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The Structure of Continuous Reservoirs in the Domanik Formation and Petrophysical Interpretation Methods

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Abstract—The properties of unconventional prospective deposits are interconnected by the processes of reservoir formation and oil and gas formation. Dispersed dolomite formed in situ during the maturation of TOC from syngenetic magnesium in the rock matrix increases the pore space of the rock, thereby forming an unconventional reservoir filled with autochthonous hydrocarbons and oil components. In the process of TOC maturation and hydrocarbon migration the TOC components are redistributed in the pore space; the released volume of rocks is thus filled with stationary resinous asphaltene substances, which sharply reduces the reservoir properties of unconventional reservoirs. As a result, the definition of "organic" porosity includes a broader concept than just the porosity of kerogen. This is a more complex physicochemical process of transformation of the organic matter itself and the redistribution of elements within the formation as a result of the maturation of TOC components and hydrocarbon migration. When assessing the oil and gas potential in the section we distinguish three groups of rocks: unconventional reservoirs with an increased TOC content and the presence of mobile hydrocarbons; bituminous rocks, in which part of the pore volume is filled with resinous-asphaltene substances, and host dense carbonate rocks without organic matter. As well, sporadically developed traditional reservoirs are distinguished throughout the section of the Domanik type rocks.

Keywords: Domanik Formation, the interpretation well-logging, unconventional reservoir, bituminous, resinous-asphaltene substances, mobile fluids, organic porosity

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INTRODUCTION

Unconventional source rock reservoirs are widely developed and are present in all petroleum basins. We note that the prospects of finding movable hydrocarbons in sediments with high content of organic matter are very diverse. Promising oil source rocks, or, according to Western terminology, "shale" deposits containing movable hydrocarbons, are identified by a set of geological, geophysical, and geochemical parameters that characterize "sweet spots" (Vashkevich et al., 2018, 2019). Thus, according to geochemical parameters, first of all, the amount of organic matter (Total Organic Carbon, TOC), its component composition, maturity, type, etc. is determined. The net thicknesses are interpreted based on core and logging data and at a qualitative level based on mud logging while drilling.

For the Volga–Ural and Timan–Pechora petroleum provinces, one of the most extensive source rocks, both laterally and vertically, is the bituminous Domanik Formation that covers the stratigraphic interval from the Upper Devonian, that is, the Middle and Upper Frasnian substages and the Famennian stage, to the lower part of the Tournaisian stage (Carboniferous) (Fig. 1).

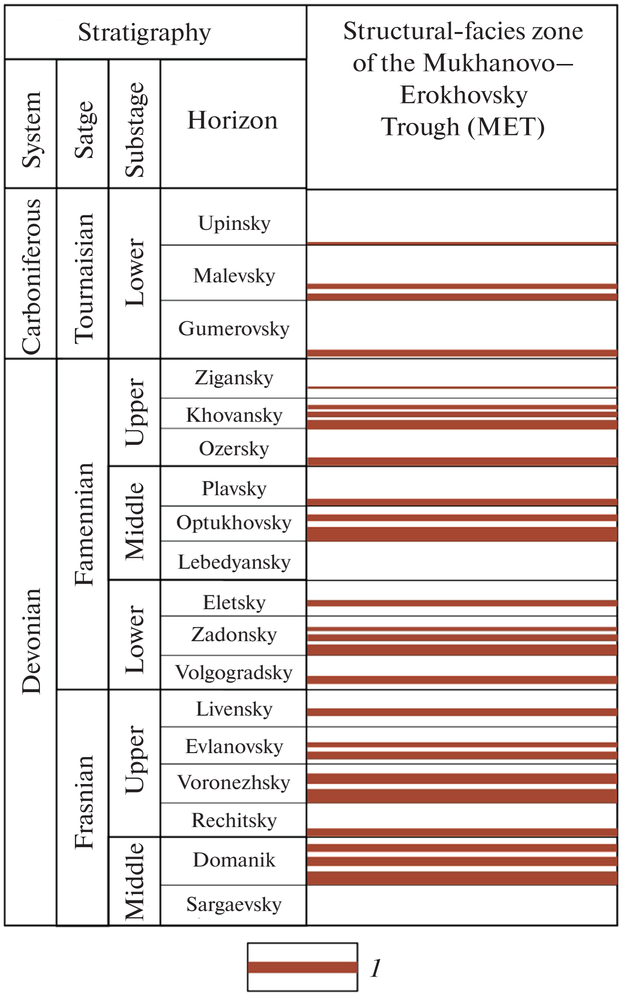

Fig. 1. The stratigraphic distribution of organic-rich rocks (domanikite and domanikoid) in the section of the Mukhanovo-Erokhovsky intrashelf Trough. (*1*) Domanikite and domanikoid rocks (TOC-rich rocks).

The studied target with its complex structure is still an object of study, although it has been penetrated by many deep wells drilled into the underlying oil and gas bearing horizons. No core was taken from the target sediments, therefore, the interval has mainly been described based on the standard logging complex. To determine the oil and gas bearing potential and net thicknesses of the Domanik sediments by well-logging data, it is very important to identify clear criteria that determine the potential (Zagranovskaya et al., 2020). The conceptual structure of promising formations should be determined and the material-mineralogical composition, the structure of the pore space of the reservoirs and their genesis, as well as the geological–geophysical and geological–geochemical features of the deposits that affect the changes in the pore space structure should be identified.

This study describes the methods of logging data interpretation for identifying oil net pays in the Domanik-type sediments, taking the identified geological, geophysical, and geochemical features according to the core data into account. The authors give examples of logging data interpretation (Petersile et al., 2003; Zagranovskaya et al., 2020) from old wells that were not cored in order to reliably estimate the reserves and resource potential of the target deposits.

MATERIALS AND METHODS

Object of Study

The materials analysis included existing cores taken from deep wells within the following license blocks of the Mukhanovo-Erokhovsky Trough: Malogasvitsky, Peshkovsky, Bogolyubovsky, and Leningradsky. As well, the authors had a chance, at different times, to study the depression facies of the Upper Devonian and Tournaisian intervals in the available cross-sections of the South and Middle Urals and South Timan. This paper describes core study materials of the Savitskaya E&A well drilled in 2020 in the central part of the Mukhanovo-Erokhovsky Trough (MET), which was cored in the entire Domanik-type interval, and a modern well-logging complex was performed. The Savitskaya well can be considered as a reference for studying the Domanik Formation sediments in the central part of the depression in the Volga-Urals Trough. As well, the study includes materials from core and thin sections studies from Malogasvitskaya Area wells (Fig. 2) and published materials on the Kashaevskaya Area wells.

The authors analyzed and performed a complex interpretation of logging data on more than 30 wells in the central part of the Mukhanovo-Erokhovsky Trough.

Stratigraphy and Generation Conditions of the Domanik Formation within the Mukhanovo-Erokhovsky Trough

The accumulation of the Domanik Formation within the Mukhanovo-Erokhovsky Trough (MET), which is part of the system of the Kama-Kinelsky intrashelf Upper Devonian depressions, covers a significant geochronological interval, starting from the Middle Frasnian and ending in the Early Tournaisian. During this time, the contours of the trough and the sedimentation conditions in its shallow-water shelf frame were changing. This affected the pattern of the vertical distribution of the TOC-rich rocks within the condensed facies of the trough.

At the first sedimentation stage, in the Domanik time, in TOC-rich siliceous–carbonate sediments, interlayers of storm bioclastic limestones are quite common, which indicates relatively moderate sedimentation depths within 50–70 m. The Domanik facies are characterized by a rich complex of nectonic macrofossils, indicating a moderate height of the

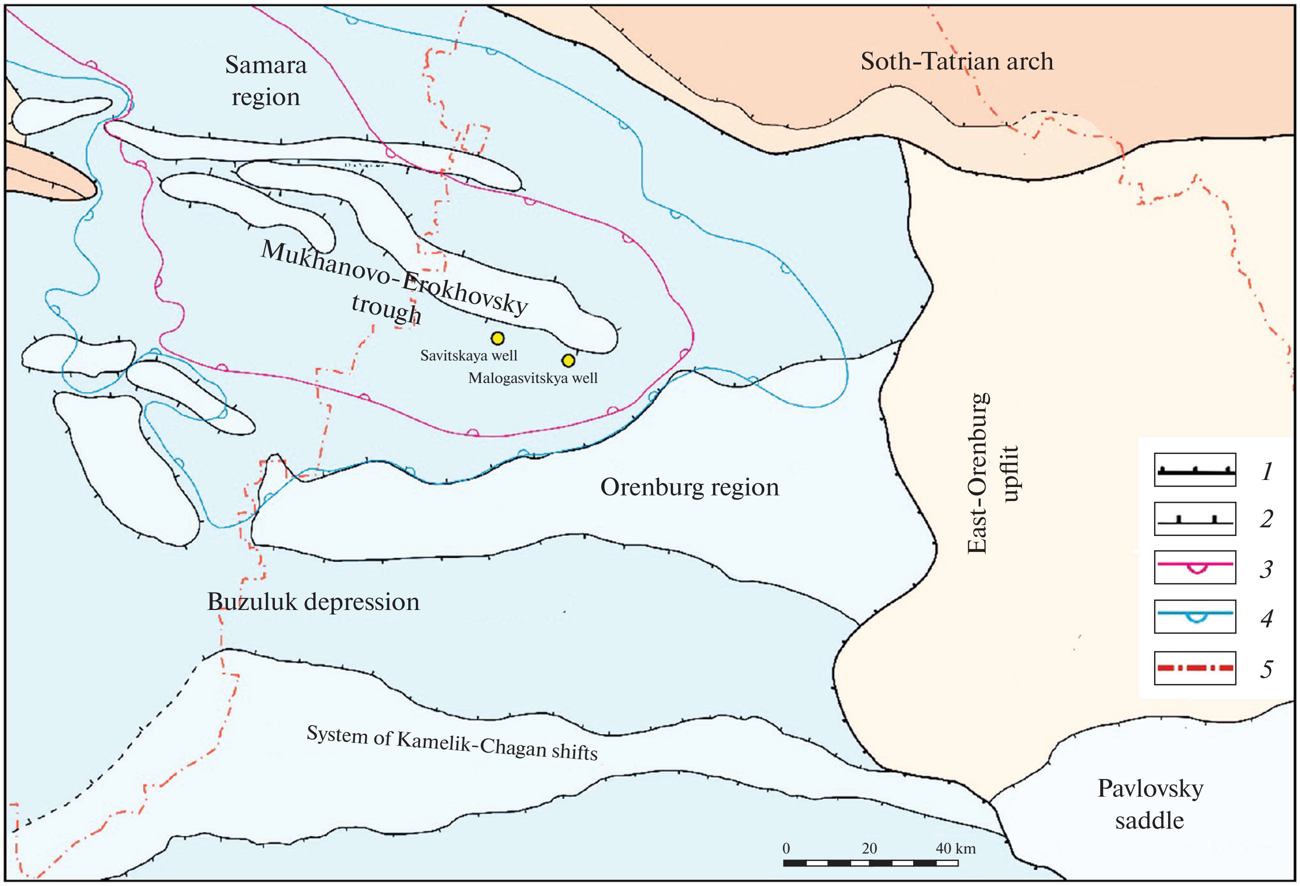

Fig. 2. A tectonic map of the main elements of the central part of the Volga–Ural basin. Legend: (*1*) boundaries of structural-tectonic elements of the first order; (*2*) boundaries of structural-tectonic elements of the second order; (*3*) borders of Mukhanovo-Erokhovsky Trough of the Tournaisian Age; (*4*) borders of Mukhanovo-Erokhovsky Trough on Famennian Age; (*5*) administrative borders of regions.

near-bottom zone of anoxia and its occasional moderate action. At a number of levels, there are intervals with signs of bioturbation (Gatovsky et al., 2015).

In Late Frasnian time, units of carbonate debris and various-grain carbonate turbidites were formed in the edge zones of the trough. This is a sign of the formation of carbonate platforms with rather steep slopes in the trough framing. Bioclastic tempestites disappear from the interval, i.e., the depths of the intrashelf depression begin to exceed the storm wave base (over 60–80 m).

In the Famennian sediments, various-grain turbidites become common sediments in the trough framework. Coarse clastic debris disappear, which is evidence of flattening of the carbonate platform slopes. The macrofossil complex becomes extremely poor. Deepening of the trough leads to an increase in the height of the near-bottom anoxia zone and the formation of lifeless conditions over vast areas of the trough. The source of sedimentary material is calcareous and siliceous microplankton that thrive in the upper layer of water saturated with oxygen and light.

In the Early Tournaisian, the trough is intensively filled with fine-grained and silty carbonate sediments that formed in vast shallow waters that have lost their reef framework. Various-grained carbonate turbidites reach the maximum thickness. The thicknesses of the Domanikoid units are naturally decreasing.

Vertically, the sediments of the Domanik Formation in the depression part of the area enclose a number of enlarged OM-enriched units that are separated by fine detrital gray limestones, and in some interlayers by siliceous rocks with a significantly lower amount of OM or without it altogether.

The Lithological and Mineralogical Characteristics of Deposits and Petrophysical Types of Rocks of the Domanik Formation and their Genetic Characteristics

The Domanik-type deposits are represented by siliceous-carbonate and carbonate-siliceous rocks with thinbedded sedimentary structures, with interlayers of carbonate breccias, limestones, and second-

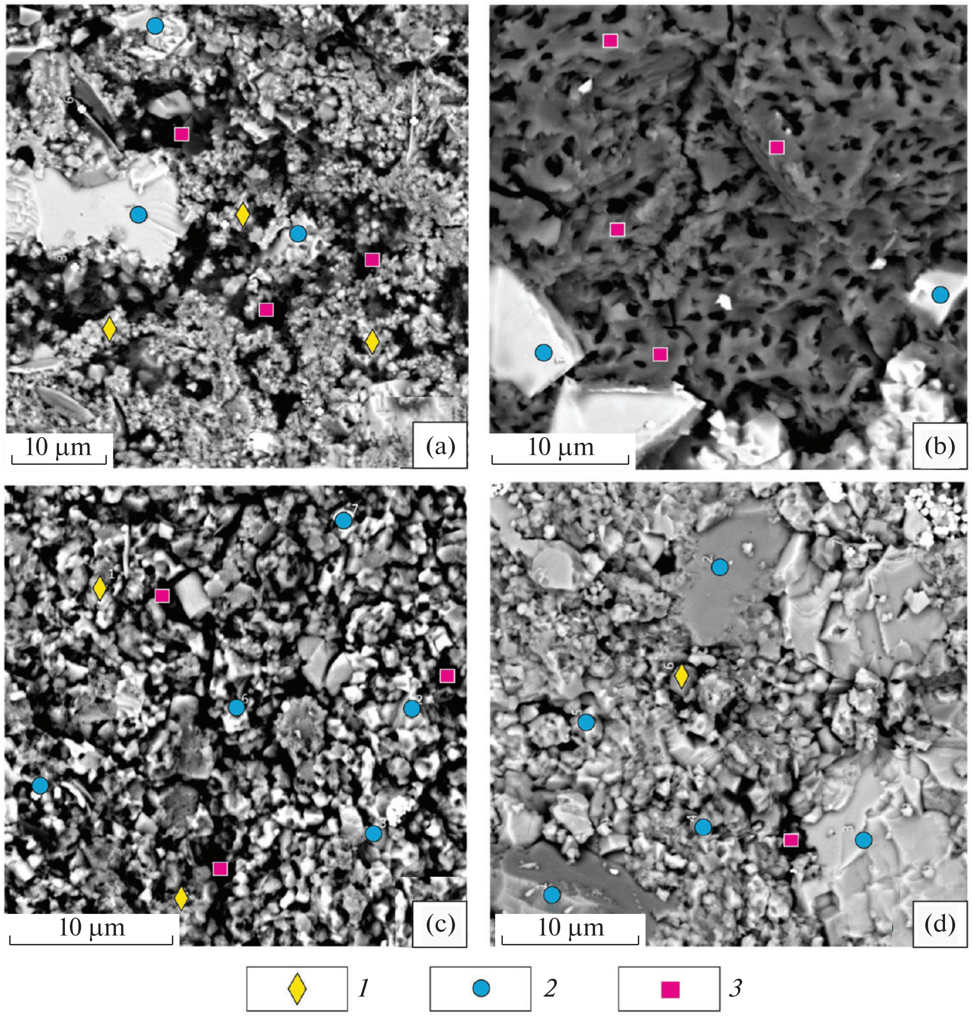

Fig. 3. A photo of Domanik formation rocks of the Mukhanovo-Erokhovsky Trough, obtained using a scanning electron microscope (SEM): (a) carbonate-siliceous rock with a loose package of matrix microcrystals; (b) the bitumen inclusion permeated by a thick network of micropores; (c) microcrystalline siliceous-carbonate rock with inclusions of organic matter in micropores; (d) siliceous-carbonate rock with bioclasts and organic matter.

ary dolomites, with higher content of organic matter (OM) (Fadeeva et al., 2015; Stupakova et al., 2015, 2016, 2017).

The rocks of the MET depression facies are composed of two main rock-forming minerals, calcite and silica (Figs. 3a, 3c–3d). Their proportion in the rock composition varies in the range from slightly siliceous limestone to calcareous chert (Stupakova et al., 2016). Impurities of other minerals (pyrite, feldspars, and clay minerals) are insignificant, a low content of clay minerals up to 4–8% is often common (Ulmishek et al., 2017). Dolomite is an exception; it can be represented by two crystalline forms.

An important component of depression facies rocks is the organic matter content, which varies from fractions of a percent to 20–25%. The bituminous content of the sediments is due to the presence of scattered organic matter (OM) in the rock matrix; bituminous content is also present in stylolites, inside tentaculite shells, and in inter crystalline pores, as well as in separate interlayers and in veins (Gorozhanin et al., 2019).

In Russia, source rocks with high TOC are traditionally referred to as Domanikoids (up to 5% organic matter) and Domanikites (5–25% organic matter). With a high content of kerogen, it becomes a significant component of the rock. In the course of hydrocarbon generation, secondary microporosity is formed in the kerogen structure, which is largely associated with the potential productivity of shale reservoirs. Externally, Domanikites and Domanikoids are represented by thin-bedded (shaley) rocks of dark gray and almost black colors. Figure 4a shows vertical slices of such rocks. They are characterized by an intense HC smell that is close to that of gasoline. The rock structure is microcrystalline and microaggregate: calcite is represented by very small crystals of micritic size, from first to 10–15 microns, and silica is represented by microaggregates of various shapes and a few microns in size.

The packing of crystals and microaggregates is relatively loose. The intercrystalline–interaggregate space forms the first level of pores and pore channels a few microns in size (Fig. 3a). It is unevenly filled with inclusions of scattered mature OM of various sizes. High resolution SEM studies show that the second level of pores is formed already in the organic matter itself (Ulmishek et al., 2017). The sizes of these pores are mainly less than 1 μm and usually much smaller. The pores of organic matter are well connected with each other by pore channels that are proportional to the pore diameters. Figure 3b shows an example of a pore system of organic matter. With authigenic dolomitization, which is expressed in the form of regular subrhombic crystals of dolomite, scattered in the kerogen–calcite–siliceous matrix (Fig. 4f), the material composition of Domanikites becomes more complex and the total porosity increases.

The described types of rocks of depression facies is the most important target of study, because it is an unconventional microporous reservoir of the MET Domanik stratum. In the cross-sections of the depression zone, the first type of rock is interpreted in the Upper Frasnian substage, Famennian, and Lower Tournaisian. Their two-level pore system (nanopores + micropores) is completely filled with syngenetic hydrocarbons and does not contain water.

The second petrophysical group of rock is outwardly similar to the first one; the rock is also dark gray and almost black in color, thin-bedded, and platy (Fig. 4b). However, the kerogen content decreases (before the transition to Domanikoids) and, accordingly, the content of calcite (mainly) and siliceous components increases. The rock structure is dominated by microcrystalline calcite, which has a tighter packing of crystals. The pore system is represented by loosely connected micropores (Fig. 3c). The rocks of the second group have almost no signs of hydrocarbons. They are common in the Middle Frasnian interval and occasionally occur further up the section. They form paragenesis with the rocks of the first group.

The third group of rocks in the depression zone is represented by limestones and siliceous limestones (Fig. 4c). They are characterized by a tight fine-microcrystalline calcite matrix with small bioclastic grains (mainly wackstone texture), less often with large fossil remains (floatstone). Figure 3d shows the microtexture of such a rock. Silica in the form of microaggregates is scattered in the microcrystalline calcite mass or replaces bioclasts. There is little organic matter; it is found in the form of inclusions, including along the shells of planktonic organisms. Such rocks are found in the Frasnian and Famennian intervals, but a significant increase in their proportion in the cross section is found in the Tournaisian, where the number and variety of rock grains increases and the structure is replaced by pack-wackstone and packstone with a high content of micrite. The third group of rocks almost does not contain any pores, or they are rare and isolated. Like the rocks of the second group, they are not of interest as potential net reservoirs.

A special group of reservoir rocks in the depression zone of the trough is represented by secondary hydrothermal dolomites (Fig. 4e) that formed as a result of the impact of high-magnesium thermal deep waters on the permeable interlayers of condensed rocks. In the Orenburg Region, the model of hydrothermal dolomitization has been described and proven for the carbonates of the Middle Devonian and the Frasnian (Vilesov et al., 2014). In the hydrothermal zones, the rocks are represented by coarse-crystalline dolomites with a common coarse size of saddle-shaped crystals. The pore space formed as a result of dissolution and replacement can be characterized as fractured–vuggy–cavernous. The rocks will have the highest reservoir properties in the intervals of hydrothermal dolomites. Such rocks belong to natural net reservoirs and are sporadically developed laterally. Similar processes of scattered hydrothermal dolomitization are observed in the Bazhenov formation, which indicates the common genesis of unconventional reservoirs (Vashkevich et al., 2018).

Thus, both Domanikites and Domanikoids can contain movable hydrocarbons in reservoirs with different types of pores; therefore, we use division into Domanikites and Domanikoids to distinguish vertical lithotypes with various contents of organic matter and for more convenient lithological grouping of rocks.

Genetic Features of Promising Deposits of the Domanik Formation

For the Domanik-type sediments, mainly in the depression part of the cross-section, a "closed" system of oil and gas accumulation is common, where the main processes occur as a result of the redistribution of matter within the sequence during dia- and catagenesis, i.e., without the introduction and removal of matter along a system of intersecting faults (Vashkevich et al., 2018, 2019). Other authors noted that the Domanik Formation sediments represented by siliceous–carbonate and carbonate–siliceous rocks that are enriched in algal organic matter have a high generation potential (Stupakova et al., 2016).

A redistribution of organic matter took place in unconventional reservoirs, as a result of epigenetic processes and the maturation of OM. The released volume of rock was filled with hydrocarbons, and syngenetic magnesium from algae formed scattered in situ dolomite (dolomitization) along the rock matrix (Fig. 4f). If the amount of magnesium in chlorophyll is 2.7%, then the concentration of Mg in the

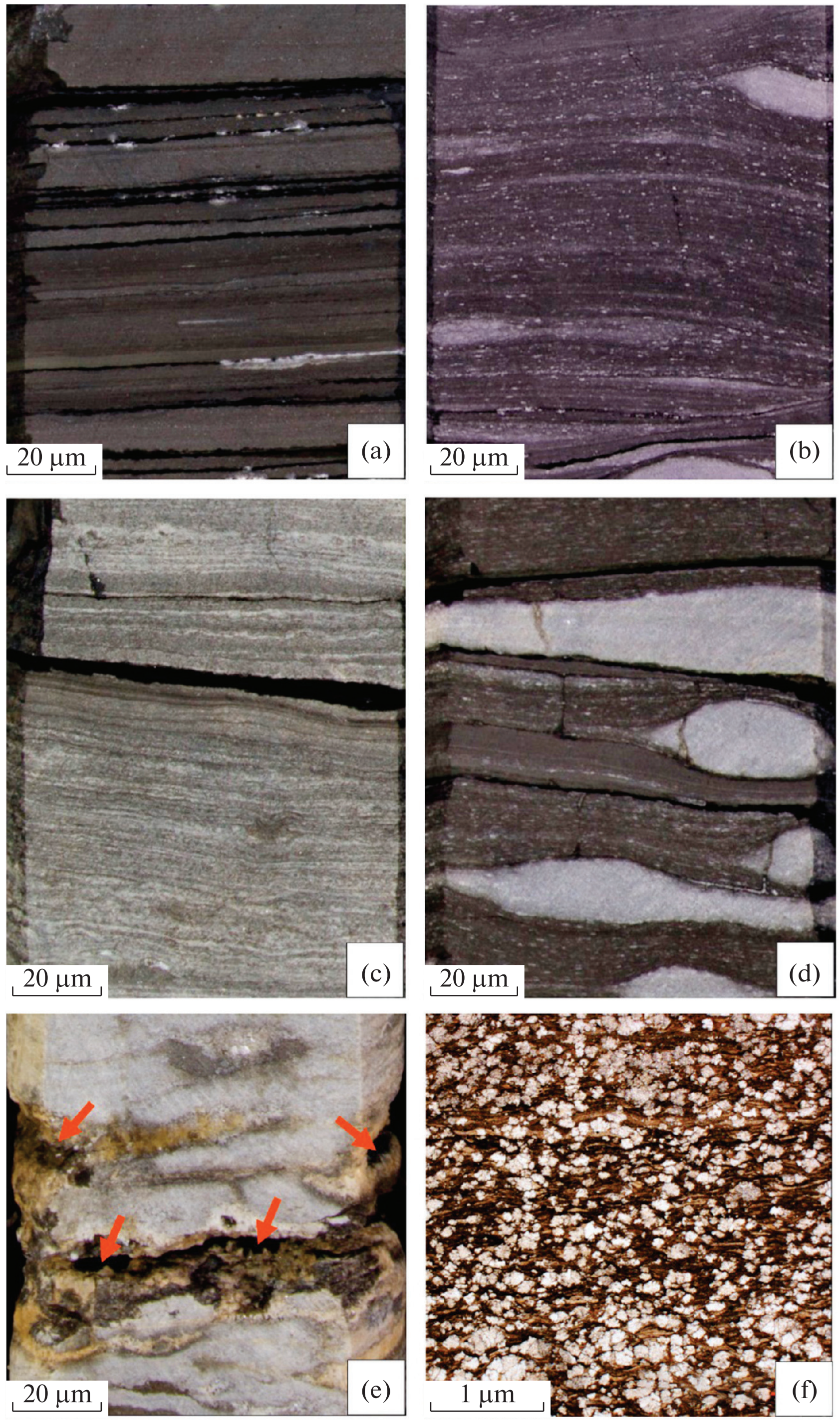

Fig. 4. Rocks of the depression facies of the Upper Frasnian of the Mukhanovo-Erokhovsky Trough, photographs of vertical sections of the core (a–e) and a thin section (f): (a) lithotype 1, oil-saturated carbonate-siliceous rock (Domanikite) with a microporous matrix and a high content of organic matter; (b) lithotype 2, siliceous-carbonate rock with numerous shells of plank-tonic organisms in the micrite matrix, the content of total organic carbon is reduced; (c) lithotype 3, fine-grained limestone with a dense micritic matrix; (d) carbonate-siliceous rock (Domanikite) with interlayers and lenses of siliceous bioclastic limestone; (e) limestone unevenly replaced by hydrothermal dolomite with large caverns; (f) Domanikite with intense dolomitization. The euhedral crystals of diagenetic dolomite are evenly distributed in the matrix containing total organic carbon.

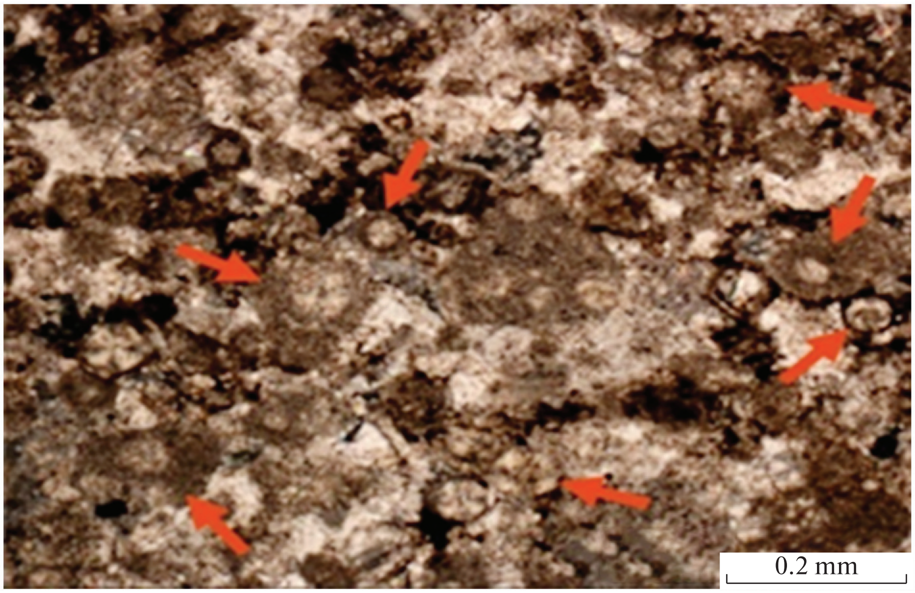

Fig. 5. Thin sections microphotograph of the medium-fine-grained bioclastic-spherical-peloid packstone with a recrystalized micrite matrix and numerous inclusions of the organic matter along the intergrain pores. Calcispheres are represented mainly by algae cysts (indicated by arrows). The Famenian Stage of the depression zone. Non-polarization light.

complexes in comparison with whole cells increases by 10 times and reaches 27% (Boychenko et al., 1968). Planktonic algae are one of the main sources of algal-sapropelic OM and, hence, the main supplier of syngenetic magnesium for dolomite generation that control secondary epigenetic porosity. For the most part, planktonic algae are buried in the form of organic matter, because they do not have a mineral skeleton. For this reason, they are difficult to see in thin sections. In fact, the Domanik-type micro-bedded sediments and veins of OM will be the compressed remains of planktonic algae and macrophyte algae (Fig. 5). The thin sections of shale reservoirs often demonstrate a “starry sky” picture with scattered in situ dolomite (Fig. 4f). We note that oil from shale reservoirs is often characterized by a green tint, which may indirectly indicate the source of OM (Zagranovskaya et al., 2021), because the chlorophyll transformation products give the oil a green hue.

Core studies have shown that the main part in the pore space structure of the Domanik Formation sediments is occupied by bitumoids with a high content of tar-asphaltene substances and reach up to 15 wt % of the rock volume. The distribution of bituminosity in the Domanik rocks is shown below in thin sections (Figs. 6, 7).

The organic matter in the Domanik sediments can be characterized by the presence of the maximum number of components: kerogen (in the smallest amounts), HC (saturated and aromatic fractions), and nonhydrocarbon components of oil, that is, resinous–asphaltene substances (RASs). In the generation processes, components of the organic matter are continuously redistributed, which is a key factor in forming the hydrocarbon extraction potential. During the migration of hydrocarbons outside the source rock, fractionation of the composition and predominant movement of saturated and aromatic hydrocarbons with a small part of heteroatomic compounds dissolved in it occurs. Resinous-asphaltene substances oversaturate the system, since they are only partially dissolved by saturated and aromatic hydrocarbons and, as a result of their high molecular weight, affect the reservoir properties of rocks, blocking the pore space, and also increase the density and viscosity of the fluid, thus preventing its extraction. Thus, in the cross-section of the Domanik-type deposits, interlayers with RAS contents that reduce reservoir properties should be separated.

Well Logging Data Interpretation

The Domanik-type deposits enriched in organic matter are interpreted within the Frasnian and Famennian stages of the Devonian interval and the lower part of the Tournaisian stage of the Carboniferous interval among tight carbonate–silicon rocks. Those are source rocks and can contain both movable or light hydrocarbons (LHC) and immovable or heavy resinous-asphaltene substances (RAS).

The initial stage in the interpretation of well-logging data is to justify the cutoff TOC (Total Organic Carbon) for separating Domanik-type sediments from the host rocks. The cutoff concentration of organic matter is associated with the measurement error of pyrolytic devices with programmable heating. Rock

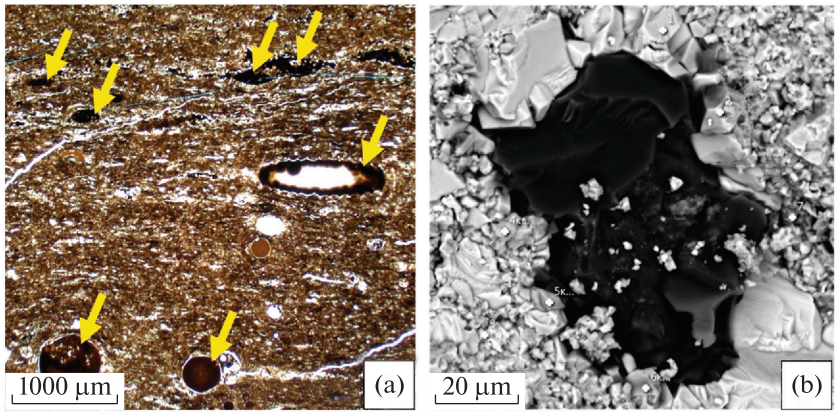

Fig. 6. The distribution of bituminous content or tarry-asphaltene substances in rocks of the Domanik type of the Semiluksky horizon of the Middle Frasnian of the Mukhanovo-Erokhovsky Trough: (a) shells of tentaculite and ostracod with inclusions of heavy hydrocarbons or tar-ry-asphaltene substances (photograph of a thin section of siliceous limestone); (b) inclusion of heavy hydrocarbons or resinous-asphaltene substances in the cavity of the recrystallized ostra-coda shell (photograph from a scanning electron microscope).

(a) (b) (c)

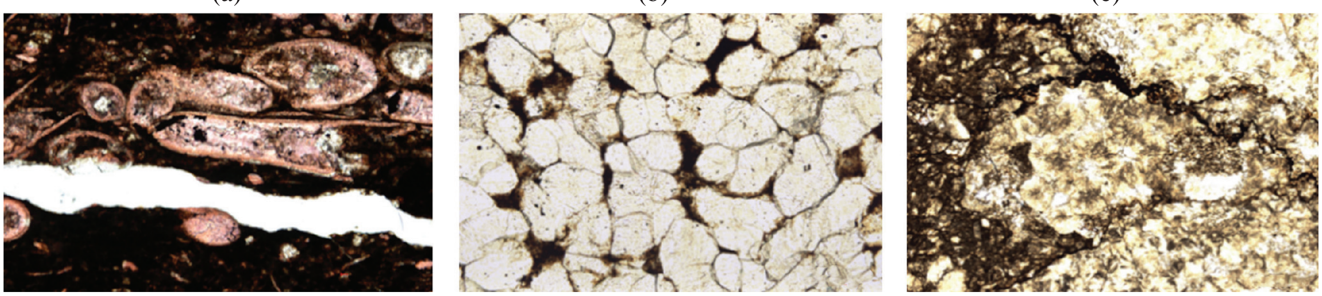

Fig. 7. The bitumen distribution in rocks of the Domanik formation (thin sections microphotographs): (a) Intraclastic-crystalline dolomitic limestone. The matrix is biomorphic-crystalline with bitumen; (b) crystalline limestone; the bitumen in the intercrystal pore space; (c) Intraclastic-polybioclastic-micritic dolomite limestone; intraclasts are fragments of algal limestone. Brown bitumen is distributed in intercrystal pore space and stylolites.

samples with TOC < 1.5% do not have clearly defined areas and recorded S-peaks, and, therefore, cannot provide quantitative parameters for the composition and properties of organic matter (Vashkevich et al., 2019). Therefore, the Domanik-type rocks are interpreted in wells by the cutoff TOC equal to 1.5%.

For pyrolytic studies of the Domanik-type deposits, it is recommended to use modes. The criteria for assessing the quality of the pyrolytic studies should be $S2b$–T_{maxb} correlations, or additional measurements on a TOC analyzer (direct analysis of organic matter concentration).

The next stage of interpretation is to determine TOC from well-logging data. For this, one should switch from core studies to well-logging methods, which allow one to assess TOC in wells without geochemical study of core and drill cuttings. The TOC should be assessed by any of the methods suggested below:

(1) if a representative core sample collection is available, establish a stable connection with the uranium component in the spectral measurement;

(2) if a representative core sample collection is available, establish a stable connection with the gamma-ray index ΔJ_{gc};

(3) determine TOC using the "core TOC—core thermophysical studies—logging" type relations.

One of the additional methods is to use noncontact thermophysical core studies. These studies provide high-resolution thermal conductivity profiles along a well built by optical scanning method and converted into continuous TOC profiles (Patent no. RF 2720582, dated May 12, 2020) (Popov et al., 2017). The high efficiency of this method is confirmed by the good match between the TOC assessed based on core thermophysical profiling and the pyrolysis TOC (Fig. 8) (Bogdanovich et al., 2009), as well as the close relationship "TOC (thermophysics)—gamma-ray index ΔJ_{gk}" after layer-by-layer upscaling of each of these parameters

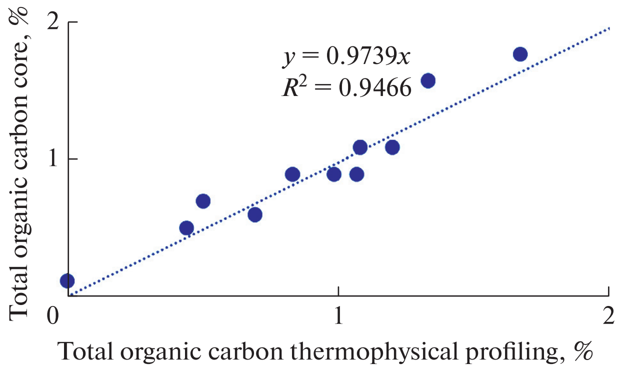

Fig. 8. Comparison of the content of organic matter from the core, obtained from the results of pyrolysis, and the content of total organic carbon, determined from the results of thermophysical profiling on the core, after layer-by-layer averaging of the results for each parameter. Baleykinsky section.

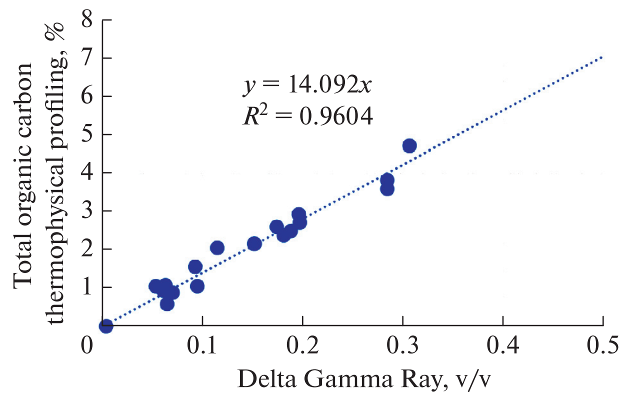

Fig. 9. The "total organic carbon by thermophysical profiling, double difference parameter" dependence after layer-by-layer averaging of the results for each parameter. Baleykinsky section.

(Fig. 9). The resulting relationships have a high correlation factor.

For the transition from the core-based cutoff TOC value to the well-logging data, it is recommended to use the cutoff values obtained for the uranium component of gamma-ray spectrometry, acoustic logging, and hydrogen content (Fig. 10).

The Domanik-type deposits include interlayers with movable light hydrocarbons and with pore space, and interlayers with immovable containing resinous-asphaltene substances (Figs. 6, 7).

Resinous-asphaltene substances fill the pore space, thereby significantly deteriorating the poroperm properties. The radioactivity of such sediments is due to the presence of scattered organic matter (OM) in the rock matrix and the presence of resinous-asphaltene substances in stylolites, inside tentaculite shells, in intercrystalline pores, in separate layers, and in veins (Gorozhanin et al., 2019; Zagranovskaya et al., 2021). Therefore, rocks with various saturating hydrocarbons should be identified according to the group composition which determines their movability. Electrical logging data should be used for this purpose. Interlayers with movable hydrocarbons will have lower electrical resistivity readings (depending on the area under study, up to 1.000 Ohm) than interlayers containing resinous-asphaltene substances. The authors provide an example of wells drilled in the Buzuluk Depression to Domanik-type deposits with the following cutoffs for separating between interlayers with movable hydrocarbons and interlayers with resinous-asphaltene substances (RAS) (Fig. 11).

We note that kerogen is also a part of OM, and, depending on the maturity of organic matter, it can contain free fluid in the pore space and be identified as a layer with porosity. In this regard, kerogen-containing layers with immature OM are included in the sample collection with tight rocks containing RAS, and kerogen-containing layers with mature OM will be interpreted as layers with organic porosity. It is not recommended to separate kerogen-containing layers according to well-logging data, because under various geological and geochemical conditions of rock transformation, they will have various poroperm properties, which will not be fully shown in the well-logging data interpretation. As well, the well geochemical studies data showed a low content of kerogen in the Domanik-type sediments, which will not be reflected in the interpretation results.

As well, according to the material composition of rocks and the presence of movable hydrocarbons, a lenticular, sporadically developed (irregularly, from case to case) natural reservoir, not correlated laterally (Vashkevich et al., 2018, 2019; Zagranovskaya et al., 2021), is interpreted in a highly radioactive cross-section.

A natural reservoir is a rock unit that is capable of containing fluid and providing it in any, even insignificant amounts, without reservoir stimulation. Usually, a natural reservoir is separated by the presence of direct logging signs (radial resistivity gradient measured by multiradii probes and narrower wellbore diameter on a caliper curve); however, the Famennian and Frasnian sections often have no direct signs, which significantly complicates net reservoir separation. In such cases, a natural reservoir is interpreted by the presence of decompaction from acoustic and density curves, lower gamma-ray and neutron readings with a cutoff porosity over 4.5%, as well as higher gas shows.

Often, a natural reservoir is confirmed by a mud logging anomaly (if available in a well-logging complex) (Petersile et al., 2003). However, the anomaly identified by mud logging is of an indirect nature, and the reservoir boundaries must be confirmed otherwise.

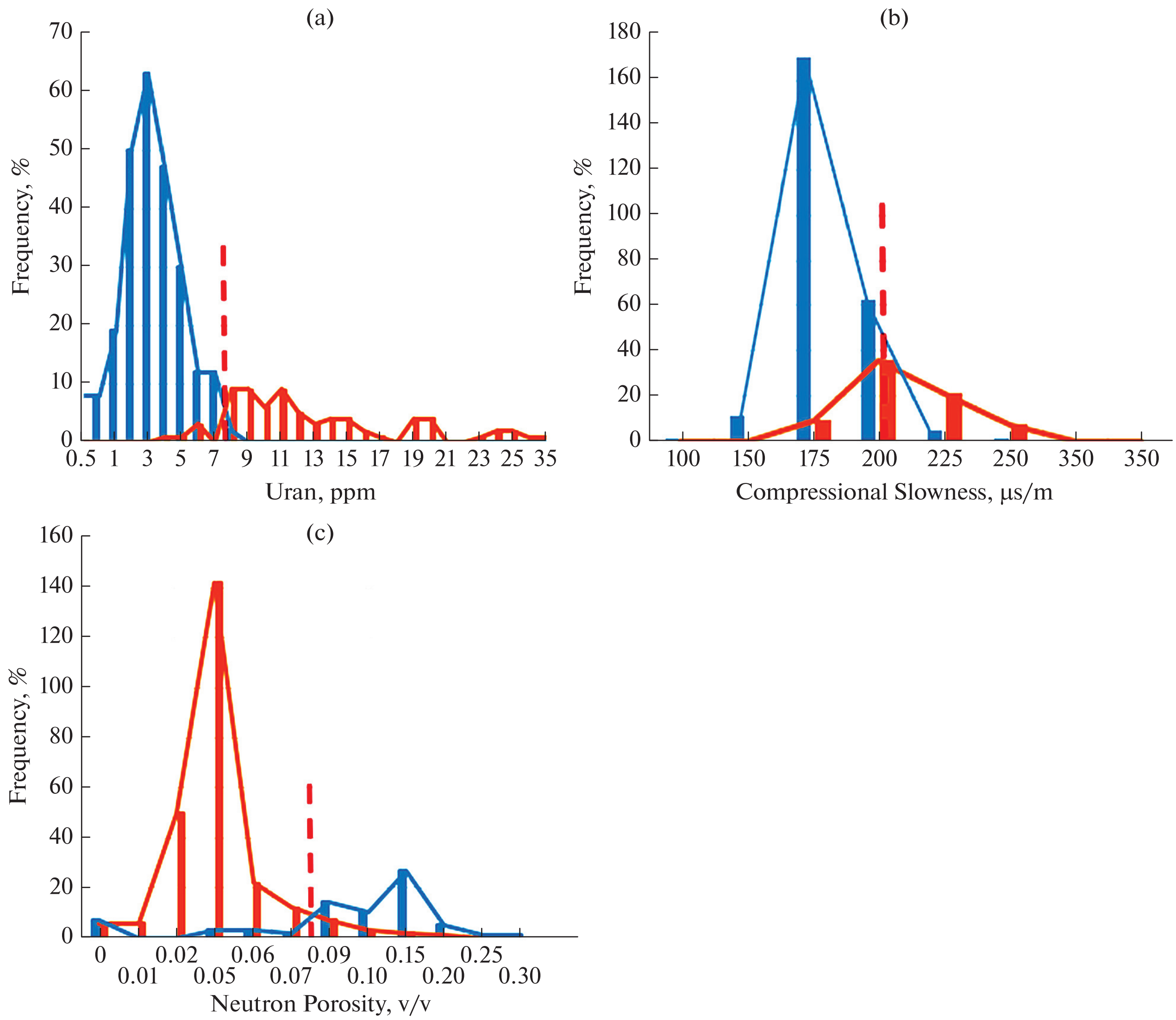

Fig. 10. The boundary value of the separation of rocks. (a) with an increased content of total organic carbon from the host by the uranium component of the spectral gamma-ray logging); (b) by acoustic logging for the entire interval; (c) by hydrogen content. The orange color in the figure shows the source rocks with a high content of total organic carbon, blue shows the host rock.

Summing up, it should be noted that within the Domanik-type sediments, three types of rocks are distinguished that contain both movable and immovable hydrocarbons and are characterized by the following parameters:

— rocks with TOC > 1.5%, resistivities of up to 1000 Ohm (depending on the area under study), with porosity, containing kerogen and light movable hydrocarbons;

— Domanik-type sediments (TOC over 1.5%), with high resistivities of up to 10.000 Ohm, containing immovable hydrocarbons (resinous-asphaltene substances) in the pore space;

— a natural reservoir with porosities above 4.5%, with direct signs or no signs. We note that, depending on the TOC content, a natural reservoir can be characterized as containing TOC > 1.5%, or without TOC. The interpretation results are shown in Fig. 12.

RESULTS

The Results of Lithological, Mineralogical, and Material Studies of the Domanik Formation and Identifying their Genetic Characteristics

As in the Bazhenov Formation, oil in the Domanik-type sediments is generated from its own organic matter. The movability of hydrocarbons depends on the connectivity of the pore space and the OM maturity, as well as on the OM component composition. The area of accumulation of movable hydrocarbons is silicon and dolomitized carbonate layers with remains of specific fauna and algae which form alternating layers 0.2–0.5 m thick (Vashkevich et al., 2018, 2019).

The pore space in the Domanik-type sediments is formed as a result of epigenetic processes and is represented by fractures and vugs, intergranular, intercrystalline porosity, and organic porosity itself. There is a relationship between higher porosity and an increase in TOC in siliceous (Ulmishek et al., 2017) and dolomitized interlayers (Vashkevich et al., 2018, 2019; Zagranovskaya et al., 2020, 2021). V.B. Tatarsky (Tatarsky et al., 1939) was the first to draw attention to the formation of oil-bearing dolomites in the presence of significant amounts of organic matter.

In the Domanik-type sediments, dolomitization is more often formed layer-by-layer, expressed in the development of dolomite crystals along the bituminous matrix. Therefore, the definition of "organic" porosity includes a broader concept than just the kerogen porosity. This is a more complex physical and chemical process of the organic matter transformation and elements redistribution within a sequence in the maturation process. We note that the degree of dolomitization varies from partial to complete and the form of dolomite segregations indicates a developed epigenetic process (Vashkevich et al., 2018). As a result of diagenetic processes at different stages of OM transformation and maturation, a redistribution of components in the rock took place. Dolomitization indirectly indicates an upward change in reservoir properties.

In the generation processes, components in organic matter are continuously redistributed, which is a key factor in the formation of the hydrocarbon extraction potential. Immovable resinous-asphaltene substances oversaturate the system and affect the reservoir properties of the rocks, plugging the pore space, thereby interlayers with a high RAS content reduce the poroperm properties of net reservoirs.

The Results of Well Logging Interpretation for the Domanik Formation Sediments

The basics of well-logging data interpretation for separating oil net pay thicknesses are justified based on the identified geological–geophysical and geochemical features of the deposits.

The host siliceous–carbonate rocks include: the oil source rocks as such which include interlayers containing resinous-asphaltene substances (RASs). Natural reservoirs are sporadically developed throughout the cross-section.

The study provides the cutoffs for the well-logging complex to separate the Frasnian–Famennian sediments of the Domanik Formation and the Lower Carboniferous into layers that contain hydrocarbons of various levels of movability.

The cutoffs identified by well-logging tools for the Frasnian and Famennian stages differ; however, in general, this does not lead to any significant difference in oil net pays.

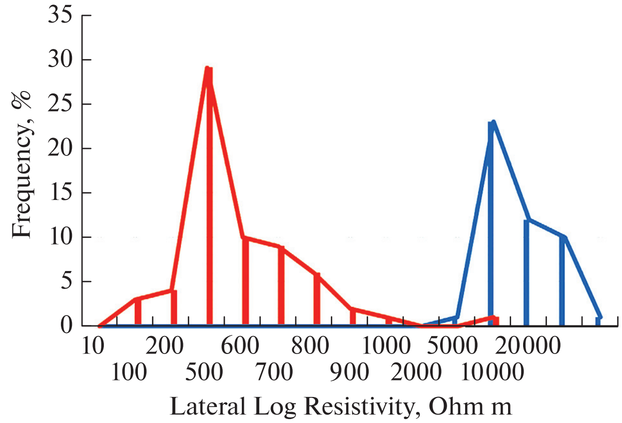

Fig. 11. An example of determining the boundary value of the resistivity for separating rocks containing light hydrocarbons from rocks with immobile hydrocarbons (resinous asphaltene substances). Orange color in the figure shows Domanik type interlayers with mobile hydrocarbons, gray – dense interlayers with immobile hydrocarbons (resinous-asphaltene substances).

More accurate "core-log" correlations on the organic matter content will be built only based on continuous thermophysical core scanning.

The net pays of the Domanik-type cross-section were separated by the following cutoff criteria according to the well-logging data:

— uranium component (by natural gamma-ray spectrometry) ≥5.3%;

— acoustic density (by acoustic logging) ≥190 US/M;

— hydrogen content (by neutron logging) ≥6.3%;

The cutoff resistivity for separating interlayers, taking the group composition of hydrocarbons and their movability (RAS and oil) into account by lateral logging data is 870 Ohm.

The sporadically developed natural reservoir is separated by:

— minimum density logging readings;

— maximum acoustic logging readings;

— cutoff porosity equal to 4%;

— confirmed by testing results and abnormal mud logging readings.

DISCUSSION

Lithological and Genetic Features that Affect Changes in the Reservoir Properties of the Domanik Formation

The oil content and properties of promising unconventional sediments are interrelated by the net reservoir formation and oil and gas generation processes.

The Domanik Formation is characterized (mainly in the depression part of the cross-section) by a

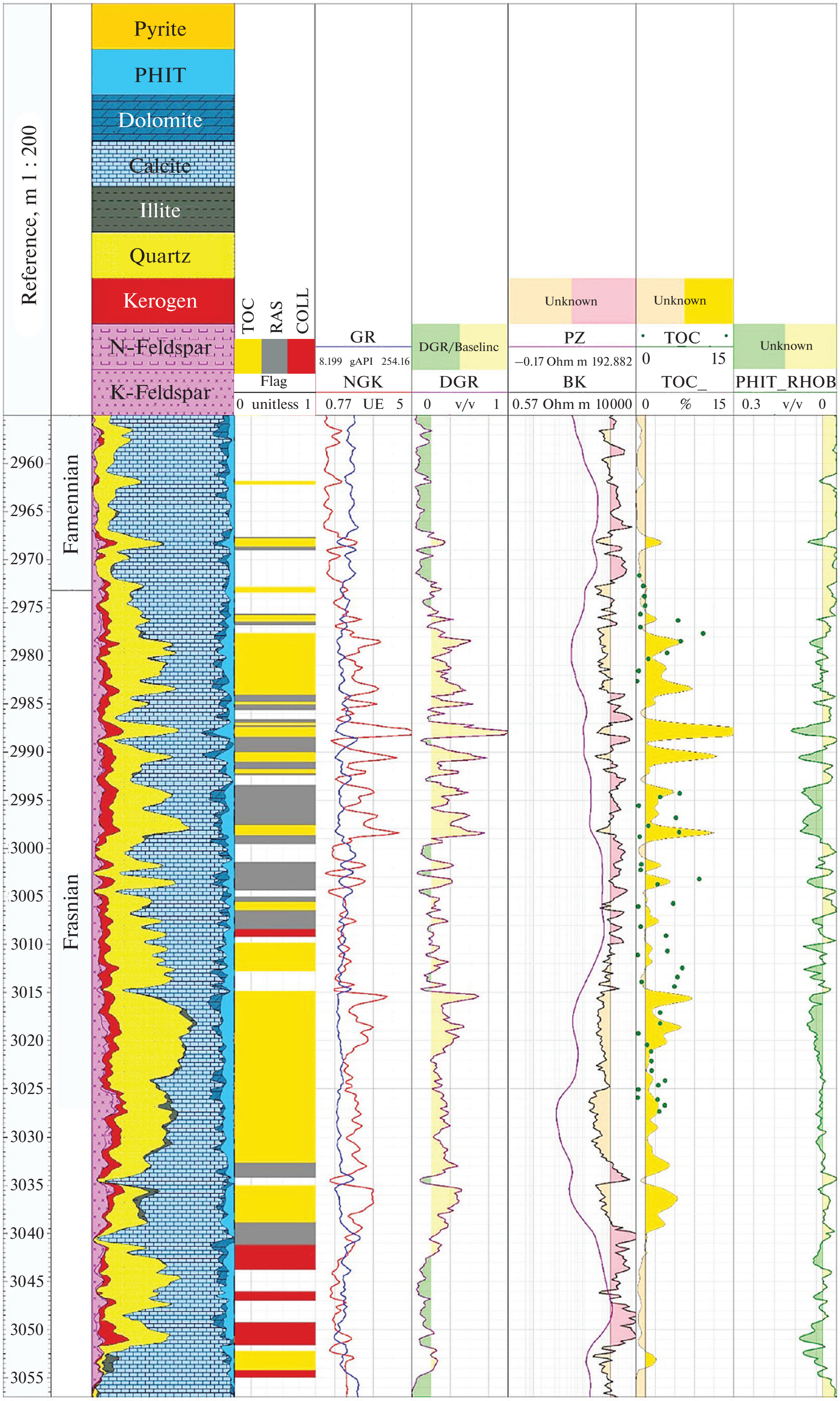

Fig. 12. Example of the allocation of the productive part of the Domanik formation. TOC, Total Organic Carbon; RAS, resinous-asphaltene substances; COLL, reservoir with porosity above 4.5%; NGK, neutron gamma; GR, gamma ray; DGR, normalized GR; BK, lateral log resistivity; PZ, potential log resistivity; PHIT, total porosity; RHOB, bulk density.

"closed" oil and gas accumulation system, where the main processes occur as a result of the matter redistribution within a sequence during dia- and catagenesis, i.e., without the introduction and removal of matter along the system of intersecting faults (Zagranovskaya et al., 2021). The volume and connectivity of the pore space in unconventional reservoirs were formed as a result of epigenetic processes and OM maturation. Syngenetic hydrocarbons filled the available pore space and redistributed the syngenetic magnesium of the algalsapropelic OM and formed scattered in situ dolomite crystals along the rock matrix. Scattered in situ dolomite in the rock matrix increases the proportion of inter-crystalline pores, thereby forming an unconventional microporous reservoir filled with autochthonous hydrocarbons and oil components.

In the process of OM maturation and hydrocarbon migration, the OM components are redistributed in the pore space; thus, the available pore space can gradually be filled with resinous-asphaltene substances, which strongly reduces the reservoir properties of unconventional reservoirs. Resinous-asphaltene substances oversaturate the system, since they are only partially dissolved by saturated and aromatic hydrocarbons and, as a result of their high molecular weight, affect the poroperm properties of rocks by blocking pore spaces, and also increase the density and viscosity of the fluid preventing its extraction. Therefore, during the interpretation, the RAS-containing interlayers that reduce the reservoir properties of the formation should be separated in the cross-section.

Thus, the definition of "organic porosity" includes a broader concept than just the kerogen porosity. This is a more complex physical and chemical phenomenon for an unconventional reservoir resulting from the organic matter transformation process and element redistribution within the reservoir as a result of OM maturation, as well as the redistribution of the OM components and hydrocarbon migration.

Recommendations for Well-Logging Interpretation for Domanik Formation Deposits

The interpretation of the Domanik Formation deposits according to well-logging data consists in the isolation of interlayers containing resinous-asphaltene substances, oil-source rocks and a sporadically developed natural reservoir.

The allocation of the effective part of the section for the deposits of the Domanik Formation is based on boundary criteria based on the data of geophysical studies of wells, which can vary and be refined depending on the studied area and changes in the lithological composition (Zagranovskaya et al., 2020). In the process of interpreting geophysical studies of wells, it is important to pay special attention to the mineralogical composition of rocks, using an extended well-logging complex and special core data aimed at studying the mineralogy of Domanik rocks, and, as a result, refining the petrophysical model. To clarify the porosity according to well-logging data in the Domanik productive deposits, it is recommended to construct a volumetric mineralogical model based on a system of linear petrophysical equations, by combining acoustic, density, and neutron methods. When constructing a volume model, it is necessary to use all possible well-logging methods aimed at assessing the lithology and understanding the pore space of rocks of the Domanik Formation.

Lessons Learned and Future Research Directions

The deposits of the Domanik Formation in the central part of the Mukhanovo-Erokhovsky trough are highly promising. Studies of these deposits are being systematically continued. As a result of the search and evaluation drilling, it is planned to select core material. The extended research program includes studies ranging from filtration and capacitance properties to fine mineralogical analysis, thermophysical characteristics (Popov et al., 2016), geochemical parameters, and isotope studies of carbonates, as well as organic matter.

In order to obtain reliable core–well-logging dependencies for the interpretation of the effective thicknesses in project wells, it is planned to perform an extended set of geophysical studies, including CMR, FMI, and Litho Scanner.

CONCLUSIONS

During this study, methodological approaches have been developed for identifying net pays in the Domanik Formation deposits according to well-logging data in order to reliably estimate the reserves and resource potential.

With a large number of existing wells and without any core material, the problem is very urgent for the Volga-Urals Petroleum Province.

A close correlation was revealed when defining the TOC by the "TOC (thermal physics)–gamma-ray index ΔJ_{gk}" technology after layer-by-layer upscaling of each of these parameters with a high correlation factor.

As a result, when assessing the oil and gas potential within the cross-section according to well-logging data, the authors have distinguished three groups of rocks: unconventional reservoirs with a higher OM content and with movable hydrocarbons; bituminous rocks with part of the pore space filled with resinous-asphaltene substances; and enclosing tight carbonate rocks without organic matter. As well, sporadically developed conventional reservoirs, which are not correlated laterally, have been distinguished throughout the Domanik cross-section.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

ADDITIONAL INFORMATION

The article was translated by the authors.

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