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Types of sections and oil-bearing prospects of the Bazhenov formation in the Nadym-Ob interfluve

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Abstract. The article presents the results of studying the geological structure of the Bazhenov formation in the Nadym-Ob interfluve of West Siberia with the aim of predicting the oil content of this black shale stratum. As a result of interpretation of a wide range of well logging represented by electric, radioactive and acoustic logging, with subsequent matching of these results with paleontological definitions of micro- and macrofauna, the distribution of the Salym, Nizhnevartovsk and Tarkosalinsky types of sections of the Bazhenov formation was clarified, transitional areas between them were identified. It has been established that the Tarkosalinsky type is more widespread in the western direction than was shown earlier and is also distinguished in the Vengayakhinskaya, Yarainerskaya and other areas. The Nizhnevartovsk type, on the contrary, has a narrower distribution and stands out directly within the same name arch and to the south by the Var'egan-Tagrinskii megauplift.

On the basis of geological, geochemical, geophysical criteria and the results of an inflow test in deep wells, a map of the oil potential prospects of the "classical" sections of the Bazhenov formation has been compiled. Regional prerequisites (high catagenesis of organic matter, significant modern concentrations of organic carbon, etc.) for the discovery of industrial accumulations of oil in the Bazhenov formation in the southern regions of the Yamalo-Nenets Autonomous District are identified. The results of the test for the inflow of the Bazhenov formation in this area in the 70–90s XX century were analyzed; repeated, interval testing of these deposits using modern methods of stimulation of the inflow is recommended. The necessity of laboratory lithological, petrophysical, geochemical study of the core of the Bazhenov formation in the southern part of the Yamalo-Nenets Autonomous District is substantiated with the aim of determining its lithological composition, identifying oil source and oil productive intervals, studying the reservoir structure and the nature of saturation of its void space, developing recommendations for calculating oil reserves and creating technology for its cost-effective production.

Keywords: Bazhenov formation, West Siberia, types of sections, oil content

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Introduction

Black shale deposits are the main source strata throughout the world. They are common in the West Siberian, Volga-Ural, Timan-Pechora, North Caucasian oil and gas provinces of Russia, the basins of North America (Williston, Appalachian, Perm, etc.), Columbia (Middle Magdalene), the Caribbean and Middle East regions, the North Sea, etc. The main feature of these strata is that they contain rocks that are both source rocks and oil bearing reservoirs. The hydrocarbon resources in these strata are classified as difficult to recover.

The experience of studying and the success of developing hydrocarbon accumulations associated with unconventional tight reservoirs and shale complexes in the United States has provided a serious incentive for the study of similar objects around the world, including in Russia. Currently, the US shale formations play an important role in the oil and gas industry of the country, among which the largest oil formations are Bakken, Eagle Ford; gas – Marcellus, Haynesville, Fayetteville, Barnet (Prishchepa et al., 2014). Also, great prospects are currently associated with the Green River kerogen-bearing formation (Soeder et al., 2019).

In the West Siberian oil and gas province, it is more and more difficult to maintain the level of oil production from traditional granular reservoirs every year. Giant and large deposits have already been discovered, and explored reserves have been largely developed. There

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is a need to involve in industrial development new, as yet insufficiently studied objects, among which the most complex, perhaps, is the Bazhenov formation. Back in 1961, the outstanding Soviet geologist F.G. Gurari predicted its possible commercial oil-bearing capacity, which was confirmed in 1967 by an oil fountain at the Salym field. In recent years, new, significantly more accurate data on the geological structure, stratigraphy and paleontology, paleogeography have appeared (Kontorovich et al., 2013; Stupakova et al., 2016; Stafeev et al., 2017; Ryzhkova et al., 2018; Kontorovich et al., 2019a) of the Bazhenov formation and its age analogs in the West Siberian sedimentary basin. Based on the interpretation of a wide range of well logging, the results of which were linked to paleontological determinations of the age of micro- and macrofossils, the authors proposed significant clarifications of the boundaries of the distribution of the types of sections of the Bazhenov Formation in the Nadym-Ob interfluve.

On the first-ever diagrams and maps, the main oil-bearing prospects of the Bazhenov formation were predicted in the Salym oil and gas accumulation zone. In recent years, these forecasts have been repeatedly detailed and supplemented (Zubkov, 2016; Kolpakov et al., 2016; Baranova, 2018; Skvortsov et al., 2018a, b; Kontorovich et al., 2019b). However, even today, the main prospects for the oil-bearing capacity of the Bazhenov formation are associated with the western (Krasnoleninskaya zone of oil and gas accumulation) and central (Salym group of fields) regions of the Khanty-Mansiysk Autonomous District. To the east, commercially productive hydrocarbons have been discovered, including in anomalous sandy sections of the Bazhenov formation, which have a genesis different from the "classical shale" sections and thus are an independent object for study. They are not considered in this study.

On the territory of the the Yamal-Nenets Autonomous District, much less analytical studies of the core of the Bazhenov formation using modern techniques (Kontorovich et al., 2018a, b) have been performed; this stratum has been tested for inflow in single wells. Nevertheless, in the south of this region at the Pyakutinskoye, Malopyakutinskoye, Vengayakhinskoye and further north at the Izvestinskoye and Palnikovskoye fields, small reserves of oil in the Bazhenov formation have been discovered, which suggests higher prospects for its oil-bearing capacity in this region. Based on the interpretation of geological and geophysical materials with the involvement of data on the geochemistry of organic matter, the authors analyzed the regional prospects for the oil-bearing capacity of the Bazhenov formation in the Nadym-Ob interfluve and proposed recommendations for its further study.

Factual material and research methodology

The study is based on data and results collected, systematized and interpreted by the authors:

1) Diagrams of electrical logging (apparent resistivity (AR – Gz3 tool), induction logging (IL), lateral logging (LL), micro-logging (MGP – microgradient tool, MPP – micropotential tool, MLL – micro-lateral logging), spontaneous polarization potential (PS), caliper logging (CL), acoustic logging (AL), radioactive logging (gamma-ray logging (GR), neutron gamma-ray logging (NGL), thermal neutron logging: long (TNLL) and short

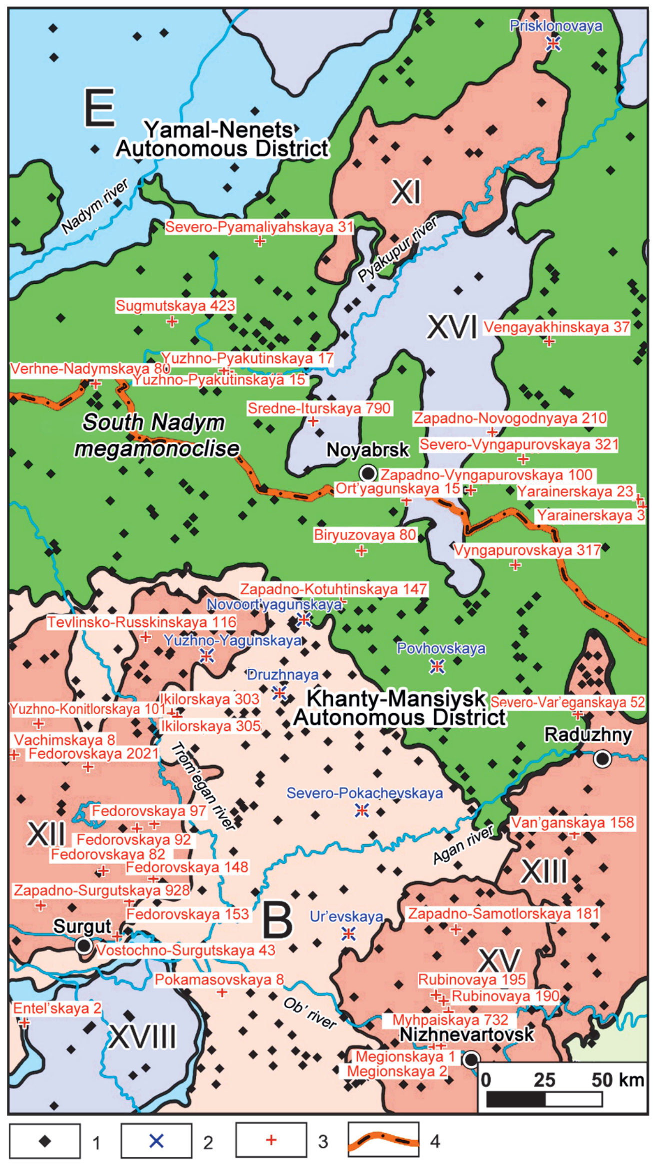

Fig. 1. Fragment of the tectonic zoning map of the Nadym-Ob interfluve (Kontorovich et al., 2001). 1 – wells in which the authors have interpreted the logging complex data; 2 – wells with the results of analytical core studies; 3 – wells with definitions of micro- and macrofauna; 4 – administrative boundaries. Tectonic elements: B – Khentei hemianteclise, E – Nadym hemisyneclise, XI – Northern arch, XII – Surgut arch, XIII – Var'egan-Tagrinskii megauplift, XV – Nizhnevartovsk arch, XVI – Pyakupur-Amputinskii inclined trough

(TNLS) tools, gamma -gamma density logging (DGL), for 546 deep wells (Figure 1);

2) 124 determination of the age of micro- and macrofossils of the Late Jurassic-Early Cretaceous age for 57 wells (Figure 1) from the data bank of IPGG SB RAS (definitions by A.S. Alifirov, Yu.A. Bogomolov, O.S. Dzyuba, V.A. Zakharov, L.K. Levchuk, S.V. Meledina, B.L. Nikitenko, B.N. Shurygin, O.S. Urman, O.V. Yazikova) and from published materials, including:

• Volga ammonites in wells: Zapadno-Samotlorskaya 181, Severo-Var'eganskaya 52, Yarainerskaya 3, Vengayakhinskaya 37 and 355, Zapadno-Vyngapurovskaya 100;

• Middle-Late Volga, Early Berriasian bivalves found in wells: Zap. Samotlorskaya 181, Pokamasovskaya 8, Ortyagunskaya 15, Severo-Vyngapurovskaya 321, Zapadno-Vyngapurovskaya 100, Vengayakhinskaya 37 and 355, Sugmutskaya 423.

• Foraminiferal assemblages of the upper Middle Volga – the base of the Boreal Berriasian found in well Vyngapurovskaya 317.

3) Results of inflow tests the sections of the Bazhenov formation in 19 wells.

In 2014–2016, a comprehensive study of the Bazhenov formation was carried out at the IPGG SB RAS. As part of this work, the core of deep wells in the Povkhovskaya, Druzhnaya, Yuzhno-Yagunskaya, Novoortyagunskaya, Severo-Pokachevskaya and Urievskaya areas was studied (Figure 1). As a result of analytical studies of core samples, the boundaries of the Bazhenov and Georgievka formations were precisely established (Figure 2). These wells were selected as reference wells for subsequent correlation of the Bazhenov formation sections.

In those wells where these deposits have not been studied by analytical methods, stratigraphic dissection of sections of the Upper Jurassic and Lower Cretaceous was carried out according to logging data, and a link was made with the definitions of micro- and macrofauna. After that, in each well, the arithmetic mean values of electrical resistivity, natural radioactivity and density (based on the analysis of the dependence on radioactivity with subsequent correlation by well data) of the Bazhenov rocks were calculated and maps of the distribution of these parameters presented below were constructed.

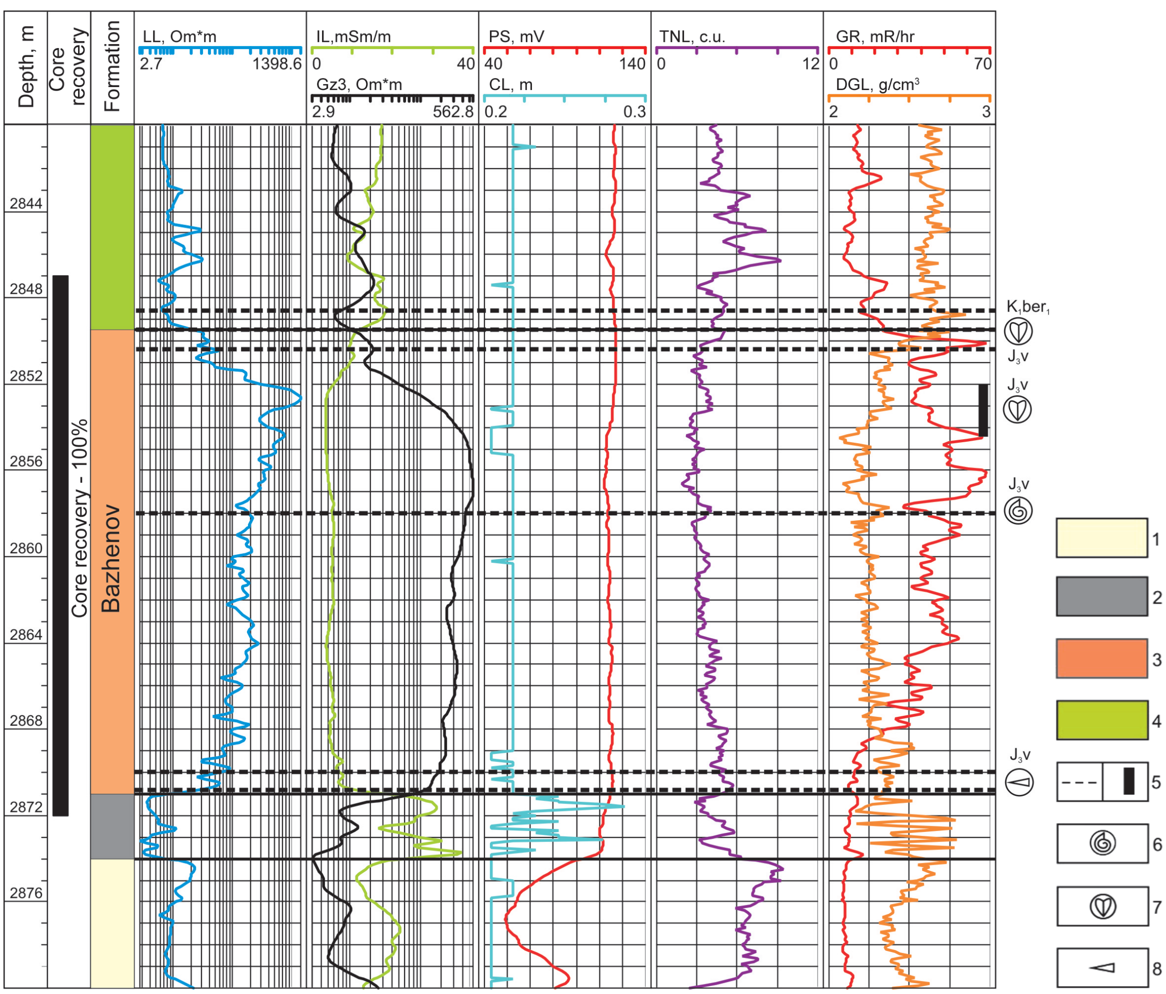

Fig. 2. Geological and geophysical log for one of the wells of Druzhnaya area. 1 – Vasyugan formation; 2 – Georgievka formation; 3 – Bazhenov formation; 4 – Sortym formation; 5 – levels with paleontological findings; 6 – ammonites; 7 – bivalves; 8 – belemnites.

Types of sections of the Bazhenov formation

The systematization of the analytical material accumulated in recent years on the lithology of the Bazhenov formation and the geochemistry of the organic matter contained in it allowed different scientific teams to independently develop classifications of its rocks based on the percentage of the main rock-forming components in them (Kontorovich et al., 2016; Kalmykov et al., 2017; Makarova et al., 2017; Nemova, 2019). In the central and western parts of the study area, the Salym type of section is distinguished (Figure 3) (Braduchan et al., 1986). In the north of the Khentei hemianteclise (Figure 1), its lower part is dominated by dark brown massive silicites and kerogen silicites with interlayers of radiolarites (Eder et al., 2016). In the northern direction, a gradual decrease, up to the disappearance, of the thickness of the silicite member is observed (Eder et al., 2017). In the Povkhovskaya area, in the lower part of the formation, a radiolarite member is distinguished (Eder et al., 2016). The middle part of the section consists of dark gray kerogen-siliceous mixtites with interlayers of silicite-radiolarites with frequent interlayers of relics of bivalve shells. The upper part of the formation is represented by interbedding of kerogen-clayey and kerogen-siliceous-carbonate mixtites with relics of coccolithophorids (Eder et al., 2016). In the same part of the section, a coccolith member is distinguished, which is characterized by high values on the LL and AR, GR curves. This member is also distinguished to the north, on the Prisklonovaya area (Eder et al., 2017, 2019), in the Tarkosalinsky type of the section of the Bazhenov formation. In the north of the Nizhnevartovsk arch, the eponymous type of section of the Bazhenov formation is represented by clayey-siliceous rocks; the coccolithic member is not distinguished in the upper part of the section (Eder et al., 2015).

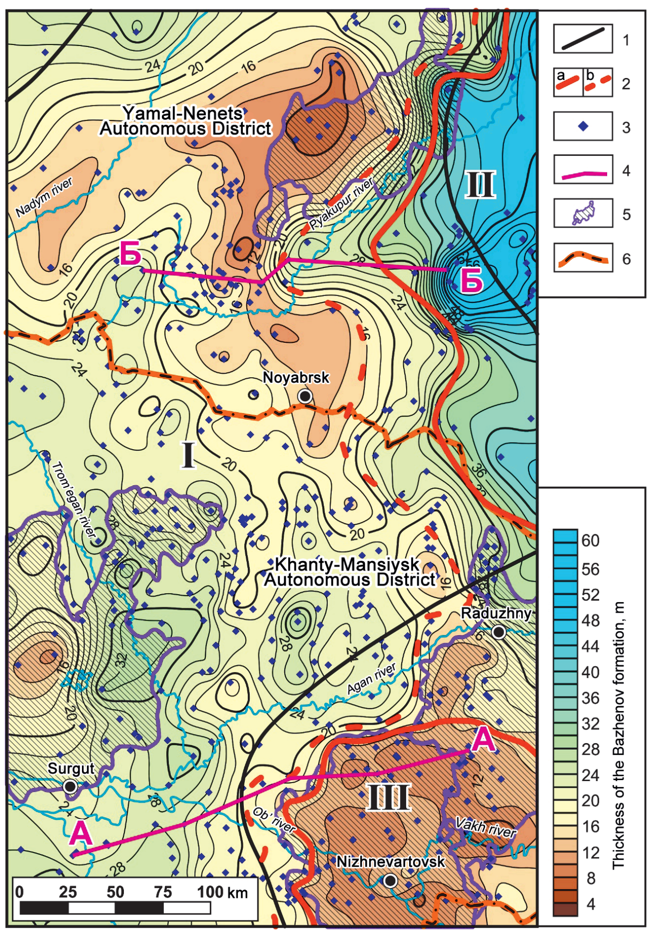

Fig. 3. Thickness map of the Bazhenov formation. 1 – boundaries between the types of sections after (Braduchan et al., 1986): I – Salym, II – Tarkosalinsky, III – Nizhnevartovsk; 2 – author's a) boundaries of distribution of types of sections of the Bazhenov formation; b) the boundaries of the transition zones between them; 3 – wells with breakdowns by the authors, used for mapping; 4 – lines of correlation profiles; 5 – boundaries of positive tectonic elements of the 1st order; 6 – administrative boundaries.

The largest thicknesses of the Bazhenov formation in the Salym-type sections are observed in the axial part of the Khentei hemianteclise and reach 30–32 m (Figure 3). They decrease to 10–12 m in the most elevated part of the Surgut arch. Another zone of low thickness is distinguished in the area of the Northern Arch, as well as to the south and west of it. In the north of the studied region, eastward, there is an increase in the proportion of terrigenous sediments in the section, which is accompanied by a gradual increase in the thickness of the Bazhenov formation – the Salym type of section becomes Tarkosalinsky, the thickness of which in the study area exceeds 55 m (Figure 3). In the southeast of the region, the Salym type of section is replaced by the Nizhnevartovsk type, which is accompanied by a reduction in the thickness of the Bazhenov formation at the Bazhenov arch to 12–14 m and less and, most likely, associated with its uplift in the Volgian age. The thickness of the Bazhenov formation was used by the authors as one of the main criteria for clarifying the boundaries of the distribution of sections of different types and identifying the transition areas between them.

The radioactivity of black shale rocks is closely related to the content of organic matter (OM) in them (Neruchev, 1976, 1982, etc.), which is a sorbent of uranium from seawater. Accordingly, the higher the OM concentration in the strata, the higher the radioactivity of such deposits will be. This relationship can be traced in the results obtained by the authors. The highest valuesof the average radioactivity of the Bazhenov formation are recorded within the Khentei hemianteclise (Figure 4A), where a high modern content of organic carbon (TOC) is recorded in it (Kontorovich et al., 2018c). Areas of increased radioactivity are observed in the saddle between the Surgut and Nizhnevartovsk arches, as well as to the north of the latter; values reach 60–70 μR/h (Figure 4A). Within the limits of the South Nadym megamonoclise, the radioactivity of the rocks is much less, it varies on average from 10 to 20, in some areas up to 25 μR/h.

For the Bazhenov formation of the Salym type, increased radioactivity is characteristic of the middle and upper parts of the section and is 50–60 μR/h, reaching 75–80 μR/h in some wells, while its values decrease in the bottom part of the formation. In the Nizhnevartovsk type, high radioactivity (up to 80–90 μR/h) is noted throughout the section (Figure 5). Only in the sections of some wells of the Vatinskaya, Mykhpayskaya, Ust-Vakhskaya areas does its average values decrease to 25–30 μR/h. In the Tarkosalinsky type of section, radioactivity is distributed in the same way as in the Salym, but its maximum values are significantly lower – most often they change in the range of 20–25 μR/h (Figure 6). Such a decrease in radioactivity is apparently associated with an increase in the proportion of terrigenous sediments in the section.

The main factor affecting the current density of the Bazhenov Formation is the organic material content in it (Kontorovich et al., 2019a), which, in turn, is closely related to the radioactivity of the rocks. The lowest rock density is observed in the southern part of the study area (Figure 4B), in the zone of high average concentrations of organic carbon (Kontorovich et al., 2018c). To the north, with a decrease in TOC content, the rock density of the Bazhenov formation increases.

The electrical resistance of rocks is also closely related to radioactivity. The authors analyzed the distribution of electrical resistivity along the section (tools Gz3 and LL) of the Bazhenov formation. There are two areas of increased average values of electrical resistance. The first is located to the north of the Surgut arch (Figure 4C, D). The maximum values of both the apparent specific resistivity and true electrical resistance reach here 600–700 Ohm*m. The second zone of increased average resistance is located between the Surgut and Nizhnevartovsk arches and is most clearly distinguished by the values of the apparent resistivity, which reach here 500 Ohm*m (Figure 4G).

On the curve of apparent electrical resistivity (AR), the Salym type of section in the southern and central parts of the region is characterized by a two-term structure, the maximum values reach 500 Ohm*m (Figure 5). In the southeastern direction, the resistance of the upper part of the section gradually decreases to 30 Ohm*m, and of the bottom – to 200 Ohm*m – this is another criterion for clarifying the border between the Salym and Nizhnevartovsk types of sections. In the northern part of the region, the Salym-type Gz3 tool curve also has a two-term structure, the maximum values in the west reach 1000 Ohm*m, gradually decreasing to the east. In the Vyngapurovskaya, Zapadno-Vyngapurovskaya areas, a third peak appears on this curve, which is characteristic of the Tarkosalinsky type; such sections are transitional. To the east, the Tarkosalinsky type of section is distinguished, which is characterized by a three-member structure of the apparent resistivity curve, maximum values up to 200–250 Ohm*m in the upper part of the section. In the middle part of the section, they vary from 60 Ohm*m in the Yarainerskaya area to 200 Ohm*m in the Vyngapurovskaya and Vengayakhinskaya (Figure 6) areas.

Thus, it has been established that the Tarkosalinsky type is wider in the western direction than was shown earlier (Braduchan et al., 1986) and is also distinguished in the Vengayakhinskaya, Yarainerskaya and other areas. The Nizhnevartovsk type, according to the authors, on the contrary, has a narrower distribution and is distinguished directly within the arch of the same name and in the southern part of the Var'egan-Tagrinskii megauplift, changing to the south and east by the Vakh type of section (Braduchan et al., 1986).

Oil-bearing prospects of the Bazhenov formation

In the Bazhenov formation, two types of reservoirs have been identified: voids (caverns) in the rock matrix and horizontal fracturing (fissility), laid down at sediment genesis. Both of these types of reservoirs are formed during catagenesis due to pseudophase transformations of kerogen (Kontorovich et al., 2018a). Thus, the concentration of organic matter and its catagenesis are the most important criteria in assessing the oil-bearing capacity of the Bazhenov formation. Comprehensive interpretation of geophysical, geological materials and data on the geochemistry of organic matter allowed the authors to predict the oil-bearing capacity of these deposits (Figure 7). Only those lands are considered as promising and highly promising lands, within which the organic matter of the Bazhenov formation is in the main phase of oil generation. On the slope of the Khentey hemianteclise, it began about 45 Ma ago (Kontorovich et al., 2019b), and later on the Surgut and Nizhnevartovsk arches (Figure 1). At these large positive structures, the thickness of the Bazhenov formation is reduced (Figure 3), and low OM catagenesis is also noted (Kontorovich et al., 2009); At the Nizhnevartovsk arch, low modern concentrations of organic carbon were recorded in the Bazhenov formation (Kontorovich et al., 2018c). All this is apparently connected with the growth of these structures in the Volgian age.

In the west and southwest of the study region, the thickness of the Bazhenov formation with a TOC concentration of 7–10% reaches 10 m or more (Kontorovich et al., 2018c). There is a high catagenesis of organic matter in these zones. In the Sorym-Iminskaya, Vat-Yoganskaya, Yuzhno-Yagunskaya,

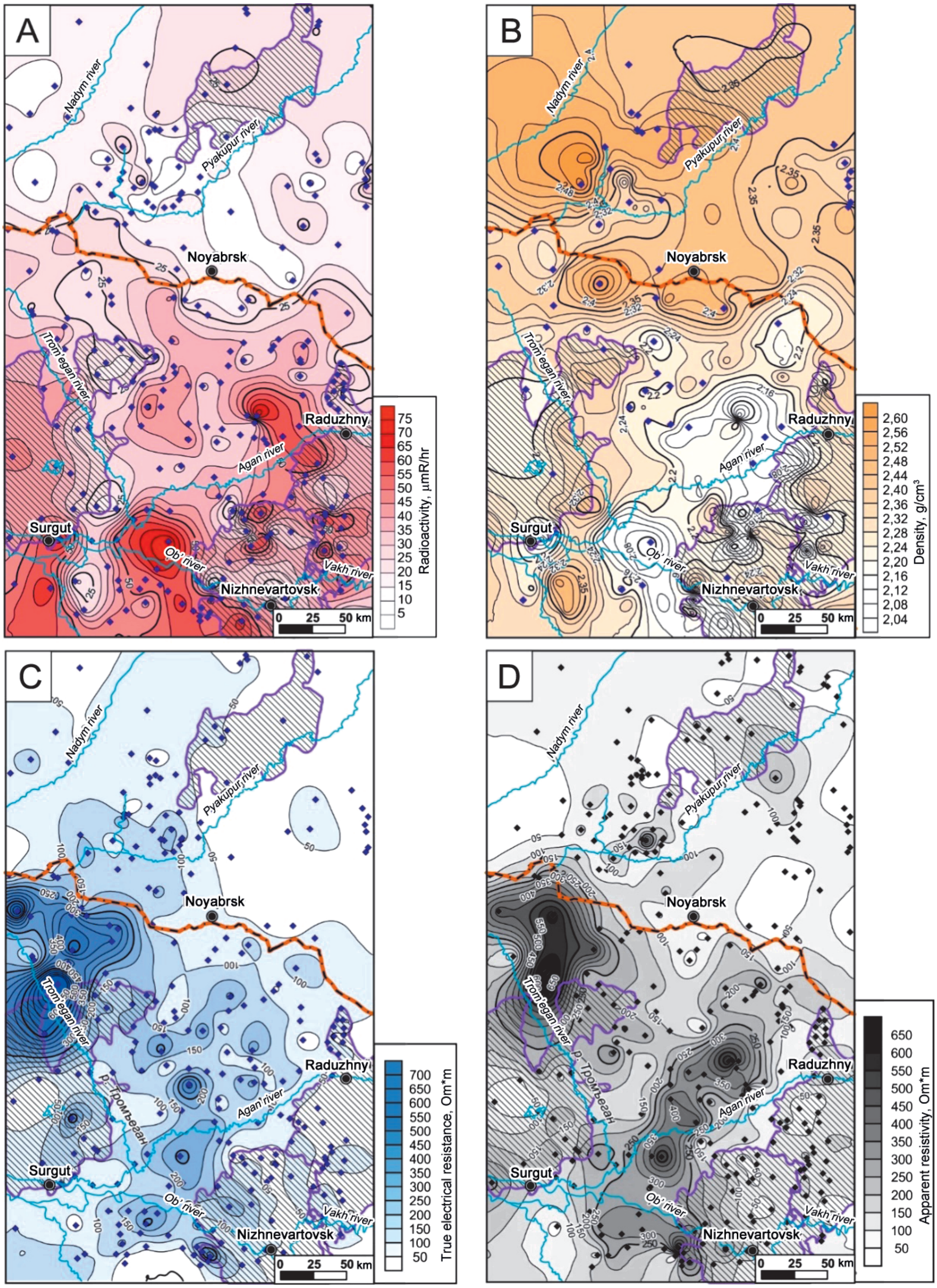

Fig. 4. Maps of average values: A – radioactivity, B – density, C – true electrical resistance, D – apparent resistivity of the Bazhenov formation. See Figure 3 for legend.

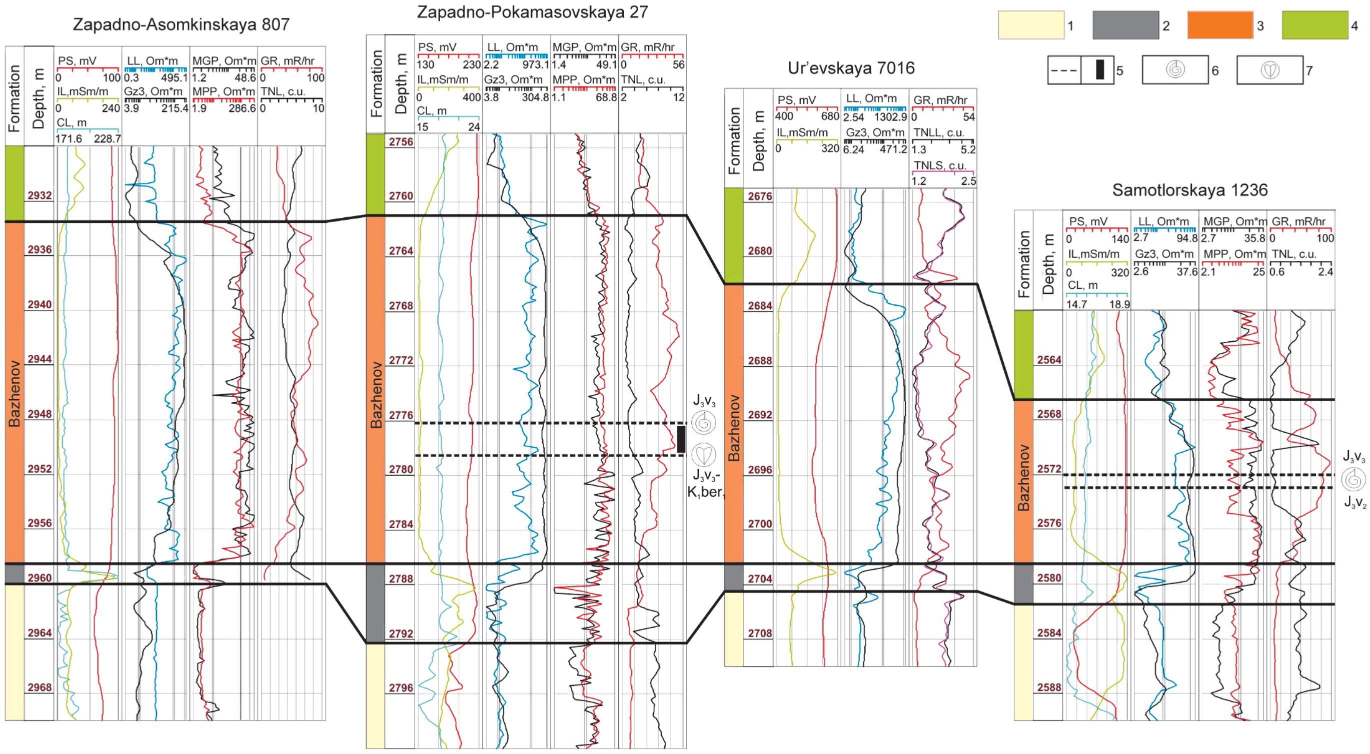

Figure 5. Correlation profile along the A-A line. See Figure 2 for legend.

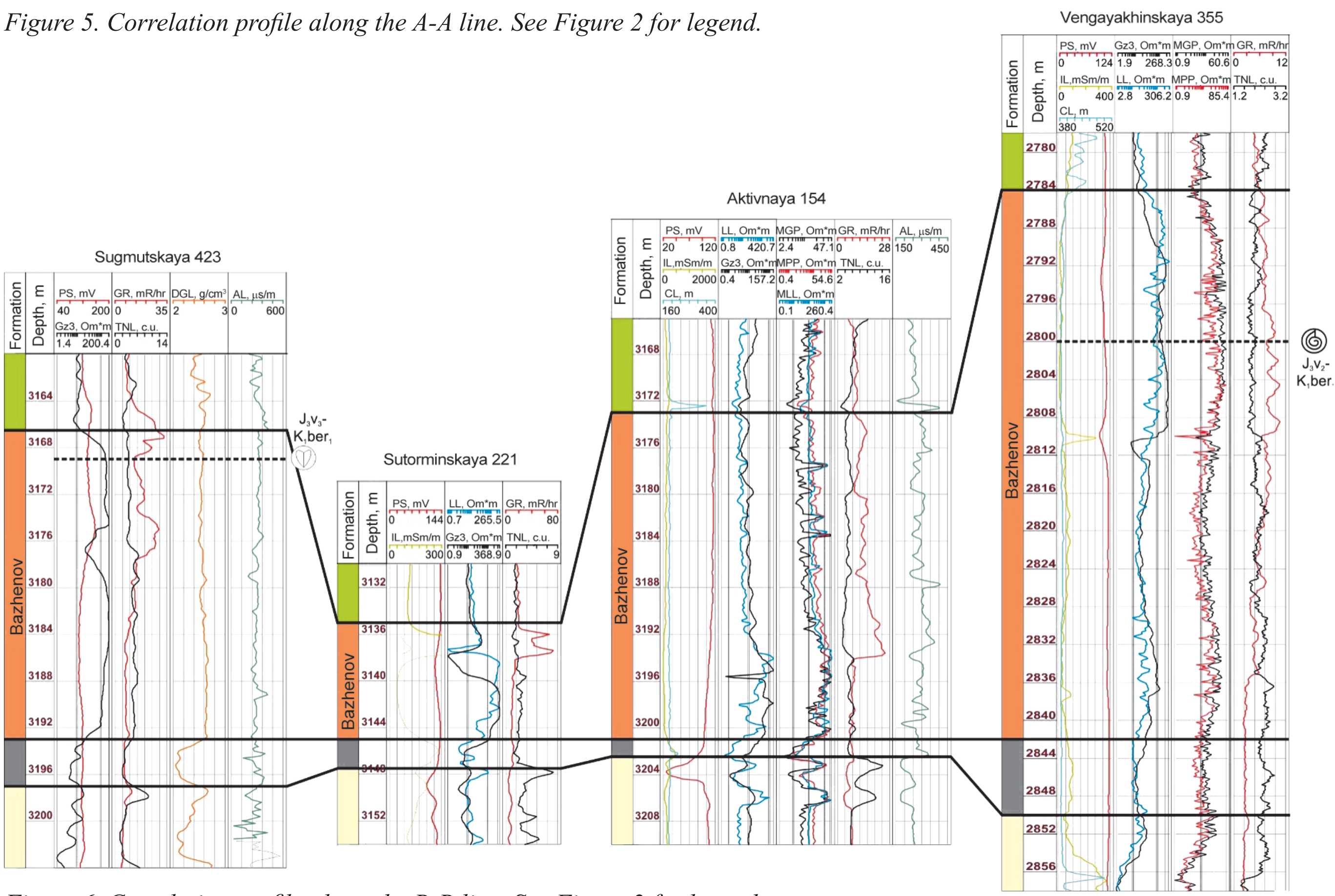

Figure 6. Correlation profile along the B-B line. See Figure 2 for legend.

Zapadno-Imilorskaya, Zapadno-Asomkinsky and Sogorskaya areas, the resulting flow of oil were obtained from the "classical" sections of the Bazhenov formation. All this allows us to highly assess the prospects of its oil-bearing capacity here (Figure 7).

As additional criteria for the forecast were also used:

- Modern temperatures at the top of the Jurassic complex (Zubkov, 2016; Skvortsov et al., 2018b);
- Thicknesses of the upper and lower impermeable layers, calculated by the authors on the basis of the results of the dissection of sections of the Upper Jurassic and Lower Cretaceous according to the well logging data;

• Average values of natural radioactivity and density of the Bazhenov formation (Figure 4A, B), which qualitatively characterize the modern content of kerogen in rocks;

• Average values of specific electrical resistance (Figure 4C, D), indicating oil saturation of the section.

The results of studying the lithology of the Bazhenov formation (Eder et al., 2016; Nemova, 2019, etc.) show that the interlayers, possibly with good reservoir properties, are distributed throughout its section. At the Sorym-Iminskaya and Yuzhno-Yagunskaya areas, oil inflows with a flow rate of 1 to 4.5 m^3/day were obtained from the middle and upper parts of the section, represented by mixtites of different composition and a "coccolith member". On the remaining areas in the southern, "Khanty-Mansiysk", half of the studied region, the entire section of the formation was tested, the inflow reaches 6 m^3/day.

In the Yamal-Nenets Autonomous District, at the Izvestinskoye, Vengayakhinskoye, Ety-Purovskoye fields, it was tested for oil inflow, mainly, the upper part of the section of the Bazhenov formation, which is composed of mixtites with various predominance of the main rock-forming components. On the Ety-Purovskaya area, no oil inflow was obtained in all wells, on the Vengayakhinskaya area it changes in the range of 0–1.2 m^3/day, on the Kraynyaya and Malo-Pyakutinskaya areas it does not exceed 1 m^3/day. The largest inflow of oil was obtained in the Izvestinskaya 704 well (22.8 m^3/day at a 6 mm choke), the Bazhenov oil reservoir in this field is on the state balance sheet. Apparently, such a large inflow is due to the significant fracturing of the formation in this area. It is important to note that tests in these areas were carried out from 1974 to 1991. The formation was stimulated by changing the clay solution to water and reducing the hydrostatic pressure. Apparently, it is the use of such an ineffective by today's standards method of testing the Bazhenov formation that explains such insignificant inflows in most wells.

In this region, in addition to Izvestinskoye, small oil deposits have been discovered at the Pyakutinskoye, Malopyakutinskoye, Vengayakhinskoye, Palnikovskoye fields. In these areas, the thickness of the Bazhenov formation with a TOC content of 7–10% reaches 4–5 m (Kontorovich et al., 2018c), it is located in the main zone of oil formation, reliably isolated by the lower and overlying seals, the current temperatures at its top exceed 90^0C. All this allows us to assume that there are commercial oil reserves in the Bazhenov formation. In the indicated and neighboring areas in the south of the Yamalo-Nenets Autonomous District, it is necessary

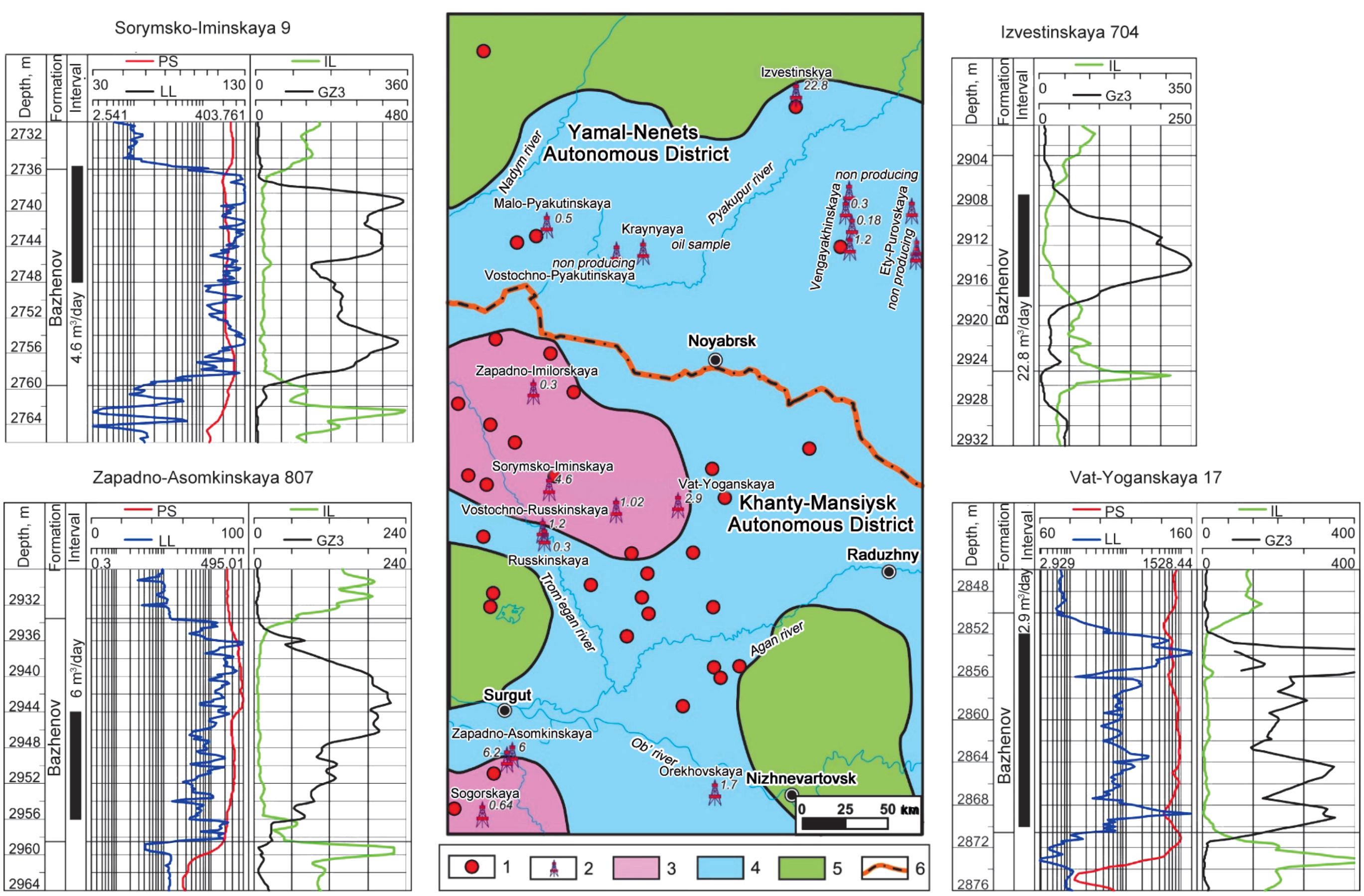

Fig. 7. Map of oil-bearing prospects of the Bazhenov formation and logs with the intervals for testing these deposits for inflow. 1 – fields with oil deposits in the Bazhenov formation; 2 – wells with inflow testing of the Bazhenov formation; 3 – highly promising territories; 4 – promising territories; 5 – unpromising territories; 6 – administrative boundaries.

to conduct repeated, interval testing of these deposits for inflow using modern technologies and methods of stimulation of inflow (hydraulic fracturing, catalytic reservoir stimulation, etc.). It is necessary to drill wells with full core sampling of the Bazhenov formation, as well as overlying and underlying sediments, and conduct its study using modern methods (Kontorovich et al., 2018a, b).

The study of this complex geological object using analytical methods will allow:

- To specify the lithological composition of the Bazhenov formation;
- Reliably identify oil source and oil production intervals in it;
- Study the structure of the Bazhenov reservoir and the nature of the saturation of its void space;
- Select the optimal well logging complex, with the help of which it will be possible to calculate the lithological composition and geochemical parameters of the Bazhenov formation in the wells that are not characterized by core material;
- Develop recommendations for calculating reserves in the Bazhenov formation;
- Develop recommendations for the creation of technologies for oil production from the Bazhenov formation.

Conclusions

Based on the interpretation of a wide range of well logging data, the authors have significantly clarified the distribution boundaries of various types of sections of the Bazhenov formation in the Nadym-Ob interfluve. It was found that the Tarkosalinsky type is more widespread than it was shown earlier and is also distinguished in the Vengayakhinskaya, Yarainerskaya and other areas. The Nizhnevartovsk type, on the contrary, has a narrower distribution and is distinguished directly within the Nizhnevartovsk arch, being replaced to the south and east by the Vakh type of section.

A comprehensive analysis of the new geological, geophysical and published geochemical materials obtained by the authors showed that in the southern part of the Yamalo-Nenets Autonomous District in the interfluve of Nadym and Kharampur, it is possible to detect industrial accumulations of oil in the Bazhenov formation. At the Pyakutinskoye, Malopyakutinskoye, Vengayakhinskoye, Ety-Purovskoye, Izvestinskoye, Palnikovskoye, Extreme fields, it is necessary to retest these sediments for inflow using modern technologies and methods of inflow stimulation. In these and neighboring areas, it is necessary to drill new prospecting and exploration wells with full core sampling of the Bazhenov formation and conduct its study using modern techniques in order to study in detail the structure of the Bazhenov reservoir and the nature of saturation of its void space.

Acknowledgments

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