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RESEARCH OF HARD-TO-RECOVERY AND UNCONVENTIONAL OIL-BEARING FORMATIONS ACCORDING TO THE PRINCIPLE «IN-SITU RESERVOIR FABRIC»

Aleksey D. ALEKSEEV[1], Vladislav V. ZHUKOV[1], Kirill V. STRIZHNEV[2], Sergey A. CHEREVKO[3]
[1] *LLS Gazpromneft NTC, Saint-Petersburg, Russia*
[2] *LLS Gazpromneft-Angara, Saint-Petersburg, Russia*
[3] *LLS Gazpromneft-Khantos, Khanty-Mansiysk, Russia*

Currently in Russia and the world due to the depletion of old highly productive deposits, the role of hard-to-recover and unconventional hydrocarbons is increasing. Thanks to scientific and technical progress, it became possible to involve in the development very low permeable reservoirs and even synthesize oil and gas in-situ. Today, wells serve not only for the production of hydrocarbons, but also are important elements of stimulation technology, through which the technogenic effect on the formation is carried out in order to intensify inflows. In this context, the reservoir itself can be considered as a raw material for the application of stimulation technologies, and the set of wells through which it is technologically affected is a plant or a fabric whose intermediate product is the stimulated zone of the formation and the final product is reservoir hydrocarbons.

Well-established methods for studying hydrocarbon deposits are limited to the definition of standard geological parameters, which are commonly used for reserves calculations (net pay, porosity, permeability, oil and gas saturation coefficient, area), but they are clearly insufficient to characterize the development possibilities using modern stimulation technologies. To study objects that are promising for the production of hydrocarbons, it is necessary to develop fundamentally new approaches that make it possible to assess the availability of resources depending on the technologies used, and to improve the methods for forecasting and evaluating the properties of the stimulated zone of the formation.

«In-situ reservoir fabric» is a collective term that combines a combination of technologies, research and methodological approaches aimed at creating and evaluating a stimulated zone of the formation by applying modern methods of technogenic impact on objects containing hard-to-recover and «unconventional» hydrocarbons in order to intensify inflows from them hydrocarbons. In 2015, the company LLS Gazprom Neft adopted a corporate standard regulating a set of studies in the ideology of the «in-situ reservoir fabric» for methodological support of the pilot projects related to development of low-permeability rocks of the Bazhenov formation by creating artificial permeable zones by multi-stage hydraulic fracturing in horizontal wells. In 2016 the first wells were built and put into operation, the results of the works confirmed the expediency of transition to a new methodological basis. After two years, we can state with certainty that the new approaches have proved their effectiveness.

Key words: shale oil, Bazhenov formation, hard-to-recover reserves, hydraulic fracturing, multi-stage hydraulic fracturing in horizontal wells

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Introduction. A modern trend in the field of replenishment of hydrocarbon resources is undoubtedly the shift in emphasis from the search for «easy-to-recover» reserves in the direction of ensuring the profitability of developing «hard-to-recover» reserves. This situation is quite natural due to the deterioration of the quality of the resource base with the growing demand for energy, which contributes to the development of technologies to stimulate inflows in wells. The influence of this trend is felt all over the world, including in Russia. In spite of gloomy forecasts, Bloomberg agency states that daily oil production in the Russian Federation continues to grow and is close to the Soviet record of 1987 at 11.4 million barrels per day, and in 2018 there are all chances to exceed this level [7]. Such results are not only due to the starting to development of new «green fields», but also largely due to the improvement of formation stimulation methods. For example, in LLS Gazprom Neft (hereinafter referred to as the Company) has oil fields where almost 100 % of new production wells are put into development after the rates stimulation through hydraulic fracturing (HF). For example, one of the Company's main assets is the Southern Licensed Territories (SLT) of the Priobskoye field, where oil deposits in low-permeability reservoirs are being actively developed, which a few years ago could not be involved in development due to unprofitable production rates. The use of multi-stage hydraulic fracturing in horizontal wells (MSHF HW) allows creating a series of artificial fracs due to which the filtration properties of the formation are significantly improved and the production rates of wells are repeatedly increased.

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Advanced technologies for stimulation of inflows in wells not only help to significantly improve the filtration properties of rocks, but they can also form them «from scratch» in geological bodies that are virtually impervious to reservoir fluids in natural conditions. Perhaps the most striking example is the development of shale formations in the United States, which in their initial state of permeability have practically no, but after stimulation through the MSHF, the HS provides profitable oil and gas production rates. On October 20, 2016, the same Bloomberg agency published an article «Chesapeake Energy Declared «Propageddon» ...», which gives an example that characterizes the possibilities of modern technologies for creating an artificial reservoir in a reservoir [8]. This is one of the leaders of the US shale industry company Chesapeake Energy, which carried out a super-giant fracturing on the gas-bearing shales of Haynesville. This story was developed in September 2016, when Chesapeake on the same shale carried out a fracturing with a sand volume of 14 thousand tons, after which the company representatives said that this would not stop. In mid-October 2016, Chesapeake vice president Jason Pigott announced that the company had set an absolute record – 25 thousand tons of sand was pumped into a gas well with a horizontal trunk length of ~3 km. Such volumes of injection proppant did not reach anyone in the history of the American shale boom, said Bloomberg. It was this operation in Chesapeake Energy that was called «propaheddone», combining two words («proppant» and «Armageddon») into one. According to Pigott, as a result of the work, the productivity of the well increased by 70 %. Generally speaking, increasing the length of the horizontal barrel and the volume of proppant is an actual trend in the development of US shale formations. Compared to 2014, the average amount of proppant doubled, and the length of horizontal sections increased by 50 %. Apparently, in this way, American shale companies are trying to survive in conditions of low prices for hydrocarbon raw materials.

If we approach the hydrocarbon production process with the use of technogenic stimulation in generalized terms, then the entire production cycle can be associated with the work of a plant or fabric, where the raw material is a geological layer, its stimulation plays the role of a processing line for preparing raw materials for processing, and the final product are reservoir hydrocarbons. Thanks to scientific and technical progress in the field of creating artificial permeability requirements for «raw materials» have significantly decreased, and the role of the «technological line» for its preparation has increased significantly. If there is a discrepancy between «raw materials» and «technological line» parameters, the output of the final product will be limited or completely impossible.

Articulation of issue. Traditionally, the study of oil deposits is limited to the definition of standard geological parameters, which are commonly used for reserves calculations (net pay, porosity, permeability, oil and gas saturation coefficient, area, etc.), but they are clearly not enough to characterize the development possibilities using advanced modern stimulation technologies. In other words, at the present time conventional approaches are not formed that allow studying the hydrocarbon-containing reservoir as a «raw material» for stimulating inflows from it. For example, sandstones: net pay 2 m, porosity 12 %, permeability 0.2 mD ($2 \cdot 10^{-16}$ m^2) in the usual sense have uncertain prospect for development, but if they are located in water-free oil zone of the deposit, they are limited by reliable barriers from the nearest aquifers and are sustained on the area, their development with the help of the MSHF HS can show very impressive results.

The research program for the purpose of effective study of objects with hard-to-recover and unconventional reserves should be organized in such a way that they not only be characterized from the standpoint of assessing geological reserves, but also determined parameters that control susceptibility to modern technologies of stimulation of the formation. The specialists have an absolutely new task in planning, building and managing the «technological lines of «in-situ reservoir fabric», so that the raw materials processed by them will provide «profitable output». These issues are particularly relevant for the development of hydrocarbon resources contained in sediments, which are commonly referred to as «shale oil formations». Their main difference from traditional oil bearing reservoirs is not only in the almost complete absence of natural permeability, but also in the diversity of the resource potential, which can be represented by gaseous, liquid and solid hydrocarbons,

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as well as solid organic matter (kerogen) that has not realized its generation potential. In this connection, «in-situ reservoir fabric» may differ in the type of «consumed raw materials» and in the technologies for preparing it for hydrocarbon production purposes.

Today, upstream companies are focused on developing hydrocarbons through horizontal wells with MSHF, thanks to which a network of technogenic fracs forming a kind of artificial reservoir is formed in the formation. In the «shale oil» formations, only a part of the hydrocarbon potential is involved in the development, namely, oil or natural gas. In this case, the technologies for developing hard-to-recover and unconventional objects are very similar. In both cases, the main task is to increase the permeability of the formation by means of technogenic stimulation. However, unconventional reservoirs are much more demanding for the fracture density and their effective development is possible only if the stimulated reservoir volume (SRV) is created, rather than a series of planar fracs [1]. In addition, in unconventional reservoirs confined to high-carbon formations, a significant part of the mobile light oil is sorbed by heavier hydrocarbons and solid organic matter (kerogen). Such oil can be involved in development only if somehow to overcome the action of forces that keep the light hydrocarbons on the surface and inside the organic component of the rock.

Another important difference is that after complete extraction of oil, the development of conventional hard-to-recover reservoirs will be completed, and unconventional reservoirs will still have a significant reserve. Unconventional formations, mainly high-carbon rocks, besides gas and light oil have a huge production potential associated with solid hydrocarbons and kerogen. In this case «in-situ reservoir fabric» will be replaced by «in-situ production fabric of artifactural HC», which would produce synthetic oil or gas through thermal destruction heavy hydrocarbons and kerogen.

In favor of the above-mentioned way of development of production technologies, the actual activity of companies for the production of «shale oil» hydrocarbons and pilot projects (PP) of large world companies, which are aimed at assessing the possibilities of in-situ synthesis of petroleum from kerogen [2]. Thus, at the current level of technology development, the development of hard-to-recover and unconventional hydrocarbons has similar tasks, the methods of solving which can be concluded in the collective term «in-situ reservoir fabric».

A striking example of high-tech wells in Western Siberia, ideologically closest to the «in-situ reservoir fabric» are horizontal wells with MSHF, built on the Bazhenov formation, which is the largest «shale oil formation» in the world. With an average gross thickness of 30-40 m, it is distributed over an area of about 1 million 200 thousand km^2. The Bazhenov formation is considered to be an analogue of the shale oil formations in the USA, for which the key to development has not yet been found. Unlike the American shale oil, in a number of cases the Bazhenov formation is characterized by very large oil inflows obtained in vertical wells without using any methods of reservoir's stimulation. This property until now determines the basic vector of its study – the development of techniques for searching highly productive zones («sweet spots»). At the same time, insufficient attention was paid to the study of Bazhenov formation technogenic stimulation impact is aimed of well rate increasing.

Methodology of investigation. Gazprom Neft began to actively engage in pilot development of the Bazhenov formation in 2013. At the first stages of the projects' implementation, the study followed a typical scenario in this case. In the first exploration well, drilled at the Palyanovskaya area of the Krasnoleninskoye field, a flowing oil inflow of 80 tons per day was received from the Bazhenov and Abalak formations, and subsequent geological exploration programs were aimed at identifying high-yield zones using seismic and potential methods fields (gravity and magnetic prospecting). After receiving the first results of area forecasts, five new directional wells were drilled in the most promising areas with coring and special logging, and then two more high deviated wells (inclination about 70°). All the wells received an inflow, but none of them reached a similar production rate even after the hydraulic fracturing. Moreover, at least some close success was not achieved on the following pilot projects that were initiated in other areas.

After extensive work, it was realized that exceptional attention to the search for highly productive zones is a dead-end way. Even if it is possible to develop the most advanced search technology,

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several wells drilled in the highly productive zones of the Bazhenov formation will not be able to support the production of oil in Western Siberia. Meanwhile, the Bazhenov formation is quite suitable for this role, it contains light oil throughout the whole section and almost all its huge area of occurrence, and there is practically no free formation water [2].

In 2015, the Company changed the principles of study in relation to the Bazhenov formation. The search for highly productive zones («sweet spots») was replaced by the idea of creating an artificial reservoir, in which oil-bearing deposits began to be studied as «raw materials» for the most modern methods of well stimulation with the help of HS with MSHS. Fundamentally new approaches to the study of Bazhenov formation began to develop in a wide range of specialists of the Company, its subsidiaries, a consortium of scientific organizations with the involvement of independent service companies. The project office «Bazhen», a part of LLS «Gazpromneft-Angara», took over the work on the managing of pilot projects, and the methodological study was entrusted to the Department of unconventional reserves of LLS «Gazpromneft STC».

First of all, it was necessary to determine the main property that controls the productivity of the formation in conditions of artificially created permeability. Theoretically, stimulation technologies can develop to such a level that they will make it possible to create an artificial permeability of arbitrarily great importance in any geological conditions, but the technical ability to make the reservoir highly permeable does not at all mean that it can be able produce oil. To do this, the stimulation object must contain it, and it must be able to move through the system of artificial cracks, i.e. be mobile in conditions of induced permeability and technically achievable draw-down pressure. The very concept of «fluid mobility» is still not strictly defined, but the important factor that significantly limits the volumes involved in development is the ability of light hydrocarbons of the Bazhenov formation to move under the influence of draw-down pressure under conditions of artificial permeability.

Light petroleum hydrocarbons can be retained in the bound state by both organic and mineral components of the rock. Adsorption of oil on the surfaces of mineral grains of rock is a common phenomenon encountered in the development of traditional deposits. The phenomenon of sorption of light hydrocarbons by heavier and kerogen is a characteristic feature of source rocks [3]. Thus, mobile hydrocarbons must first of all be movable (free) and have positive mobility (mobility is the ratio of the permeability of the formation to the viscosity of the fluid) under conditions of natural and induced fracturing permeability. In this case, mobile HCs can be contained both in communicating voids, and in isolated (or loosely bound). Formal criteria for assessing their volume have been specially developed within the framework of scientific and technical support for pilot projects of Gazprom Neft and are described in the article [2].

The share of mobile hydrocarbons is a fundamental property of the reservoir that does not depend on technogenic factors (for example, such as the configuration of the SRV). This parameter is responsible for the volume that can potentially be involved in development under conditions of ideal stimulation of the formation, but it does not in any way characterize the conditions in which it is to be carried out. The possibilities for creating artificial permeability are due to the properties of a different nature, which determine the susceptibility of the rocks composing the formation to this type of technogenic impact. For hydrochloric acid treatment, the amount of carbonate material and the nature of its distribution in the formation are important, for the technology of fracturing, the geomechanical characteristics of the formation on which the geometry of the stimulated zone depends, i.e. the effectiveness of the coverage of rock containing mobile hydrocarbons. Theoretically, one can imagine a situation where the greatest efficiency of stimulation will be achieved when initiating from an interval in which there are no mobile stocks at all, or it is outside the boundaries of the development formation. Therefore, in the case of stimulation of a formation by means of hydraulic fracturing, geomechanical parameters are also independent fundamental characteristics of the formation, which must be studied.

In order to characterize the oil-bearing formation as a «raw material» for oil extraction by means of hydraulic fracturing according to the principles of the «in-situ reservoir fabric», it is

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necessary to construct the mobility profiles of formation hydrocarbons and minimum horizontal stresses (or brittleness) [2]. Intervals with mobile HC in the region of low horizontal stresses (increased brittleness) are the main objects most susceptible to stimulation by means of hydraulic fracturing.

The developed approaches to the assessment of the prospects of the oil-bearing section are slightly different from those generally accepted. In order to integrate them into the current regulatory documents regulating the calculation of reserves and the development of hydrocarbon fields, a differentiated method has been proposed, which is introduced as a corporate standard of the Company when working with unconventional reservoirs. The essence of it is as follows. With respect to any technology of rates stimulation in the wells, it is possible to distinguish at least three types of rocks: natural reservoirs (NR), stimulatable rocks (SR), non-stimulatable rocks (NSR). NR is able to produce fluid without any stimulation, and their productivity index does not matter in this case. SRs can produce fluid only after stimulation. Non-stimulatable rocks are insusceptible to the selected type of formation stimulation technology and cannot produce fluids neither before nor after stimulation. It is obvious that behind such a division there should be formalized criteria allowing one type of rocks to be separated from the other [2].

Thus, the effect of stimulation of the formation is determined not only by purely technological parameters, but also by the fundamental characteristics of the constituent rocks that need to be studied. To form an artificial permeability in the formation by hydraulic fracturing, i.e. «In-situ reservoir fabric», such characteristics are the volume of mobile hydrocarbons and geomechanical parameters. Having studied the stress profile and the mobile oil distribution in one place, it does not mean that similar characteristics will be kept in another one, located at some distance. In the conditions of development with the help of HS with MSHF for horizontal sections steering, a tool is needed to predict reservoir properties between the reference wells. In this connection, the third «pillar» of the ideology of the «in-situ reservoir fabric» is suggested to be the geological concept, which characterizes the laws of vertical and lateral variability of the formation properties, based on the conditions of sedimentation and tectonic factor of the territory.

The geological concept is a convenient tool for planning horizontal wells and developing the field as a whole. Within its framework, the role of area forecasting methods is slightly modified, the results of which not only serve to rank the territory in terms of productivity in the conditions of technogenic interference, but also provide a solution to the purely technical issues associated with horizontal wells steering. Under existing conditions, when advanced high-tech logging while drilling tools (LWD) are not available due to sanctions restrictions, the role of reliable geological concepts of lateral and vertical formation variability, formalized in the form of a geological concept, is significantly increasing.

The practical application of a new type of thinking in the ideology of the «in-situ reservoir fabric» has already brought the first fruits – two horizontal wells with nine stages of hydraulic fracturing built by Gazprom Neft on Palyanovskaya area showed an significant oil rates from the Bazhenov shale oil formation. It is noteworthy that one of the wells was drilled in the unpromising zone according to the area forecasts made in the logic of traditional approaches, and its result is absolutely regular within the framework of the new ideology, thanks to which the promising oil-producible zone has significantly expanded. It's not difficult to see this if you go a little deeper into the details.

Discussion. As already noted, in 2013 a flowing oil inflow of 80 tons per day was received from the Bazhenov and Abalak formations, at the Palyanovskaya area of the Krasnoleninskoye field, after which a forecast was made for «sweet spots» using various technologies for processing 3D seismic data. According to its results, the greatest prospects are associated with the fault zones concentrated in the areas of the high of the pre-Jurassic basement, and the depression part, timed to its submerged sites, is unpromising. The wells drilled in the framework of the pilot project with coring and special logging with the help of new techniques made it possible to identify intervals with mobile oil and provided the possibility of constructing reliable geomechanical models.

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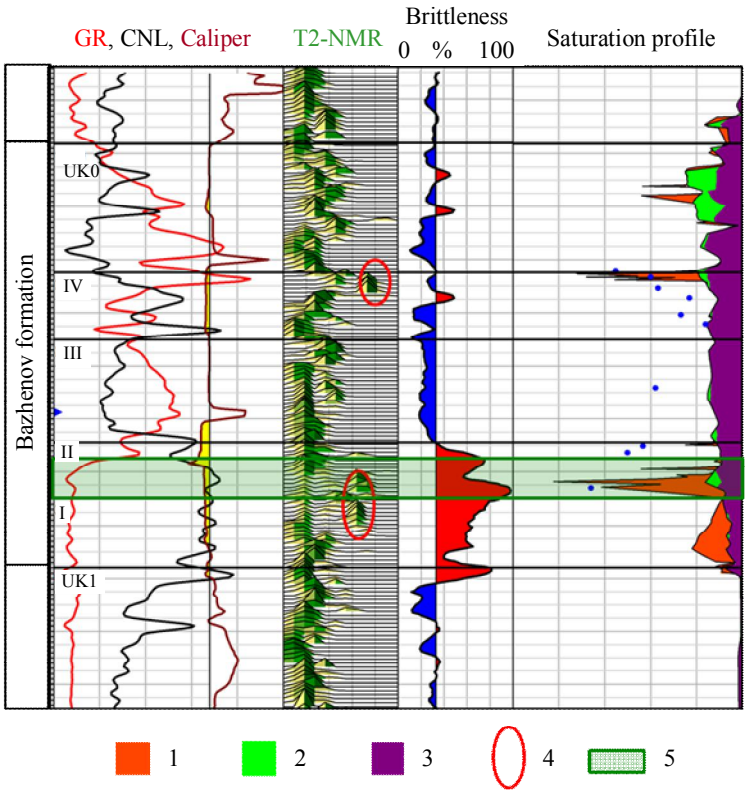

Fig.1. Petrophysical evaluation plot aimed to substantiate perforation intervals hydraulic fracturing initiation points and design of horizontal borehole (1 cell – 1 meter)

GR – gamma ray logging; CNL – compensated neutron log; Caliper – well diameter according to caliper data; T2-NMR – parameter T2 of nuclear magnetic resonance; Saturation profile – oil saturation profile in porosiry units, p.u.; UK0 – Bazhenov formation index as an object of development; UK1 – the Abalak formation index as an object of development

1 – light live crude of connected voids; 2 – light live crude of isolated (either poorly connected) voids; 3 – associated light crude; 4 – free hydrocarbons according to NMR; 5 – radiolarite interval: blue dots show the core porosity measured by standard technique; Roman numerals indicate the number of the Bazhenov member

On the petrophysical evaluation plot (Fig.1) shows the log data, the profiles of the Bazhenov formation of the Palyanovka area, relative to their brittleness and oil saturated volume, differentiated in terms of the mobility of light oil. Pay attention to the layer of Bazhenov member II, in which the maximum volume of mobile oil and the largest brittleness index in the section are revealed.

The most stimulation efficiency could be achieved if to steer a horizontal wellbore along the intervals that are most favorable from the point of growing hydraulic fractures within layer contains mobile oil. For this, it is necessary to have an idea of the vertical and lateral properties variability of the entire formation, on which the consistency of each individual interlayer in an area in terms of thickness. You can «carry out reconnaissance by battle» with the help of expensive logging tools while drilling, or you can follow the provisions of a geological concept that describes the laws of vertical and lateral formation variability. In this case, when steering a horizontal wellbore, reliable and sustained reference boundaries can be used that are characterized by contrasting appearance in the fields of standard methods of LWD: gamma-ray and resistivity logging. The variant with the use of the geological concept from all points of view is more rational, but requires a certain elaboration and geological knowledge about the object.

The sedimentation of the Bazhenov formation within the Krasnolenin arch was occurring in a vast epicontinental marine basin below the wave action, mainly in anaerobic conditions. Sedimentation was extremely slow and did not compensate for the deflection of the basin, in which biogenic sedimentation predominated over the terrigenous sedimentation. This determined the high lateral consistency of the strata as a whole. The boundaries of the cyclites of the Bazhenov horizon are quite distinct, formed in the conditions of a change in the background terrigenous-biogenic sedimentation to a purely biogenic one. The biogenic layers correspond to the periods of the penetration of cold, oxygenated Arctic waters into the Bazhenov basin of sedimentation, which led to outbreaks of bio-productivity of zooplankton, the skeletal remains of which formed large interlayers [2].

Thus, from the analysis of sedimentation conditions it can be concluded that within a single local area, such as Palyanovskaya, the main factor controlling the lateral variability of the deposits of the Bazhenov formation at the stage of sedimentogenesis could only be the paleorelief of the bottom of the basin. In the submerged parts of the sediment accumulated more, less in elevated, and in the rest of the sediments are characterized by insignificant variability. In other words, in the study area, the conditions for sedimentation of the Bazhenov formation have ensured a strict sequence of occur-

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rence of the layers with thickness that are controlled by the paleorelief, and in other respects the superficial epigenetic processes play a decisive role in the formation of vertical and lateral variability.

The centers of secondary transformations in the Bazhenov formation are associated with the influence of hydrothermal-metasomatic transformations and gravitate toward the high of the pre-Jurassic basement, which has a disjunctive-block structure [6]. Due to the influence of epigenetic processes, the rocks of the same stratigraphic level of the Bazhenov formation above the high of the pre-Jurassic basement and in the depression parts may have different types of voids and its volume, and also have different lithological composition.

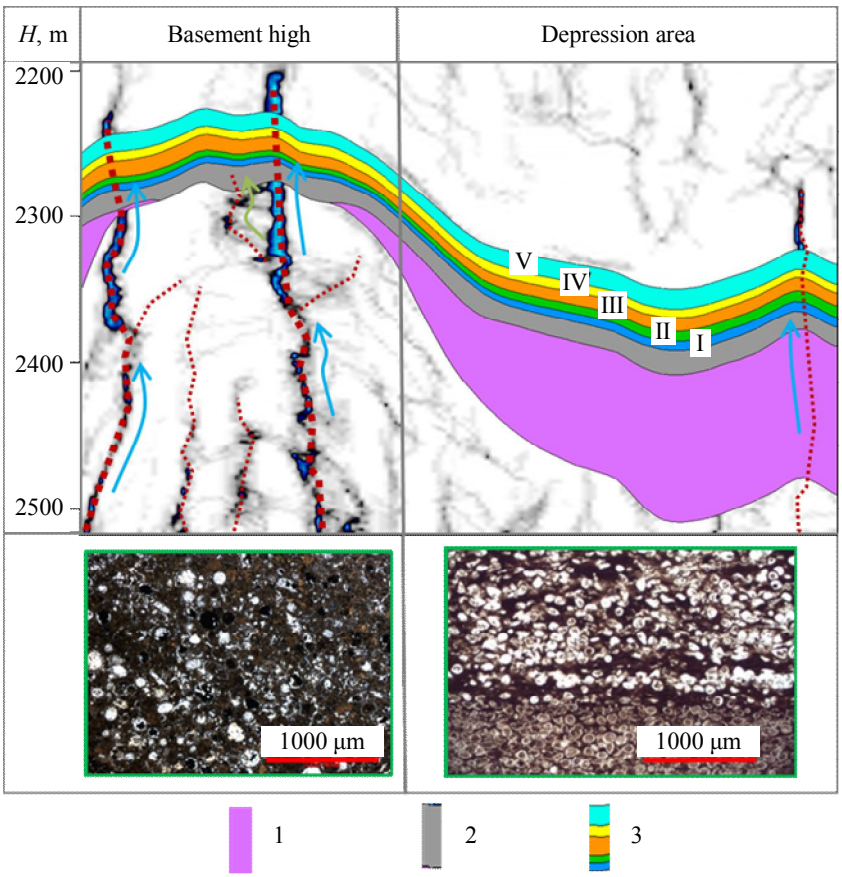

Fig.2. An illustration of a geological concept on a seismic cross-section, built on the technology of ant-tracking [5]

1 – Tyumen formation; 2 – the Abalak formation; 3 – Bazhenov formation; Roman numbers indicate the member of the Bazhenov formation

The main idea of the geological concept of the Bazhenov formation of the Palyanovka area of the Krasnoleninsk deposit is shown in Fig.2. To illustrate the effect of epigenetic processes, the same layer of pack II is taken (see fig.1, condition designation 5), represented by a silicide with various types of cement. In the zone of high of the pre-Jurassic basement, it undergoes epigenetic transformations associated with its partial carbonatization and/or phosphoritization, and retained the primary (relic) radiolarian structure in the loaded sections. In both cases, the initial precipitate was a radiolarite, almost entirely consisting of skeletal remains of zooplankton – radiolarians, which have a flint skeleton. It is the radiolaritic interlayer that corresponds to the highest content of mobile hydrocarbons and the highest brittleness in the section (see Fig.1).

Secondary epigenetic processes can contribute to both improvement and deterioration of the reservoir properties. For this area, epigenetic carbonatization and phosphoritization in the zone of protrusions of high of the pre-Jurassic basement together with active tectonic development of the territory contributed to the formation of improved reservoir properties of the Bazhenov and Abalak formations, which in some cases allow achieving high production rates without any stimulation, as happened in the first exploration well in 2013. But the subsequent drilling of five vertical wells and two high deviated wells has shown that for this zone the result of the first exploration well is more likely an accident than a regularity. Even the hydraulic fracturing did not improve the situation. Such a discrepancy in expectations could be explained by an inadequate reliable prediction of the foci of epigenetic transformations, but the core studies showed that the wells were actually drilled in the zones of active hydrothermal-metasomatic transformations of the rock. Thus, it can be concluded that not all the factors affecting the productivity of the Bazhenov formation were taken into account when the wells were put in place and that the current level of reliability of the area forecasts is not enough to replicate the positive experience with the aim of organizing commercially successful production.

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In the current situation, the organization of the development of the Bazhenov formation according to the ideology «in-situ reservoir fabric » can guarantee a higher and stable result, as it relies on reservoir characteristics that can be reliably measured and predicted today. In this concept, the primary responsibility for ensuring the level of production is shifted from technologies of searching highly productive zones for vertical wells to design the efficient operation of the «technological line for the preparation of raw materials», i.e. on technogenic stimulation of the reservoir by MSHF HW. The experience of constructing thousands of horizontal wells with multistage fracturing in the USA showed that with a modern level of well construction technologies and their development, the «in-situ reservoir fabric» has a high chance of success. For a large-scale development of the Bazhenov formation, this circumstance is much more important than improving the technologies of searching highly productive zones for vertical wells. The area of which is incommensurably smaller than the total area, which is potentially oil-bearing, provided that artificial permeability is created.

In Russia, the experience of building high-tech wells with the help of which «shale oil» is produced in the US has not yet been accumulated; therefore, in the current situation, the most correct first step would be testing of proven technologies abroad. For this purpose, the first horizontal well (1000 m length of horizontal wellbore) with nine stages fractured by Slick Water technology, was drilled on the zone of high of the pre-Jurassic basement of Palyanovskaya area, which is considered to be the most promising. Slick Water frac is the most effective for shale oil technology of hydraulic fracturing using high injection rates (at least 12 m^3/min v.s. the standard fracturing ~3.5 m^3/min) ordinary water with a proppant and a friction reducer is pumped into the formation. The new well showed a good result, although somewhat lower than expected. Perhaps this is due to the fact that some part of the horizontal wellbore has fallen into the zone of influence of the historical development, which was confirmed by hydrodynamical study during frac operations. Low reservoir pressure evaluated in two stages located close to the big fault crossed by the well. Under the conditions of development of conventional reservoirs, the zones of depletion have mainly concentric forms, but in case of Bashenov shale oil formation they can be stretched considerably along faults, which could not be predicted when this well was spud.

Of course, according to the results of drilling one well, one can't show a certain systemic nature and expectation of a repeat of the result. To this end, it is necessary to build and test at least a few wells in identical geological conditions and to stimulate them with help the very same technology. The uniqueness of such wells for Russia, the lack of competition in the services market, the restriction of access to western technologies due to sanctions – all of this makes such wells very expensive. Thus, it is still far from a statistically representative result. Nevertheless, as a proof of the validity of the main provisions of the new concept of studying and developing hard-to-recover and unconventional hydrocarbons, called the «in-situ reservoir fabric», one more convincing example can be cited.

In accordance with the above geological concept, the prospects of the depression zone of the Bazhenov formation of the Palyanovskaya area are obvious, for which the following are characteristic:

- increased gross thickness of the formation (including the radiolaritic layer, with the maximum concentration of mobile hydrocarbons);
- increased net volume associated with the preserved relict porosity of radiolarites;
- absence of faults, which ensures good traceability of the cross-section by area;
- absence of influence of historical development.

However, from the point of view of traditional approaches, this is an absolutely hopeless zone, since:

- the results of drilling exploration wells did not show any significant rates;
- all predictions by various methods are characterized this zone as hopeless;
- experience of the Bazhenov development another fields indicates a lower prospectivity for depression zone.

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The increased gross thickness of the section and the porous character of the net volume of the radiolaritic layer (in the zone of the basement high it is mainly fractured and vugular due to epigenetic processes) suggest a higher reserve density of the depression zone. Therefore, depression zone more attractive for development with help MSHF HW. In addition, this is study of strategic interest, because allows to significantly expand the perspective area up to the boundaries of the Palyanovskaya area. Surely, the traditional ways of developing couldn't allow produce these significant reserves.

In order to clarify the prospects for the development of the more depression zone of the Bazhenov formation, a second horizontal well was drilled at Palyanovskaya area, the length of horizontal wellbore is the same 1000 m. This well has nine stages of fracturing. This is the first well in Russia designed to be as close as possible to the wells produce shale oil in the United States. It is cemented with the rotation of 1000 m length horizontal liner and stimulated by plug&perf technology with the help of hybrid high injection rates fracturing. A new well, built in accordance with the principles of «in-situ reservoir fabric» in a zone considered unpromising before that, gave natural flowing oil rate 45 tons per day! The result obtained even exceeded expectations somewhat, since the production rate was planned to be obtained at a lower bottomhole pressure under artificial lift conditions.

These described examples don't consider technological aspects of creating an artificial reservoir which play one of the leading roles. The Russian way of studying the Bazhenov formation left practically unaddressed the questions of compatibility of technological liquids and proppants with rock, as well as the influence of the main parameters of the frac-design (injection rate; volume and rheology of slurry; volume, type and size of the proppant) for SRV geometry. At the present time there is no certain way to «fine-tune» the «In-situ reservoir fabric for the Bazhenov formation», taking into account its unique features in one or another region of Western Siberia. It should be understood that this task is not limited to «consumables» (chemistry, proppants, casings, liners, liner hangers, plugs) and equipment (hydraulic fracturing fleet, coiled tubing). In addition, there is an urgent need for reliable frac-simulators and tools for controlling the parameters of stimulated reservoir volume. For this purpose, the Company together with the Moscow Institute of Physics and Technology is developing an frac-simulator and is doing a lot of research work to monitor the parameters of the stimulated zone and improve the efficiency of the hydraulic fracturing. These works are in the initial stage of implementation, so the questions of justifying the optimal characteristics of the hydraulic fracturing are still outside the scope of this article.

Conclusion. In community of specialists in oil and gas industry, the theme of the «shale oil revolution in Russia» raises heated discussions. Both optimists and pessimists are asking themselves a question that, in the opinion of the majority, is the main one: «How long must it take to achieve the shale "oil revolution in Russia"?». The materials of this article, according to the authors, clearly show that the actual issues of involving in the development of the potential of the «main shale oil formation of Russia» – the Bazhenov formation are far from being measured only by the number of years spent studying. Since the first natural flows were received in the late 1960s years have passed not a few. A much more accurately marked problem is characterized by unsolved problems the existence of which even a few years ago researchers did not even think about. All of them are united by one main question: «How will modern (and very expensive) technologies of formation stimulation show themselves in the geological conditions of the Bazhenov formation?» The number of unsolved problems should be correlated with the number of new high-tech wells that will be drilled to solve them, as well as the amount of money that must be invested in pilot projects. Only in this case can we estimate the required time depended on the scale and success of the pilot projects.

On April 26, 2017, the Minister of Energy of the Russian Federation Alexander Novak, in accordance with the decree of the Government of the Russian Federation N 1217-r dated July 3, 2014,

assigned the project of the company Gazprom Neft to create a package of domestic technologies and high-tech equipment for the development of the Bazhenov formation. In late October 2017, Gazprom Neft and the government of the Khanty-Mansiysk Autonomous District signed an agreement on the launch of the Bazhen Technological Center. Thus, the State at the federal and regional levels has demonstrated a keen interest in developing domestic technologies for the production of «shale oil», which will be a new impetus for the development of the entire Russian oil and gas industry.

REFERENCES

1. Nenasheva M.G., Demo V.O., Zhukov V.V., Shevchuk T.N. Probabilistic Assessment of Single Well Source Rock Oil Recovery in Terms of Geological and Technological Uncertainties. SPE Russian Petroleum Technology Conference and Exhibition, 24-26 October, Moscow, Russia. https://www.onepetro.org/search?q=SPE-182077-RU (in Russian).

2. Alekseev A.D., Antonenko A.A., Zhukov V.V., Strizhnev K.V. The Differentiated Approach of the Reserves Estimation for Source Rock Formations. SPE Russian Petroleum Technology Conference and Exhibition, 24-26 October, Moscow, Russia, https://www.onepetro.org/search?q=SPE-182074-RU (in Russian).

3. Kostenko O.V. Blocking nature of distribution of high-molecular compounds of bitumoid in pore system of Bazhenov formation (West Siberian basin). *Neftegazovaya geologiya. Teoriya i praktika.* 2014. Vol. 9. N 1, p. 1-13 (in Russian).

4. Nemova V.D. Conditions of reservoir formation in deposits of Bazhenov within the junction of Krasnolenin arch and Frolov megadepression. *Neftegazovaya geologiya. Teoriya i praktika*. 2012. Vol. 7. N 2, p. 1-14 (in Russian).

5. Tolmachev E.O., Alekseev A.D., Glavnova E.N., Zhukov V.V., Shevchuk T.N. Construction of a three-dimensional geological model of the Bazhenov formation in the north-eastern side of the Krasnoleninsky arch. *PRONeft'*. 2017. N 1(3), p. 23-27 (in Russian).

6. Strizhnev K.V., Zagranovskaya D.E., Zhukov V.V. Selection of promising oil and gas bearing area formations for unconventional reservoirs Bazhenov Suite. *Nedropol'zovanie XXI vek*. 2015. N 1(51), p. 46-51 (in Russian).

7. Bierman S., Lee S., Khrennikova D. Russia Smashes Post-Soviet Oil Supply Record as OPEC Weighs Curb. http://www.bloomberg.com/news/articles/2016-09-28/russia-smashes-post-soviet-oil-supply-record-as-opec-weighs-curb

8. Carroll J., Wethe D. Chesapeake Energy Declares «Propageddon» With Record Frack. http://www.bloomberg.com/news/articles/2016-10-20/chesapeake-declares-propageddon-with-record-frack-in-louisiana

***Authors*: Aleksey D. Alekseev,** *Candidate of Geological and Mineralogical Sciences*, *Leading Expert*, *Alekseev.AlDm@gazprom-neft.ru* (*LLS «Gazpromneft STC»*, *Saint-Petersburg*, *Russia*), **Vladislav V. Zhukov,** *Head of Department*, *Zhukov.VV@gazpromneft-ntc.ru* (*LLS «Gazpromneft STC»*, *Saint-Petersburg*, *Russia*), **Kirill V. Strizhnev,** *Doctor of Engineering Sciences*, *Executive Director*, *Strizhnev.KV@gazprom-neft.ru* (*LLS «Gazpromneft-Angara»*, *Saint-Petersburg*, *Russia*), **Sergey A. Cherevko,** *Deputy Director General*, *Cherevko.SeA@hantos.gazprom-neft.ru* (*LLS «Gazpromneft-Hantos»*, *Khanty-Mansiisk*, *Russia*).

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