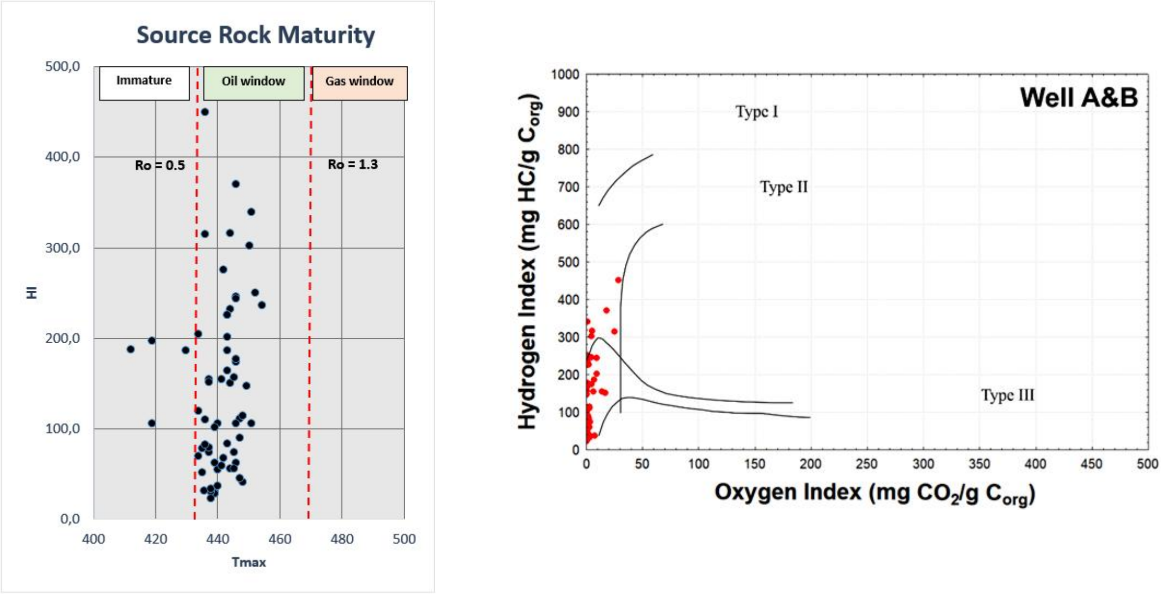
The type of kerogen is characterized by the ratio of hydrogen (HI) and oxygen (OI) indices. In term of kerogen type, the modified van Krevelen diagram shows the HI vs. OI plot based on the hot shale V-23 and organic-rich carbonates V-24-25 pyrolytic data, which is taken from wells A and B, indicates that the source section is gas-prone and of type II-III kerogen (Fig. 14, *b*).

The Production index is an indicator of the amount of volatile "free" hydrocarbons that is related to the presence of migrated oil or the amount of redistributed liquid hydrocarbons (generated by the cracking of kerogen) by primary migration. The PI in horizon V-23 corresponds to values of 0.11–0.42, with an average value of 0.2, which characterizes the deposits as sufficiently mature for hydrocarbon generation.



a b

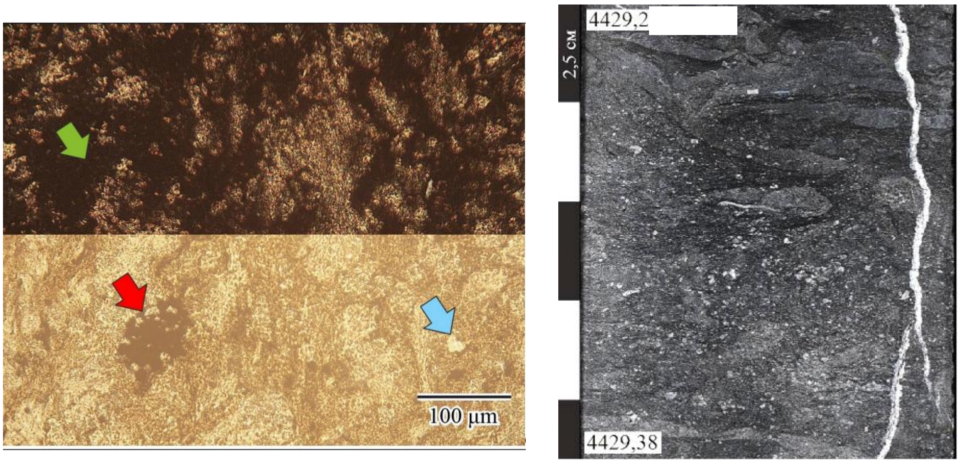
Fig. 13. TOC vs Depth for V-23 and carb. V-24-25 Formations (a); Cross-plot of depth versus Ro (b).



a b

Fig. 14. Plot of Hydrogen Index vs Tmax (a); Plot of Van Krevelen Diagram (Well B) (b).

For carbonate platform with organic-rich argillite beddings the values of PI varies from 0.14 to 0.51. The average value is even higher than in black shale formation – 0.31, suggesting the presence of redistributed hydrocarbons, or migrated oil, in most of the non-contaminated samples. The Hydrogen Index (HI) ranges from 23 to 451 HC/g TOC mg for V-24-25. In organic shales V-23 these values are between 31 to 275.8 HC/g TOC mg. All results are shown in Table 2.



a b

Fig. 15. Thin section analysis: a – Well A – Blue arrow – detrital quartz grain, red arrow – agglomeration of bituminous substance, green arrow – accumulation of organic matter. Upper part with the analyzer, bottom without it: b – Well B – Bioturbated layer and crack, filled by white carbonate.

Conclusions

In this paper, using an integrated approach for analyzing organic-rich shales and carbonates of Lower Visean formations in DDB were presented in case of study the hydrocarbon production potential from unconventional type of reservoirs. The main shale gas parameters – TOC, Vitrinite reflectance, type of kerogen and mineralogy were received. The new data and precise approach for preparing core samples and their analysis gave a possibility to get more robust and accurate results in comparison with previous studies of this formation.

The potential of black shale and carbonate formations of Lower Visean shows from good to very good hydrocarbon potential level, and are classified into phase early to peak maturity, which means they could generate oil & condensate and has type II and III kerogen. Microscope characteristics of samples indicate the presence of kerogen and organic matter. The shale has high organic matter content with TOC up to 7.6 wt % which corresponds to the good preservation of the matter. The values of total organic carbon for carbonates formations (V-24-25) are lower than for V-23, but are still high and acceptable to be good hydrocarbon potential rocks (up to 5.2 wt %).

The Pyrolysis analysis reveals that both carbonates and black shales show quite high values of S1 and S2, which corresponds to the possibility to produce and generate hydrocarbons from our target formations. The values of Tmax are mostly >435 ºC which confirms our early suggestions about the potential of Lower Visean shales and carbonates.

The Rudov beds shale is dominated by quarts minerals and carbonates, followed by clays, feldspars and pyrite. Average clay content is 25.6 %, it means that this target formation are characterized by excellent brittleness. The horizon V-24-25 mostly consists of calcite and quarts and is an acceptable rock for multistage fracks and oil & gas producing. At the same time, a lot of opened and filled fractures in most of core samples are observed. These fractures are usually filled with calcite (Fig.15 b.) These signs confirmed that target formation is naturally fractured and may demonstrate positive production results with additional multistage fracturing. Our further studies will focus on detailed petrophysical and geomechanical properties by using core analysis results and advanced modern logs data.

As a conclusion, there are two unconventional targets for shale gas exploration at the study area. First one is Rudov beds shale formation (V-23) which was named as “world-class” source rock in previous studies by other authors. The second one is a carbonate platform with organic-rich rock content. This fact makes it of very good potential considering quite huge thickness of this formation (>100 m) [Iuras, et al., 2021]. Favorable factors for shale gas accumulation in unconventional targets are: 1) high

TOC content and high maturity of rocks; 2) big thickness and large areal extent of shale and carbonate; 3) high rock brittleness of formations; 4) stable anoxic deep-water sedimentary environment. 5) naturally fractured.

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ПОТЕНЦІАЛ НЕТРАДИЦІЙНОГО СЛАНЦЕВОГО ГАЗУ НИЖНЬОВІЗЕЙСЬКИХ БАГАТИХ НА ОРГАНІКУ ТОВЩ ГЛИНСЬКО-СОЛОХІВСЬКОГО ГАЗОНАФТОНОСНОГО РАЙОНУ

Актуальність розвідки нетрадиційних ресурсів газу в Україні дуже висока, особливо для досягнення енергетичної незалежності України та Європи. Видобуток з наявних нафтових і газових родовищ та використання альтернативних джерел енергії є недостатнім для задоволення потреб населення сьогодні. Поки що неможливо повністю заповнити ці прогалини за допомогою енергоресурсів. В статті досліджено геологічне середовище, вік, мінералогічний склад та термальну зрілість нетрадиційних сланцевих і карбонатних газових колекторів нижнього візе в одному з найбільших родовищ Дніпровсько-Донецького басейну (ДДБ). Представлено вуглеводневий потенціал двох основних досліджуваних горизонтів В-23 і В-24-25 з використанням інтегрованого підходу до інтерпретації наявних даних аналізу керна. Результати геохімічного аналізу показують, що в рудівських шарах (В-23) рівень термальної зрілості сланців міститься в нафтовому вікні (Ro~0,8 %), що може давати змогу генерувати нафту в ранній фазі зрілості. Подібний рівень зрілості спостерігається у візейських карбонатів В-24-25 (Ro ~ 0,77 %). У досліджуваних породах високий загальний вміст органіки (TOC) – у середньому від 2 % для карбонатів, багатих на органіку, до 5,6 % для сланців, що свідчить про порівняно хороший або відмінний генеративний потенціал материнської породи. За даними XRD аналізу мінералів чорносланцевої товщі переважають кремнеземні мінерали (54,6 %), кальцит та глини (25,6 %) з незначною кількістю альбіту, польового шпату та піриту. Карбонатний горизонт В-24-25 логічно має значно більший вміст кальциту – 52,2 % за невеликої кількості доломіту – 5,5 %. Також є характерним доволі високий вміст кварцу – в середньому 30,7 %. Глинисті мінерали не ідентифікуються в кожному зразку, але за середніми значеннями їх вміст становить близько 18,9 %. Вміст піриту становить близько 6,8 %, що свідчить про безкисневе середовище цільових візейських утворень в межах Глинсько-Солохівського газонафтоносного району. Ці дані підтвердили, що горизонти В-23 і В-24-25 є крихкими шарами, сприятливими до багатостадійних гідророзривів. Аналіз шліфів підтверджує результати з мінералогічного погляду. Наявність тріщин у зразках керна є додатковим індикатором для здійснення гідророзриву та видобування газу з таких типів колекторів. Отже, нижньовізейські багаті на органіку шари Глинсько-Солохівського газонафтоносного району В-23 і В-24-25 є термально зрілими, мають високий вміст органічного вуглецю, достатню потужність (30–120 м) та велику площу залягання. Їх можна розглядати як потенційний об’єкт для видобутку газу.

Ключові слова: материнські породи; нетрадиційного типу колектори; загальний вміст органічної речовини; XRD; рудівські верстви; нижче візе; термальна зрілість; крихкість.

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