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The main problems of developing deposits of unconventional hydrocarbons in ultra-low-permeable and shale sediments

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Abstract. The shale revolution and the great progress in the US in the development of deposits in tight, ultra-low-permeable, shale strata put the issues of studying and developing unconventional deposits on the agenda. The special geological structure of the deposits of unconventional oils makes it necessary to use new (different from traditional) methods of prospecting, exploration and development of such deposits. And this, in turn, requires a new approach to studying the features of the geological structure and the creation of geological and hydrodynamic models, taking into account the fracturing fields and heterogeneity in the distribution of the reservoir's oil content and the productivity of producing wells. The article deals with the problems of studying the fracturing of rocks and the need to take it into account in the geological and hydrodynamic modeling of oil and gas deposits. The obligatory use of innovative seismic technologies in studying the geological structure of fields and new technologies for studying sludge during drilling is the key to a successful study of unconventional reservoirs and shale strata at various stages of geological exploration and development of oil fields.

Keywords: deposits with hard-to-recover oil reserves, unconventional oil deposits, low permeable, tight, ultra-low-permeable layers, deposits of super viscous oils and natural bitumen, oil recovery factor, pilot-industrial works, shale rocks, hydraulic fracturing, geological and geological-hydrodynamic models

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The experience of the United States and other Western countries shows the huge oil and gas potential of tight rocks, the basis of which, they believe, are shale formations. But the latter, based on the experience and accumulation of these types of rocks, are only part of the general concept of tight rocks. Thus, the work (Prishchepa, Averyanova et al., 2014) states: "On the one hand, the concepts of "shale oil" and "gas and oil and gas of tight rocks" can be considered not to coincide, primarily because of the criteria for their separation, and on the other hand, it is necessary to understand that the latter completely absorb the former. The term "oil from tight rocks – low-permeable reservoirs" that most commonly used in the US oil industry today is more used to denote the whole diversity of unconventional sources of oil, for the extraction of which special technologies are needed, including drilling of multi-layer horizontal wells, multi-stage fracturing, microseismic and microscopic observations."

Table 1 shows the classification of rocks according to the main parameter – permeability, which unequivocally indicates our lag behind the leading global trends. Thus, the interval of standard permeability values from 1.0 to 10 mDa established for fields of the Republic of Tatarstan is hopelessly outdated. The reservoir rocks, the permeability of which is enclosed in this interval, according to the above classification, belong to medium-permeable, and oil reserves in reservoir rocks with a permeability less than 1.0 mD must be taken into account, since they are objects of industrial development using modern production technologies. The categories of tight rocks (from low-permeable to nanopermeable) should be studied as hydrocarbon-saturated, taking an active part in the processes of in-situ filtration and oil production, and the low-permeable group of rocks is of interest from the standpoint of potential oil production facilities.

Today, leading oil and gas companies with experience in developing both conventional and non-conventional oil and gas production facilities adhere to the classification of hydrocarbon (HC) accumulations in terms of the technological aspect of their development (Fig. 1):

- conventional deposits confined to conventional reservoir rocks and controlled by impermeable beds and traps;

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Permeability, D	Rock permeability quality	Reservoir
More than 1,00	Very high permeable	Conventional
From 1,00 to 0,10	Highly-permeable	Conventional
From 0,10 to 0,01	Permeable	Conventional
From 0,010 to 0,001	Mid-permeable	Conventional
From 0,001 to 0,0001	Low-permeable	Unconventional
From 0,0001 to 0,00001	Ultra-low-permeable	Unconventional
Less than 0,00001	Extra-low-permeable	Unconventional
0,000000001	Nano-permeable	Unconventional

Table 1. Characteristics of permeability of reservoir rocks regardless of the type of voids (Prishchepa et al., 2014)

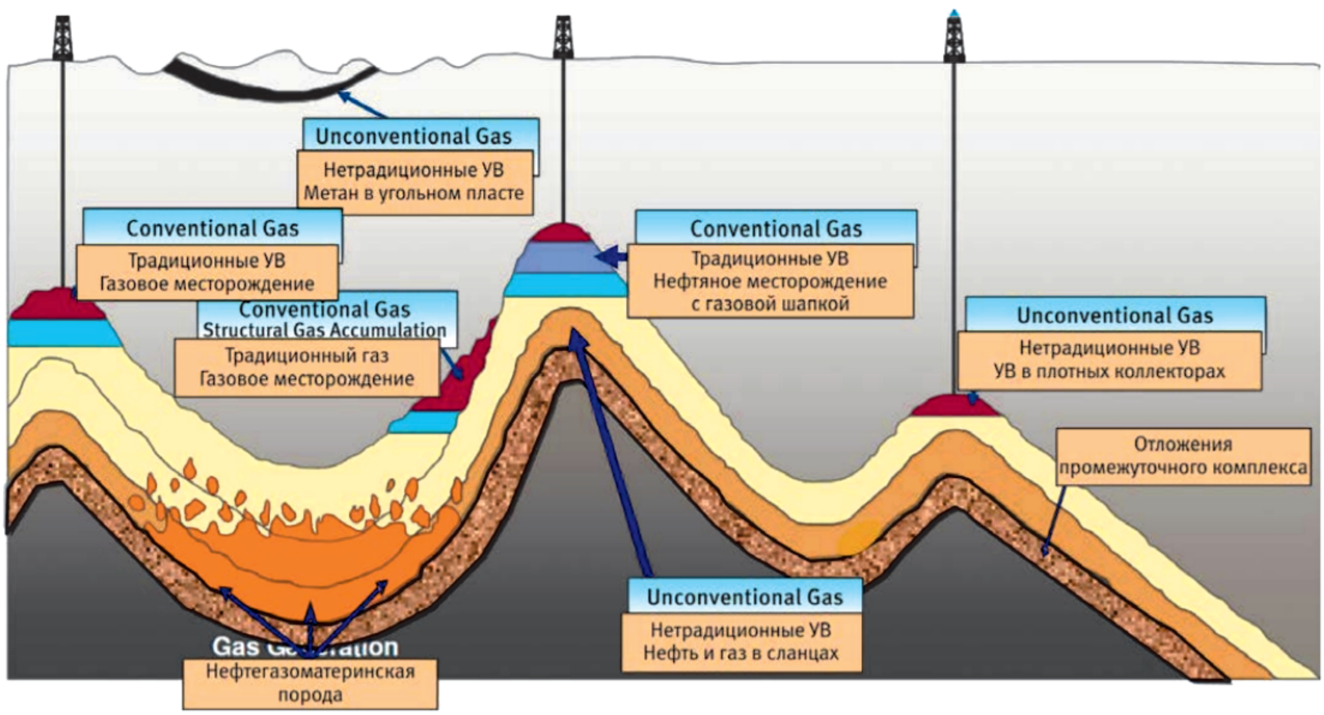

Fig. 1. General ideas about the localization of conventional reservoir rocks and unconventional deposits in tight and source rocks (Shuster, Punanova, 2018)

- unconventional accumulations in high-carbon shale strata not controlled by the structural factor and impermeable beds;
- unconventional accumulations in tight rocks or semi-reservoirs – clayey sandstones, aleurolites, carbonate rocks, which may also not be controlled by the structural factor and impermeable beds (Prishchepa, Averyanova, 2014a).

Important features of oil and gas deposits in shale oil reservoir and tight oil reservoir that distinguish them from conventional deposits are the following:

- continuity, when hydrocarbons are "everywhere and nowhere" in the dispersed state in rocks with low matrix permeability (Morariu et al., 2013; Prishchepa, Averyanova et al., 2014; Prishchepa, Averyanova, 2014b);
- uncontrollability of structural and stratigraphic factors;
- controllability of the lithological factor, as well as fractured fields.

Unconventional reservoir rocks, the oil content in which is controlled mainly by the lithological factor, can have a very wide area distribution. Consequently, the calculation of reserves in them requires different approaches.

Performed at the Kazan Federal University under the leadership of V.P. Morozov's analysis of the distribution in the carbonate sediments of the lower and middle Carboniferous of conventional and tight oil-bearing reservoir rocks revealed a certain type of section in the Tournaisian sediments, which can be attributed to unconventional reservoir rocks (Morozov et al., 2016).

This type of section is most fully studied on the eastern side of the Melekessky depression in the Kizelovskian and Cherepetskian sediments of the Upper-Tournaisian subsurface. Probably, such deposits are widespread, as indicated by the absence of conventional carbonate reservoir rocks in the Tournaisian deposits in many fields on the eastern side of the Melekess depression.

Such unconventional accumulations are characterized by low values of reservoir properties and oil saturation. The porosity of such rocks, as a rule, rarely exceeds 5%, the maximum permeability is the first MD, and the oil saturation by mass varies from 5-8%.

Such tight oil-saturated carbonate rocks have significant advantages:

- the estimated large area of distribution (about 5 thousand square kilometers);
- large thickness – up to 30 m;
- estimated large geological resources;
- the presence of mobile oil fluid (according to thermal analysis of rocks).

Based on the work performed, the calculation of geological resources of oil in tight carbonate rocks was carried out. Studies show that the geological resources of oil, concentrated in the Upper-Tournaisian subsurface on the eastern side of the Melekess Depression, are tentatively estimated at 8025 million tons (Morozov et ak., 2016).

Oil-gas-containing tight rocks in nature are much more than conventional reservoir rocks, due to the conditions of sedimentation and the subsequent transformation of sediments. This is evidenced by available data on the resources of conventional oils and liquid hydrocarbons of shale deposits. To assess oil reserves in tight and shale rocks, specific types of research are needed, and for their extraction, technologies that are fundamentally different from technologies for recovering hard-to-recover reserves. The increase in permeability and drainage area by creating artificial cracks and filtration channels is common to these technologies. At present, this is done by drilling horizontal wells and complexing them with multi-stage hydraulic fracturing (HF). This technology is no different from technology for conventional tight rocks and shale deposits. The latter differ from the former only in terms of sedimentation. One definition of shale is as follows (Downey et al., 2011): "Oil shale – fine-grained sedimentary rocks containing minerals and a large amount of kerogen, which, in turn, is valuable as a raw material for subsequent processing into shale oil".

The first three parameters are usually considered: fracturing, porosity and permeability, which play a major role in the accumulation of hydrocarbons in oil shale and the ability to extract these hydrocarbons from productive strata.

The formation of cracks in rocks during the transformation of organic material into kerogen can occur in two directions: in rocks rich in organic material, due to dehydration with the formation of small cracks with low permeability (subsequently, as a result of tectonic influences, secondary cracks are formed in the rocks); in rocks containing smaller volumes of organic material (cracking occurs on a smaller scale than in the first case). In general, the width of the cracks is extremely small (less than 0.05 mm), but its length can be thousands of times more than the width. Cracks in oil shales represent a small volume and cannot play a significant role as storage of basic organic material.

In the structure of the pore space in the productive strata of shale oil deposits, three main components can be distinguished: the porosity of the rock matrix; porosity formed by micro- and macro-fracture; porosity of syngenetic organic matter dispersed in the rock. The first two types of porosity do not play a noticeable role in the mechanism of conservation of shale oil resources. The porosity of the kerogen, as well as the space between it and the grains of the rock matrix can be in the range of 2.4-2.7%. But when samples of such shale are heated, its porosity can dramatically increase to 25-50% (depending on the amount of organic matter (OM) contained in it).

This heterogeneity leads to the fact that in a large area of development of shale and similar deposits there are no oil flows from the drilled wells, or they are non-industrial. However, in some areas drilled wells receive abnormally high flow rates. In the US, such sites are called "sweet spots". This is typical of Bazhenov deposits in Western Siberia and, to a lesser extent, in the Domanic deposits of the Volga-Ural oil field.

On the territory of Tatarstan, the prospects for the development of oil shale fields may be associated primarily with the rocks of the Upper Devonian domanicoid formation, with the Semilukskian (Domanic) horizon, as well as with the Rethitskian (Mendymian) horizon and domanicoid formations of the central and onboard zones of the Kama-Kinel deflection system (Fig. 2).

First of all, it should be noted that, in fact, deposits of shale oil and gas, as well as the oil-bearing capacity of Domanicites and Bazhenites, have not continuous distribution (carpet), as was previously supposed and still seems to many researchers, but are localized in certain areas.

In the analytical review of S.M. Akselrod (Akselrod, 2011, 2013) it was noted that according to the logging of productivity, performed in a large number of horizontal wells, the actual productivity of the well correlates poorly with the length of the horizontal wellbore, which is probably due to lateral heterogeneity of shale. This is also the reason for the uneven distribution of inflow over the length of the trunk: in many wells 90% of the total inflow accounts for one third of the perforated intervals.

As the analysis of the selection dynamics has shown, 12-18 months after the well has been commissioned, its production rate drops to 20-40% of the initial one and then continues to decline. Therefore, to maintain the required level of production from the field, it is necessary to drill a large number of wells. This is a very important point, indicating that in tight low-permeable reservoirs of shale fields, oil does not migrate laterally, is not "pulled" to the well when developed due to the small radius of drainage. The productivity and oil-bearing capacity of shale fields is highly heterogeneous, and their development itself is a gradual and phased development

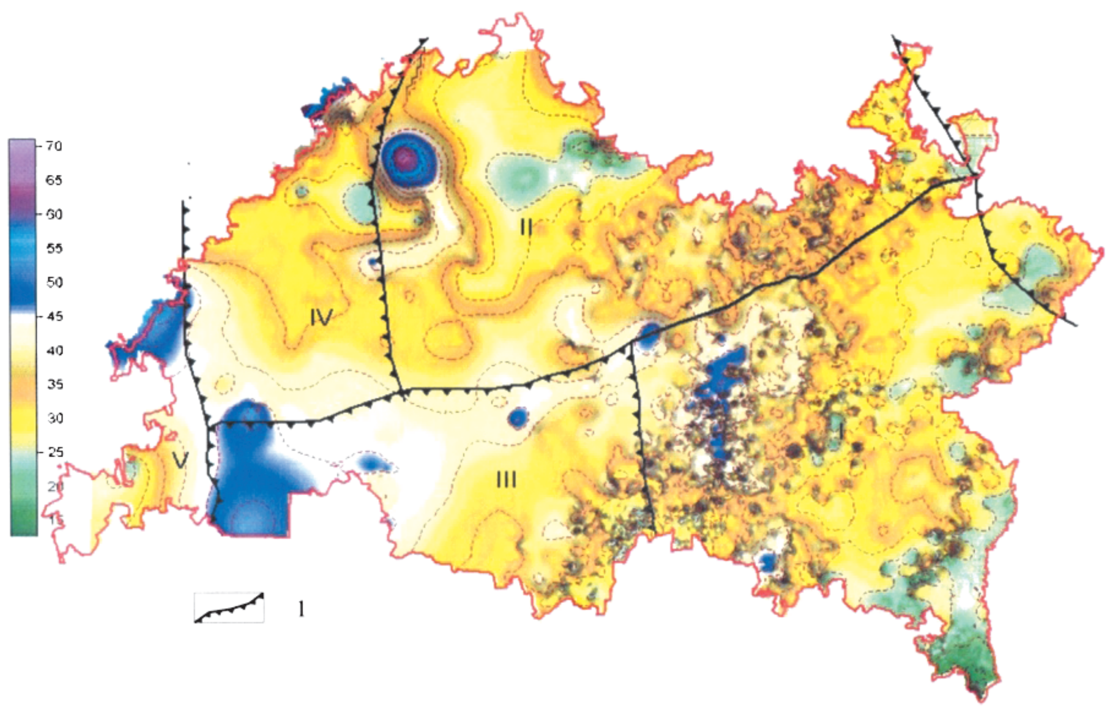

Fig. 2. Capacity map of the Semilukskian horizon of Tatarstan (according to Khisamov et al., 2010). 1 – modern boundaries of the structures of the 1st order; I – South-Tatar arch, II – North-Tatar arch, III – Melekess depression, IV – Kazan-Kazhim aulacogen, V – East slope of the Tokmov arch.

of separate (apparently hydrodynamically unrelated) sections of the sequence, the formation of which is most likely due to local foci of fracturing.

Consequently, the study of the development of fractured fields in areas is one of the methods for searching promising areas within which local oil deposits can form not only in the Sargayevskian-Rechitskian complex of rocks, but also in the overlying sediments of the carbonate Devonian.

Thus, the primary task is the search and detailed exploration of areas confined to fractured zones. And the increased fracturing is controlled by deep faults of the sedimentary sequence, going into the basement. In zones of fracturing, well flow rates depend on the material filling these cracks (these are small or coarse-grained siltstone, or even grains of sand fractions) (Lukin, 2011).

Modeling for the purposes of prospecting and exploration consists in estimating the forecast resources in large areas of development of promising objects. Here the following data appears: thickness, porosity, organic content, its maturity, silica content and tight limestone, geological and geochemical features of shale strata are studied. Such models are sufficient to search for promising areas.

Exploration work on models should be carried out taking into account the peculiarities of the geological structure of tight rocks and shale formations. In most cases, the usual methods associated with the search for elevations do not work here. Shale deposits, tight rocks often form fields, overlapping with underlying deposits. However, the areas of interest for the search for hydrocarbons do not have a continuous development due to the large zonal heterogeneity.

Special searches are needed to search for sites of interest. Here, such methods as seismic side-scanner, seismic location of emitting sources, low-frequency seismic prospecting can be used. The best results are obtained by combining methods for studying areal variations of the gamma-field, gravity prospecting and modern methods for interpreting 3D seismic data. Such studies will localize the most promising productive areas. There is also a large role of geochemical and laboratory studies of rocks and fluids and dispersed organic matter that saturate them.

The lack of genetic relationship between syngenetic organic matter of domanicites and oil of Pashian, Kynovskian horizons (Plotnikova et al., 2013), as well as the presence of domanic migration of bitumen, similar in composition of oil terrigenous Devonian, said the formation of deposits of oil in Semiluki, mendymskom and overlying horizons in fractured reservoirs due to the upward vertical migration from below (Ostroukhov et al., 2014, 2017; Plotnikova et al., 2013, 2017).

The study of areas outside the structural uplifts is one of the most important areas in the search for unconventional oil deposits in the domanikites; it is necessary to study the entire territory of the license area, including areas outside the structural uplifts and contours of existing deposits in traditional reservoirs.

An analysis of the distribution of deposits in shale reservoirs of the Sargayevskian-Rechitskian complex showed that it does not obey the structural factor. Thus, the object of the search for deposits in unconventional reservoirs should be the entire area of the license area, including the marginal areas of uplifts and the space between them.

The use of high-precision gravity survey made it possible to visually verify that the mineralogical density of ordinary limestones and rocks of the Domanic facies, enriched with organic matter and silica, is significantly different. The increase in the share of organic matter in the rock naturally leads to a decrease in its density to 2.3 g/cm^3 and less. Thus, the areas where Domanicites dominate the Semilukskian horizon can be identified with the help of high-precision gravity prospecting. In addition, it is established:

- all the fields and deposits of hydrocarbons in the gravitational field correspond to characteristic local negative anomalies;
- the contours of local anomalies correspond to the contours of hydrocarbon deposits, and in the case of a multilayer deposit – to the external contour of deposits;
- the magnitude of the amplitude of local anomalies serves as an indicator of projected hydrocarbon reserves.

In addition to the above, considerable resources in tight, ultra-low-permeable reservoirs are available at existing fields. Such rocks have so far almost not been studied.

In order to study promising ultra-low-permeability rocks in existing and new oil fields, downhole methods for determining fracturing are needed (today they are available in practice).

The study of fracturing according to the logging and the results of drilling wells. At the end of the last century under the leadership of R.P. Gottikh (Gottikh et al., 2004; Gottikh et al., 2006; Gottikh et al., 2007) a method was developed for mapping areas of heightened fracturing of the geomedia based on the analysis of areal gamma field variations in the Semilukskian horizon and in other later sediments.

The confinement of the majority of fields to the centers of increased permeability of rocks poses the problem of identifying fractured zones as one of the most important in exploration. First of all, they are solved in Tatarstan with the use of seismic materials.

The decisive role of inherited fracturing in the migration of fluids, the association of hydrocarbon accumulations to their development areas, the possibility of registering permeable zones based on the anomalous values of areal gamma-field variations suggest recommending the use of radioactivity in rocks as an unconventional method to search for missed deposits in exploited fields, especially in complex reservoirs that are the carbonate rocks of the Upper Devonian and Lower Carboniferous.

The study of fracturing geosystems by seismic data. Currently, new fracture field mapping technologies have been successfully applied at existing fields. In particular, the processing of 3D seismic survey materials makes it possible to obtain cubes of fracturing and oil saturation development using different types of waves. According to the results of 3D seismic survey data processing in Texas (shale), Iran, Orenburg region, Western Siberia, very interesting results were obtained – well production rates are determined by fracturing fields, oil inflow zones in the reservoir and fluid flow directions in the reservoir (Kuznetsov et al., 2016; Kuznetsov et al., 2017). Uniform placement of the project production wells without taking into account the development of fracture fields and fluid flows leads to the drilling of low producing wells, while the main production is achieved due to a small percentage of high-production wells.

To increase the field and geological efficiency of seismic prospecting, especially for hydrocarbon deposits in low-permeable and shale strata, it is proposed to apply a new seismic research methodology based on the integrated use of waves of different classes: specularly reflected, diffusely reflected and microseismic emission, which have a dominant dependence on different geological parameters : structures, fluid saturation and fracturing of the geological environment, respectively (Kuznetsov et al., 2016; Kuznetsov et al., 2017). These waves make it possible to obtain independent information about the structural form of the trap, heterogeneity (oil, gas or water?) and non-uniformity of its fluid saturation and spatial distribution of open fractuinring in the geological environment, including low-permeability and shale hydrocarbon-rich strata. A comprehensive analysis of this information allows us to select the optimal locations and directions of drilling of vertical and horizontal trunks, respectively, to ensure the maximum possible inflow of hydrocarbons. The implementation of this methodology is carried out on the basis of a complex of seismic studies, including the standard CDP technology and the innovative technologies "Seismic side-view locator" and "Seismic location of emission foci", created in 1990 and 2005, respectively, by scientists and Specialists of the Scientific School of Oil and Gas Seismic Acoustics of prof. Kuznetsov O.L. to study fracturing, fluid saturation type ("oil-gas-water") and other characteristics of the geological environment. The results of research on these technologies are confirmed by dozens of wells in oil and gas fields in various regions of Russia and abroad: Iran, Brazil, USA, Vietnam, etc.

Gas logging and the study of shale slurry. One of the most effective ways to obtain information about the structure and fluid saturation of shale strata can be improved and modified gas logging, equipped with modern analytical tools. The most detailed this issue is considered in the works of S.M. Akselrod (Akselrod, 2011, 2013). In particular, in its scientific review, devoted to the problem of development of shale formations, new technologies of gas logging and on-line analysis of sludge in the process of drilling are considered in detail. The author of the review notes that such important characteristics of shale as relative fragility (brittleness), as well as thermal maturity of kerogen, according to logging data, are not defined in principle. And other significant parameters, such as mineralogical composition, organic matter content, mobile and stationary oil, permeability necessary for the assessment of reserves and productivity, according to logging, are estimated with a certain degree of uncertainty. Therefore, when drilling wells, an important and necessary component of identifying and studying oil deposits in shale and low-permeable carbon-containing carbonate strata are gas logging and research of cuttings, which are produced directly in the drilling process, both at the well and quickly in the laboratory.

Currently, such technologies for studying sludge in the study of shale are developed by Weatherford International Ltd and are already being successfully used in practice. The technology includes the determination of TOC (total organic carbon), thermal maturity of kerogen, the assessment of the presence of residual oil and the conduct of distillation by means of mobile equipment. One of the principal elements of this technology is advanced gas logging, which uses semi-permeable membranes that are placed directly into the jet of washing fluid, which allows ud to capture gaseous hydrocarbons immediately from the mud, and not from the air. The analysis is made for 50-60 s.

Sludge analysis is performed directly on the well with a set of special mobile equipment. This equipment allows us to:

- Carry out the extraction of sludge, which allows to evaluate the content of hydrocarbons C1-C8, benzene and toluene, as well as gases CO_2 and N_2;

- Evaluate the mineral composition of rocks using X-ray fluorescence (XRF) and X-ray diffraction scattering (XRD) instruments, which can be obtained within 45-60 minutes after taking sludge from a vibrating sieve with an accuracy not inferior to laboratory research using the same method. In the course of such an assessment, the content of quartz, opal, plagioclase, and potassium feldspar is determined. The total clay content, the presence of carbonates, pyrite, anhydrite, barite and other minerals are also determined. It is assumed that these studies can replace lithological logging on the cable.

- Assess the TOC and fragility of rocks. It should be noted that in recent years, a new generation pyrolyzer HAWK has been successfully used to determine TOC and geochemical characteristics of oil and gas fluids in the rock, which allows it to promptly obtain comprehensive geochemical information directly at the well to assess the presence of mobile oil in the reservoir and its industrial accumulation.

- Assess the fragility of the shale according to its ability to crack with minimal external stress, which is necessary to predict the effectiveness of hydraulic fracturing. The fragility index (brittleness index) depends on the mineral composition of rocks and is determined according to XRD and XRF (with proper calibration). And now, experts have already proposed an algorithm for determining the brittleness of shale of both quartz and carbonate composition.

Currently, a new modification of gas logging, carrying out the study of additional pyrolytic parameters for the sludge, as well as mineralogical studies and the study of the geomechanical properties of the sludge during drilling, allows to obtain comprehensive information without coring.

The introduction of this technology in Russia and Tatarstan will make it possible to obtain the necessary lithological-geochemical information and assess the prospects of the domanicites already at the drilling stage, without spending large funds on the selection and study of core.

Currently there are a sufficient number of methods for searching and detailed study of fractured zones. Some of them are used on an industrial scale, some are at the stage of pilot works, others at the stage of research and development. These methods are sufficient to address exploration.

However, for the design of modern technology development, especially the application of new innovative methods and methods for enhancing oil extraction, their effectiveness is insufficient. We need their further improvement.

Production methods depend mainly on the geological and physical features of the deposits. Choosing them requires tremendous analytical and researched work. Here, depending on the composition of hydrocarbons, the development of reserves will require the integration of the aforementioned basic technology with physical (wave), thermal (for highly viscous hydrocarbons), gas methods. In the future, obviously, other technologies will be developed (for example, plasma-pulse), which will significantly increase the oil recovvery factor. Of course, we will not be able to dwell on the technologies that are widely used today by the Americans, which make it possible to extract about 10% of oil contained in shale oil (natural depletion regimes of deposits) from the depths. This will be a classic dilution of mineral reserves with the creation of enormous difficulties for their further extraction, even with the possible use of future effective oil recovery technologies.

The method of hydraulic fracturing may be the most popular method in the development of oil deposits in shale and similar rocks and, in general, in tight rocks with a permeability of 1 mDa and below. Without this method, the exploitation of such deposits is currently not even discussed. Other enhanced oil recovery methods can be used after hydraulic fracturing.

As an alternative to hydraulic fracturing, today we can consider a local gas-dynamic fracturing created in the Avangard Design Bureau. LGDF does not need to fix cracks with proppant, it is much cheaper than classic fracturing (6-10 times) and can be used in certain areas of exploited fields with hard-to-recover reserves and especially in conditions of bottom-hole contaminated wellbore zones. The same tasks can be performed by oscillators for treating wells under various names, such as, for example, hydrodynamic well oscillators (Muslimov, 2014).

Hydromechanical wave technologies of the new generation are currently combining one of the new and promising areas of engineering and technology developed for the first time in the world at the Scientific Center for Nonlinear Wave Mechanics and Technology of the Russian Academy of Sciences (Ganiev, 1998).

When choosing a complex of research and technologies for the extraction of hydrocarbons, today we can outline two directions. In most cases, two types of hydrocarbons are present in shale strata: conventional (usually light) oil and kerogen. This can be explained by the conditions of their generation: conventional light oil is of inorganic, kerogen-organic origin. At present, it is obvious that conventional oil is being extracted, since the existing technologies do not allow extracting hydrocarbons of the second group. Therefore, the accepted oil recovery factor (0.08-0.12) refers to the production of this group. For decades, this oil has been extracted at several deposits (mendym-domanic deposits) of the Romashkino field in Tatarstan. They were identified along the way in the wells drilled on sediments of terrigenous Devonian. The potential for increasing oil recovery factor for this group of oils is still available.

Oil production can also be obtained from kerogen through its in-situ processing. Such oil in its usual state is absent in the reservoir and may appear as a result of warming and pyrolysis of the primary kerogen.

At present, the first direction is technically feasible, while the second can only be implemented in the long term.

This requires special, expensive laboratory and field experiments.

However, obtaining information for the implementation of the second direction should be carried out now, using the wells drilled on the terrigenous Devonian, to collect information about the mineral composition of the Sargayevskian-Rechitskian complex, its fluid saturation, OM content, its thermal maturity, and the generation potential of these sediments. All of these studies, which are currently being conducted, will allow to determine the distribution boundaries of the rocks of the Domanic facies in the section, will give all the necessary information about it and significantly reduce the cost of research of shale strata in the future, when the introduction of technologies for in-situ shale processing will become profitable.

As for just ultra-permeable rocks that make up a significant part of the sedimentary deposits of Tatarstan, here the presence of kerogen is not necessary. There can only be oil of the first group. Accordingly, other technologies are needed that are not related exclusively to intra-layer pyrolysis of HC.

But at this stage, the study of various types of fracturing of the geological environment is the most important. Therefore, it was not by chance that in March 2018 a scientific and practical seminar was held in the Academy of Sciences of the Republic of Tatarstan on the topic “Fracturing and fluid dynamics of the Earth’s crust and their role in the formation and development of oil and gas fields”. The seminar summarized the experience of studying the fracture of the geological environment in the Russian Federation and outlined further areas of scientific research on the voiced problem. The seminar protocol is given in this issue.

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