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Part 1

International Scientific and Practical Conference

"HORIZONTAL WELLS AND HYDRAULIC FRACTURING TO IMPROVE THE EFFICIENCY OF OIL FIELDS DEVELOPMENT"

September 6-7, 2017
Kazan, Russia

GEORESURSY SCIENTIFIC AND TECHNICAL JOURNAL

Dear readers!

You are presented with a Special Issue of the Scientific and Technical Journal Georesources (Georesursy), in which the main plenary reports of the International Scientific and Practical Conference «Horizontal wells and hydraulic fracturing to improve the efficiency of oil fields development» are collected, as well as relevant and significant articles of leading Russian and foreign scientists, experts in the field of horizontal drilling and hydraulic fracturing. The uniqueness of this collection is that scientific publications dedicated to the development of unconventional hydrocarbon deposits in low-permeability reservoirs, evolvement of horizontal drilling technology, development of new geological and hydrodynamic models are collected in a single publication.

This issue is a tribute to the memory of Alexander Mikhailovich Grigoryan, our compatriot, a great oil scientist, and founder of the drilling technology of branched horizontal wells. The technology of horizontal drilling developed by him was first implemented industrially on the deposits of Tatarstan and Bashkortostan in the 60-70s of the last century. In the following, thanks to this technology in the world oil industry, the development began of offshore and other oil and gas fields that are difficult to access by vertical drilling, as well as massive carbonate reservoirs.

Currently, horizontal drilling, hydraulic fracturing, complex combination of these technologies are becoming one of the most effective and promising methods of intensifying oil production and increasing oil recovery for fields at a late stage of development.

I am sure that the Special Issue of the Scientific and Technical Journal Georesources (Georesursy) will be of interest to a wide range of oil industry practitioners, scientists, students of branch educational institutions.

The President of the Republic of Tatarstan R.N. Minnikhanov

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This Special Issue is dedicated to the International Scientific and Practical Conference «Horizontal wells and hydraulic fracturing to improve the efficiency of oil fields development», which was held in Kazan, Russia, 6-7 September, 2017. This Issue contains a selection of reviewed papers from the Conference.

Table of Contents

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GEORESOURCES

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Part 2

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Table of Contents

A.M. GRIGORYAN – GREAT RUSSIAN ENGINEER, FOUNDER OF A NEW DIRECTION OF OIL AND GAS INDUSTRY DEVELOPMENT

Through the efforts of many generations of geologists, drillers, technologists and specialists of other professions, a mineral raw material base was created in the country. One of such researchers was Alexander Mikhailovich Grigoryan (1914-2005), who devoted his life to the development and introduction of a new direction in drilling wells – horizontal drilling of multilateral wells.

A.M. Grigoryan was born in Baku in 1914. Since 1932 he worked as an assistant driller, and in 1939 graduated from the Azerbaijan Industrial Institute, with a major of mining engineer in the oil industry. Until 1944 he worked in the Experimental Bureau of Turbine Drilling in Baku and Krasnokamsk, then in the Department of Turbocharging of the Ministry of Oil Industry and until 1980 – in the All-Union Scientific Research Institution of Drilling Equipment.

In 1941 he developed the technology and drilled the world's first inclined wells with a hydraulic downhole motor. Bought by the US (in the 60's), this technology allowed the development of all marine and other hard-to-reach hydrocarbon fields, ensuring the growth of oil production in the second half of the 20th century.

Since 1949, he had developed the technology of branching wells, and since 1953 – horizontal drilling. Then (until the 50s of the last century in the former USSR), broad opportunities were created for any seemingly fantastic, commercial experiments, scientific and design developments that led, as is known, to the creation of turbine drilling, electric drilling, inclined and branched horizontal drilling.

Creation of a new type of wells and methods of their use was carried out by the author directly in the field conditions and accounted for up to 80% of the total volume of works in this direction. In these conditions, invaluable support (contrary to the tendencies of higher authorities) was provided by oil specialists from the heads of associations to drilling masters. V. Bragin (co-author), V. Muravlenko, K. Kovalenko, A. Dergachev, K. Stukalov, B. Fuks, Osintsev, V.Galeyev, L.Shtemberg, N.Shliukhin, A.Slastnaya and many others provided an opportunity for drilling dozens of branched-horizontal wells.

A special place in the work of A.N. Grigoryan was held by N.K. Baibakov – a former Minister of the Oil Industry, then Deputy Chairman of the Council of Ministers – Chairman of the State Planning Committee of the USSR. His participation and personal recommendations helped to move the method from pure drilling to a powerful tool for improving oilfield development systems.

Horizontal drilling began at the Oil and Gas Production Department Ishimbayneft of Bashneft Association. Here, first at well No65/45 (1952), and then on the famous well No 66/45 (1953) for the first time several horizontal trunks were drilled (Fig. 1). The daily production rate was 120 tons, which is more by 17 times than the production rate of conventional vertical wells, with drilling costs only 1.5 times higher.

A.M. Grigoryan obtained even more striking results while drilling wells at old fields. A striking example of such a phenomenon is a branched-horizontal well that was drilled by him at the old section of Borislavneft. Branched-horizontal well with five trunks was commissioned with a 28 tons/day daily production rate, whereas at a distance of 30-40 m from it, in old wells (operated since 1914), the oil production rate was only 0.2-0, 4 tons per day, i.e. from five branches the production rate was not 5 times, but 80 times higher! It is quite obvious that despite 40 years of operation with such a dense spacing of conventional wells, significant residual reserves remain in the formations, including in the immediate vicinity of their faces.

Since 1949, A.M. Grigoryan began developing the technology of branching wells (without whipstocks), and since 1953 – horizontal drilling. Until 1970, at the All-Union Scientific Research Institution of Drilling Equipment under the leadership of A.M. Grigorian, a group of specialists developed a theory of drilling such wells and an efficient technology for their boring. Former Minister of Oil Industry V.D. Shashin, having learned from the American magazine "Offshore" (May, 1975, p. 303, 304 (the article was written by the observer for the USSR)) about the works of A.M. Grigoryan in a number of regions of the USSR, instructed him to introduce Tatneft to the simplest elements of this technology.

In an interview with Yu.A. Volkov in 2002 chief geologist of Tatneft R.Kh. Muslimov said: "Him (Grigoryan) and I evaluated the capabilities of horizontal drilling in Tatarstan. We decided to drill several such wells. First we drilled, if I recall correctly, three wells, then four, seven wells total. We listened Grigorian's proposals, and then selected the wells, which, in our view, were the most optimal for horizontal drilling. We believed that layers of high thickness are the most suitable for horizontal drilling. We had no experience of drilling horizontal wells. We

Molotovneft. Krasnokamsk. Ultra short turbo drill. 1948

Ishimbayneft. Branched-horizontal well No 68/45. Tapping of the branch, Alexander Grigoryan before the brake. 1953

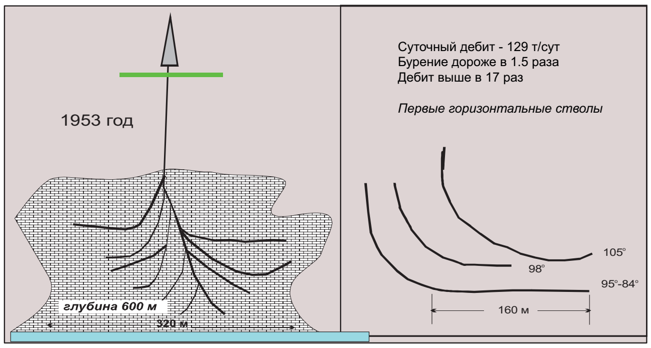

Fig. 1. The world's first branched-horizontal well No 66/4, drilled by A.M. Grigoryan in Ishimbayneft in 1953. The profile of this well was demonstrated at the 4th International Petroleum Congress in Rome in 1954, and then was published in the Journal «Drilling» in December 1955.

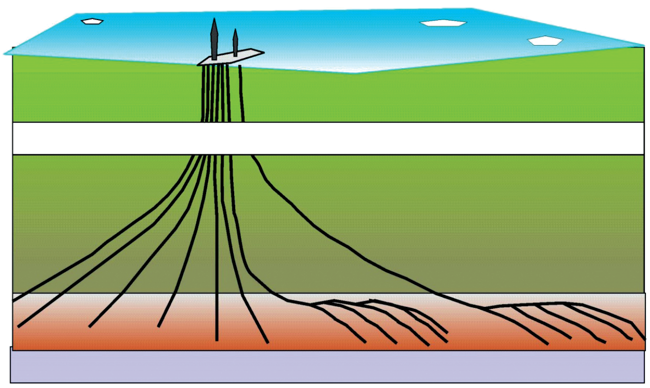

Fig. 2. Wells-Giants (project)

chose the Sirenevsky field, and, strangely enough, this very first horizontal well, which was drilled at the Sirenevsky field (well No. 1947), proved to be the most effective. Previously the exploration well No. 478 was drilled, that is, we knew geology of this area very well. Now we would call this well a pilot one, if we drilled it. We did not want to risk, so we drilled in the place with known geology. These are the wells No. 1947, 1918, 1990. The first well was the most successful. At first it produced about 40 tons of fluid during development. It was practically water-free oil (water was about 5%). Then the production rate of 25-28 tons per day was established in this well. For these deposits, the rate was three times higher than for the vertical well. That is, the very first well gave the best result. Then there was a well No. 1918, it also showed good results of inflow. The well No. 1990 was worse, because it was then flooded, the rates were low, no more than in conventional vertical wells."

In 13 districts of the former USSR with direct participation of A.M. Grigoryan more than 30 branched-horizontal wells were drilled with very high productivity.

A.M. Grigoryan created new approaches to the development of oil fields and the technology of drilling the Wells-Giants (Figure 2). As usual, the new technology in Russia has experienced great bureaucratic obstacles during implementation. Despite the support of such an influential and creative person as N.K. Baibakov, things were not going very well for him. Desperate in attempts to drill branched-horizontal wells, Grigoryan left for France, giving them some of his technologies.

Due to lack of commercial experience in the former USSR, technology of inclined drilling by the government of the former USSR was sold in the US for a pittance, and technology of horizontal drilling the author donated to the French Institute of Oil (FIN) for their promise to help with the implementation. As later A.M. Grigoryan wrote himself: "Of course, they lied." FIN and Elf Akiten created the firm Horwell ("Horizontal Well") for the sale of technology and fully appropriated the authorship. The sad experience of "commercial activities" adopted in France, yet allowed the author to fully retain in his hands the most important technology – drilling from the surface of the Earth special branched-horizontal wells and methods of their application. Such wells have a rate of dozens of times higher than conventional vertical wells and increase the total recovery of hydrocarbons.

A.M. Grigoryan wrote himself: "I am the only specialist in this world of this technology, whose wide application is equivalent to the discovery on the Earth of a new type of cheap energy in huge quantities that has long been mastered in use."

UK oilmen followed with interest the successes of horizontal drilling in the USSR, and only after the successful application of a number of such wells in Russia, they decided to use them. This technology is more successful than the inclined drilling, bought by the USA from the USSR. But, in this technology, a tricky part is the boring of wellbore in the area where the horizontal part of the well is inserted into the productive layer.

The drilling technology of branched-horizontal wells was created not at the desk, but directly in the process of drilling (and operation) in the fields in various geological and technical conditions of the oil producing industrial enterprises of the former USSR. During the years of work, dozens of branched-horizontal wells were drilled with a very high economic effect.

A.M. Grigoryan summarized these results in his monograph, which he published in 1969.

Russia got interested in the widespread use of horizontal drilling rather late. In 1984, an international conference in Budapest surprised with the abundance of reports on horizontal technologies. Naturally, there were no reports from Soviet specialists on this subject. After the arrival of the delegation's home, everything was reported to the Ministry of Oil and Gas Industry. After that, the minister assembled the board, at which it was decided to develop a program of horizontal drilling. Thus, horizontal drilling technologies created in our country began to return to our country through Western companies.

He is a Candidate of Technical Sciences and has about 100 scientific works and inventions. A.M. Grigoryan emigrated to the USA in 1988, moving to Los Angeles, California. There he founded the company "Grigoryan Branched-Horizontal Wells", and became its president. He explains the motives of emigration to the US: "It is a pity that in Russia there is yet no legal protection of inventions. And this is the main reason. Otherwise, I would not contact the West."

In the United States, Alexander Mikhailovich developed all his talent. The technology of drilling multilateral wells began its development in the USA due to his efforts. And from there it has spread to other countries. The significance of the works of our great compatriot cannot be overestimated.

R.Kh. Muslimov

SOLVING THE FUNDAMENTAL PROBLEMS OF THE RUSSIAN OIL INDUSTRY IS THE BASIS FOR A LARGE-SCALE TRANSITION TO INNOVATIVE DEVELOPMENT

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Abstract. The powerful technical progress in the West in studying and developing deposits of unconventional hydrocarbons has a great influence on increasing the efficiency of conventional oil and gas deposits. Based on the foundation of modern oil science, it is necessary to calculate reserves and carry out design taking into account geological, off-balance and recoverable reserves. The necessity is substantiated of an innovative approach for the whole chain of hydrocarbon fields exploration and development, the new ideology of construction of geological and hydrodynamic models, the transition to a new level of calculation of development indicators and the oil recovery factor. Particular attention is paid to the improvement of development systems based on various categories of horizontal and multi-hole wells and the application of various fracturing technologies in hard-to-recover oil reserves and tight reservoirs, the selection of new technologies, and pilot commercial development in the field.

Keywords: reserves, tight rocks, hard-to-recover oil reserves, unconventional oil deposits, oil recovery factor, EOR, hydraulic fracturing, horizontal and multistage wells

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The powerful technical progress in the West in studying and developing deposits of unconventional hydrocarbons has a great influence on increasing the efficiency of conventional oil and gas deposits. Based on the foundation of modern oil science, it is necessary to calculate reserves and carry out design taking into account geological, off-balance and recoverable reserves. The necessity is substantiated of an innovative approach for the whole chain of hydrocarbon fields exploration and development, the new ideology of construction of geological and hydrodynamic models, the transition to a new level of calculation of development indicators and the oil recovery factor. Particular attention is paid to the improvement of development systems based on various categories of horizontal and multi-hole wells and the application of various fracturing technologies in hard-to-recover oil reserves and tight reservoirs, the selection of new technologies, and pilot commercial development in the field.

A feature of the current development stage of the oil industry is that until now, science has dealt mainly with the problems of involving deposits with hard-to-recover oil reserves in active development. This problem also remains one of the most important for the future. But this is not enough for the further development. New directions of the world development for the hydrocarbon branches of the fuel and energy complex require solving the problems of development of unconventional objects – deposits of heavy oils and natural bitumen, deposits in shale and similar sediments, and, in general, in tight rocks. The resources of heavy oils and natural bitumen in the world are comparable to the resources of conventional oils. The same situation exists in the Republic of Tatarstan.

Oil-gas-containing tight rocks in nature are much more than conventional reservoir rocks, which is due to the conditions of sedimentation and subsequent conversion of sediments. This is evidenced by the already available data on the resources of conventional oils and liquid hydrocarbons in tight and shale sediments. To assess the oil reserves in tight and shale rocks, specific types of research are needed, and their extraction require for technologies that are fundamentally different from the extraction methods for reserves that are difficult to recover.

Along with the new directions, the old problem remains to ensure the effective development of the so-called active reserves (or standard according to the western terminology) of long-developed highly productive fields. Here the design oil recovery factors reach values of 0.4-0.45 and, rarely, 0.5 and higher. The increase in oil recovery at these facilities to the values of displacement efficiency is the highest priority for the old oil producing regions.

The above-mentioned areas of development require solving the fundamental problems of the industry, both accumulated over the entire long history of the oil industry, and emerging again. Today, there is a need to assess the geological resources of oil, since balance and recoverable reserves, in the old, established understanding, leave behind substandard reserves, and they, according to preliminary estimates, may amount to 15-20 % of approved ones. At the same time, it is necessary to understand that geological reserves mean the entire amount of oil in the subsoil, regardless of whether it can be extracted from the subsoil today (Muslimov, 2016a). With this approach, the total resources will increase, and the oil recovery factor values will decrease. It seems advisable to develop a methodology for calculating geological reserves, taking into account the enormous progress in the West in the field of geological research and the available experience in extracting hydrocarbons from tight rocks (or even shales) (Prishchepa et al., 2014).

In modern conditions it is time to move to a new level of calculations of development parameters and oil recovery factor. To this day, thanks to the concept of absolute pore space, the initial petrophysical dependences are based on the results of mass determination of non-informative values of the absolute permeability coefficients for gas and open porosity (on dry cores). According to the concept of effective pore space, petrophysical dependencies must be built on the results of determining real effective permeability coefficients and effective porosity, because the degree of reliability of petrophysical dependences within the effective pore space concept is significantly higher than in the absolute pore space concept. Then it is obvious that the reliability of logging data for building 3D models will be much higher (Zakirov et al., 2006).

We must fundamentally change the ideology of constructing models, taking into account the allocation of geological, off-balance and recoverable reserves. Currently used methods of preparing information are not enough to build such models. First of all, it is necessary to significantly diversify and deepen laboratory studies of rocks and fluids that saturate them, and to improve logging methods (Muslimov, 2016a).

The foregoing obliges us to take a new approach to the stages of field development adopted in the 1970s (Ivanova, 1976). So far, we have also adhered to the identification of four stages of development of oil fields. But at the same time, the IV stage of development (in terms of significance in the formation of high oil recovery factor values and long development periods) was understood quite differently (Muslimov, 2012). But at present it is obvious that it is necessary first of all for the large fields to allocate also the V stage of development, which will mainly exploit the oil reserves previously not accounted for either in the official oil balances or in the accepted development projects (reserves in tight strata, earlier immobile reserves in operated facilities). With this in mind, a new stage of development is shown in Fig. 1.

All this is supported by modern achievements in the development of oil reserves in particularly complex geological conditions: tight (substandard) strata, highly watered long-term developed deposits. They include the technology of horizontal drilling, drilling of branched-horizontal wells, multi-hole wells, intermittent, directed hydraulic fracturing, the integration of horizontal wells with multistage fracturing, horizontal wells with wave methods, chemical compositions for producing highly watered strata, use of CO2, pulsed-plasma method, etc. A number of these technologies (physical and chemical) have been created in the Republic of Tatarstan, and the rest are successfully used.

The next problem is the rationale for oil recovery factor and measures to increase it, which is very important for the late stage of development, where almost all the significant fields in Russia are located. The fact is that the entire huge volume of field, geophysical, hydrodynamic research, and analysis of constructing geological and hydrodynamic models was reduced to

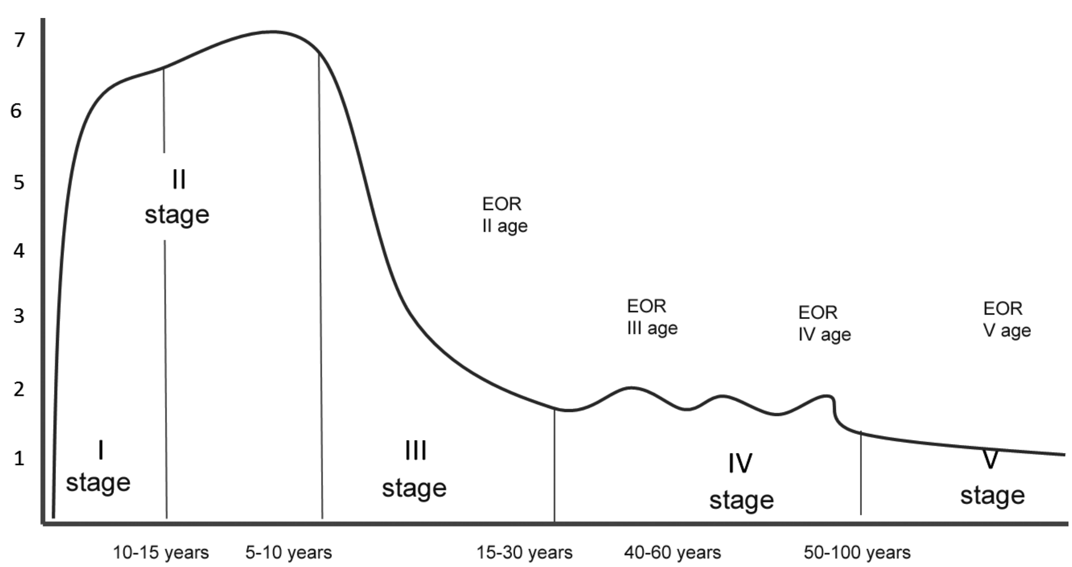

Fig. 1. Stages of development of the operational object (according to R. Kh. Muslimov)

determining the degree of water cut of the reservoirs and strata, and ultimately to determining the sweep efficiency Kokhv. At the same time, the displacement efficiency (Kv) determined by the primary calculation of reserves by laboratory methods was adopted. It is determined by injecting water through the core, or “infinite flushing of the formation” as written in all the textbooks. There was no doubt in the definition of Kv. But with the accumulation of experience in the development, we noticed that in washed areas in a number of cases very high Kv was obtained. When Kv was taken on these sites, according to laboratory data Kohv should have been close to unity and even more, which in conditions of really heterogeneous beds is impossible.

It has not been possible so far to solve the problem of reliable laboratory determination of Kv and its transfer to commercial conditions. A paradox turned out – we should probably have the maximum value of Kv (“infinite flushing”) in cores, but in real layers it is bigger. An explanation for this is given in the work (Zakirov et al, 2009).

But the main reason in our opinion is fracturing, which in laboratory conditions cannot be identified, but in real layers it is the main factor of oil displacement. From here we can draw a fundamental conclusion: if in most cases we have an underestimated Kv, then we, in analyzing the oil recovery factor in the developed areas, overestimate Kohv, i.e. the main (not less than 80-90%) geological and technological measures in the fields are carried out according to this factor. To achieve the project oil recovery factor, it is necessary to increase the volumes of geological and technical measures to achieve the project Kohv. There is why we need to drill more wells and stimulate more the basin. This fundamentally changes the approach to design development, planning of geological and technical measures and practice development of deposits.

Currently, despite the formal updating of standards, design is essentially carried out at the level of the 70s of last century. The analogy method used by the authors of the projects (especially in geological and physical characteristics of the deposit), the imperfection of modeling methods and hydrodynamic calculations, ignoring conventional classical methods for solving development problems, the lack of a profound professional analysis of the reserves development, insufficient control and regulation of development processes is the way to the unknown. All these problems lead not only to a short “life” of projects, but also to dilution of oil reserves.

Based on the world trends in the development of the industry, development systems using a fundamentally new type of wells (horizontal and multi-hole wells of different configurations), various fracturing technologies, new methods of increasing oil recovery and treating the wellbore zone of the formation are the priority. The technologies of horizontal drilling with a modern complex of research equipment came to Russia from the West mainly due to the efforts of our compatriot A.M. Grigoryan.

In the last quarter of the last century, drilling of horizontal wells in the world developed at an unprecedented rate. Later this boom came in Russia. Various types and designs of horizontal, multi-hole, branch-horizontal wells, and later sidetracking in previously drilled (old) wells appeared. In the last quarter of a century, Tatarstan has accumulated extensive experience in the use of horizontal wells to develop hydrocarbon deposits. However, despite the long period of use of horizontal wells in the Republic, their efficiency is relatively low: the rates of horizontal wells are only 1.5-2.2 times higher than the rates of vertical wells. The main reason is the non-systematic application of horizontal wells and the consequent disregard for the principles of rational development of oil fields, established by 70 years of practice and theory of development of oil fields by vertical wells (optimization of allocating operational objects and wells spacing, technological regimes of rational well operation, separate stimulation on reservoirs with different permeability; control and regulation of oil displacement processes).

The experience of using horizontal wells showed that they alone do not ensure the complete coverage of the reservoir’s reserves by drainage. The horizontal well itself, drilled by the common filter by the oil displacement coverage, differs little from the vertical well. In both cases, only a small part of the penetrated interval of the reservoir is operated. The greater the heterogeneity, the smaller the share of drained interval. To increase the sweep efficiency of the deposit, separation of intervals is necessary with permeability different from each other by 2-3 times or more.

But the experience of the Fedorovsky field in Western Siberia shows that in the most complicated geological conditions of oil and gas object AS4-8 (a small oil rim lying between gas cap and underlying water, an unfavorable ratio of the oil viscosity to the water viscosity is 13.6, high heterogeneity and dismemberment of layers) the use of traditional vertical well development systems can not provide sufficient current production levels and more or less acceptable oil recovery. The use of horizontal well development systems significantly increases current production and ultimate oil recovery (Muslimov, 2016c).

The need for a systematic approach to the development of fields with hard-to-recover oil reserves is evidenced by the experience of developing the Kizelian deposit of the Bavlinsky field. To solve the problem of rational development of the entire Kizelian deposit of the Bavlinsky field, it was decided to carry out pilot commercial development for the Korobkovsky section by the system of production horizontal wells and injection vertical wells using vertical-lateral waterflooding of S.N. Zakirov (Zakirov, 2009). Analysis of the prospects of this section with the further implementation of the projected technology until the end of the development with the water cut of 98% shows that it is possible to achieve the oil recovery factor of 0.369, and taking into account the correction of balance reserves (with the transition to geological) – about 0.3. This will be a real oil recovery factor, increased against the project one of 0.2 (Muslimov, 2016c, Zakirov, Zakirov, 1996).

Having remarkable results in the development of the Kizelian deposit of the Korobkovsky section, it is time to design such a system for the Kizelian deposit of the entire Bavlinsky field. It will allow to almost double the recoverable reserves of the deposit.

For the development of multi-layer, multi-level inefficient fields by a system of multi-hole horizontal wells it is necessary to have a fundamentally different geological model based on the fundamental positions of geology (Muslimov, 2017).

In general, further increase in the effectiveness of horizontal drilling is possible on the path of the most complete use of modern systems of rational development of oil and oil and gas fields developed during decades by vertical wells. These systems remain basic.

Horizontal wells expand the field of application of waterflooding in poorly permeable reservoirs (permeability of less than 1-5 mD), low-thickness (more than 10 m) oil rims in gas-oil deposits, thermal methods in deposits of highly and ultra viscous oils and natural bitumen. In such difficult conditions, horizontal wells are the most optimal, ensuring cost-effective operation. For the development of shale objects and generally tight rocks (permeability of less than a 1 mDa), the use of horizontal wells should be supplemented with methods that increase the reservoir permeability (hydraulic fracturing), as well as other methods of enhancing oil recovery (wave, thermogas, pulse-plasma, etc.). Industrial development of unconventional deposits in shale and tight rocks without the use of various modifications of horizontal wells at the current level of development is not possible at all.

In old oil-producing regions, which primarily include the fields of the Volga-Ural oil and gas province, the main fields have been drilled with sufficiently dense well spacing. Most of them are in the late stage of development. But there are great opportunities for involvement in the active development of the existing systems of reserves that are not developed by the existing ones, and even greater possibilities of extracting residual oil from the developed sites. On a multi-object multi-layer Romashkino field, despite more than 70 years of development, less permeable layers and interlayers and previously recognized substandard layers are not operated on a large area. Their development is possible with the use of lateral horizontal trunks and new stimulation technologies.

Currently, the efficiency of drilling lateral horizontal trunks in the Romashkino field is low due to the unresolved number of technical and technological problems, but the prospects for their application are very large.

Our analysis showed (Muslimov, 2014) that today, after a long development in this field, there are plots that are simultaneously developed on all four stages. The strategy for their further exploitation is given in Table 1.

The application of lateral horizontal trunks will allow developing weakly permeable layers from the II stage of development, carrying out pilot commercial development for the production of tight strata – from the I stage. Drilling lateral horizontal trunks on long-exploited fields (especially in the system version) will increase the oil recovery beyond the design level, and at inefficient multi-layer fields with reserves difficult to recover – will increase geological and recoverable oil reserves. This entails conventional deposits of oil.

In addition, the latest researches of particularly large fields in the context of both operated and non-operated objects predict the presence of oil in the so-called tight rocks or semi-reservoirs (Morozov et al., 2016). The work conducted by V.P. Morozov et al., has substantiated the presence of tight oil-saturated carbonate rocks among the studied sections, which have potential industrial oil content.

Thus, the sections studied by core of the lower and middle Carboniferous show that among the carbonate rocks in terms of the degree of oil saturation, we can distinguish:

- oil saturated rocks
- tight rocks without any signs of oil;
- tight oil-saturated rocks, intermediate between them (reservoir rocks).

Drilling of the lateral horizontal trunks will be necessary to determine the availability and potential of such reservoirs by carrying out pilot commercial development to extract oil from the exploited fields of Tatarstan. After assessing the possible productivity of tight strata in existing and new fields with the help of lateral horizontal trunks, there will be opportunities to design their development using development systems with horizontal wells. In all cases of oil reserves development of low-permeability reservoirs in conventional deposits and tight strata in unconventional deposits after drilling lateral horizontal trunks horizontal wells, the introduction of hydraulic fracturing remains the main element of the development system. From

Site (reserves) categories	Management objectives, development systems, technologies	Technical support
Sites (reserves) is tight reservoirs that are below the conditional values in the I stage of development	Development of reserves allocated as an independent development facility, intensive increase in oil production due to drilling of injection branched horizontal wells, if necessary, producing branched horizontal wells, areal systems, first-generation methods of enhancing oil recovery (fracturing, wave, local gasdynamic fracturing, possibly gas), flooding by reservoir water with reservoir temperature	Individual low-performance high-pressure pumps with adjustable capacity; Overflow of reservoir water from the underlying aquifers
Sites (reserves) in low permeable and highly productive clay reservoirs in the II stage of development	Ensuring and maintaining the maximum of oil production through the allocation of reservoirs into an independent facility, the completion of the design stimulation system: complex technologies of developing terrigenous reservoirs, recovery enhancement and buttonhole treatment methods of the 1st generation (fracturing, local gasdynamic fracturing, horizontal wells, multi-hole wells, wave, chemical methods), flooding with reservoir or sewage water with preservation of temperature	Individual high-pressure pumps, drilling of horizontal wells, multi-hole wells, special water preparation for water injection
Sites (reserves) in the III stage of intensive decline in production	The goal is to extract more oil, less water, unbundling of operational facilities, infill of well spacing, drilling of injection branched horizontal wells for separate stimulation on reservoirs, massive introduction of second-generation EOR (chemical, physical, microbiological, wave, complex), ASKU-VP, CES, BDN introduction.	Available technical equipment for development, ASKU-VP, second-generation methods of enhancing recovery, KES, BDN, perforation-depressive methods, modern technologies of horizontal drilling
Sites (reserves) in the IV (late) stage of development	Stabilization and growth of oil production due to intensive reservoir development due to the introduction of ASKU-VP, the massive application of the EOR of the third and higher generations with the transition to the forced fluid withdrawal in non-stationary, pulsed operation of wells with regular pauses for perforating the deposit	High-performance pumps for fluid extraction, KES and BDN, to equip the ASKU-VP, methods of enhancing recovery for highly watered areas (water cut - up to 98-99%)

Table 1

domestic oil companies OJSC Surgutneftegas is the most advanced in the use of hydraulic fracturing as an important element of development. The company has been actively carrying hydraulic fracturing since 1993 (Malyshev et al., 2004).

The basis for the successful mass application of hydraulic fracturing is the selection of objects and the active learning of advanced domestic and foreign experience, as well as the maximum adaptation of the technology for conducting it in the geological conditions of the selected objects. The objects are selected on the basis of generalized criteria that take into account the features of geological structure of the reservoir, the current state of its development, and technological capabilities of the fracturing. To improve the criteria in selecting sites for fracturing, continuous monitoring of operation of all wells with hydraulic fracturing and surrounding wells is carried out. Here, in strata with high thickness, a stepwise (intermittent) or selective fracturing is used with different schemes for disengaging the productive intervals.

Gas-oil zones with separating shields less than 4 m thick are not traditionally considered to be objects for hydraulic fracturing, since during its development in the process of cracking, there is a high probability of disruption of shield integrity and the appearance of interplastic overflows. At such facilities, Surgutneftegaz is successfully using the technology of screen-based hydraulic fracturing, based on the inclusion of a composition in the process fluid that fills the peripheral zones of the created crack and prevents the entry of water. The results of more than 70 completed works showed that the success of such fracturing exceeds 70%, and the average expected additional oil production is 7500 tons.

OJSC Surgutneftegas uses hydraulic fracturing as a system of cost-effective development of reserves difficult to recover. The most effective type of stimulation on the Jurassic and Achimovian deposits is the large-scale fracturing, which, due to the injection of a large amount of proppant (50-80 tons), allows the creation of an extended, highly conductive crack that covers the entire productive thickness of low permeable, highly dissected reservoirs. As a result, the deadlock and stagnant zones of the formation are unlocked, the sweep efficiency, drainage rate, residual oil saturation are significantly increased, as well as the oil recovery. The experience of such fracturing in the strata of the Achimovian and Jurassic deposits of the Bystrinsky field showed that the multiplicity of the increase in well production increases with the increase in the amount of proppant, and its values approach the corresponding values obtained for wells with flat and horizontal trunks that penetrate objects of a similar structure. Sometimes this leads to the fact that wells from the category of unproductive are transferred to the category of medium-productive ones. As a result, production from the facility as a whole becomes profitable.

In the Priobsky field, where without fracturing, the majority of wells have very low production rates (up to 5 tons/day), the fracturing increases them to 35-40 tons/day or more. Calculations of the designers showed that, without fracturing, the oil recovery factor for the main deposits would be 0.23, and with fracturing – 0.33. And for a number of fields in Western Siberia, hydraulic fracturing is used from the very beginning of putting the wells into operation. For such fields, the task of determining the technological efficiency of hydraulic fracturing is complicated because of the lack of a reference base. To do this, we have to resort to the analysis of production rates up to the fracturing along the wells of neighboring fields in terms of the geological structure of the field in question.

In highly permeable reservoirs, fracturing cannot be considered as a method of enhancing oil recovery. In this case, a method of accelerating the extraction of the projected amount of oil is used. Moreover, in certain geological conditions, this acceleration can lead to a significant decrease in oil recovery. The mechanism of this phenomenon is quite simple. Creating additional cracks in high-permeability reservoirs increases the natural inhomogeneity of the reservoir, which leads to an increase in the processes of uneven advance of injected water, premature watering of wells through artificially created cracks to the limiting value.

Therefore it is necessary to disconnect the well from the development and to leave oil reserves in a significant, unreached by flooding volume of the formation. In some cases, this process is less visible at the beginning, and may manifest itself at a late stage of site development. And in some cases this process manifests itself immediately. Thus, at the Upper Kolik-Egansky field, a fracturing at 44 wells of the reservoir of the Yu12-3 facility resulted in a sharp increase in water flooding. The watercut increased sharply from 21.8 to 48.6%.

However economically, hydraulic fracturing even under these conditions proved to be quite effective, and it seems that hydraulic fracturing was used on a weak permeable facility (according to available data, the permeability of the formation was 0.077 μm^2). But, apparently, these values are underestimated, as evidenced by the operation data of wells: high production rates before the fracturing (30-70 tons/day), observed fracturing effects on the rates of neighboring wells with a distance between them of about 400 m. Sufficiently exacerbating the negative impact of hydraulic fracturing on developing oil reserves was facilitated by unregulated development of the reservoir – the stationary injection of large volumes of water without its regulation.

With a more competent approach to the application of hydraulic fracturing, this method can give positive results. Thus, the hydraulic fracturing at the object BS10 of the Yuzhno-Yagunsky field allowed to increase oil production rates by 3-4 times while the watercut either remained at the same level, or even decreased.

The efficiency of hydraulic fracturing in Tatarstan is low, additional oil production per well is only about 3 tons per day. This is mainly due to geological conditions (depletion of the main fields, low productivity of small deposits). Here it is necessary to point out the unsatisfactory selection of wells and geological control over the works conducted. Suffice it to say that the rate of production is up to 1 ton/day in 30% of wells, from 1 to 3 tons/day – in 34% of wells, and only 36% of treated wells proved to be quite effective (the increase was from 3 to 10 tons/day).

But with a more competent approach to the application of hydraulic fracturing, even at sufficiently depleted objects at a late stage of development, good results are achieved. In Oil and Gas Production Department Almetyevneft at the Romashkino field, the average daily production rate for sand reservoirs averaged 4.6 tons per day for 6 years, and 2.1 tons per day for clay reservoirs. A multiple increase in production rates was obtained.

At the same time, the growth in the productivity factor was 2.9 times in the weakly permeable reservoirs, 3.3 – in clay reservoirs, 3.2 – in highly productive reservoirs, and 3.2 – on the average. Lower values of the increase in production rates (about 2) are explained by the unrealized production potential due to the lack of due attention to the improvement of the reservoir pressure maintenance system. The same can be said about the area application of hydraulic fracturing in the 2nd block of the Minnibayevsky area, when the increase in production was a maximum of 1.5 times – this is not enough due to the lack of a complete approach. However, for a late stage, even such a result can be considered acceptable (Gumarov et al., 2012).

Therefore, there are reserves for increasing the efficiency of hydraulic fracturing in the Republic of Tatarstan. But they will be even greater when combining fracturing with wave methods using technology developed under the guidance of Acad. R.F. Ganiev (Ganiev, 1998).

Even on geologically more complex (than in PJSC Tatneft) conditions of fields operated by small oil companies, an increase in oil production is on average

3 tons per day, and in some small oil companies – up to 4 tons per day. With a total average flow rate of about 2.5-3 t/day, this effect can be considered high.

The permeability values for classifying reservoirs as weakly permeable should be determined for each field based on pilot commercial development by the nature of the layers formation. But to determine the possibility of using hydraulic fracturing to develop such reservoirs, it is not enough only to know the permeability values; it is necessary to know the conditions of occurrence and hydrodynamics of oil deposits. Thus, the weakly permeable, highly dissected reservoirs of the Achimovian strata in the Western Siberia contain hard-to-recover oil reserves. Separate layers in the wells are poorly correlated with each other. However, the experience of hydraulic fracturing shows high efficiency. Obviously, this is due to the hydrodynamic connection of these layers among themselves and influence of fracturing.

On the contrary, at the Romashkino field, the weakly permeable layers of the D1D0 horizons are characterized by a very small dissection, although they are fairly well correlated with each other than the Achimovian deposits of Western Siberia. However, hydraulic fracturing here does not give positive results due to low reservoir pressures.

Based on the foregoing, it can be said that the fracturing in the Achimovian stratum is a typical high-efficiency method of enhancing oil recovery, and it is inefficient in the weakly permeable reservoirs of the Romashkino field without the organization of a reservoir pressure maintenance system.

In the most difficult conditions (unconventional reservoirs of Bazhenov deposits), OJSC Surgutneftegas, based on world experience, has conducted fracturing operations in horizontal wells and also in sidetracks with a horizontal face. Experience has shown that existing fracturing equipment can be used in horizontal wells – creating a crack increases the effective drainage zone of the formation.

The hydraulic fracturing method can be the only method in demand for the development of oil deposits in shale and similar rocks and, in general, in tight rocks with permeability of 1 mD and below. Without this method, the exploitation of such deposits is not even currently being discussed. After the fracturing, other methods of enhancing oil recovery can be used.

Today, we can consider the local gasdynamic fracturing of a reservoir created in KB-Avangard as an alternative to hydraulic fracturing. It is associated with the use of ZGRP-01-1 charges based on missile ballistic fuel, the combustion of which emits powder gases. They have a high-energy impulse effect, which leads to the formation of cracks in the bottomhole zone, cleansing of paraffin sediments, asphalt-resinous substances, products of chemical reactions, destruction of bottomhole zone contaminated in the drilling process, areas of colmatation, phase, water-oil and hydrodynamic barriers. The local gasdynamic fracturing does not need to be cured with proppant, much cheaper than conventional fracturing (6-10 times), and can be used in certain areas of exploited deposits with hard-to-recover reserves, and especially in conditions of contaminated bottomhole well zones. The same tasks can be performed by oscillators for treating wells under different names, such as borehole hydrodynamic oscillators.

Hydromechanical wave technologies of the new generation now unite one of the new and promising areas of engineering and technology developed for the first time in the world at the Scientific Center of Nonlinear Wave Mechanics and Technology (Academician R.F. Ganiev). The authors carried out in California tests and comparisons of this technology with the classical hydraulic fracturing. It is shown that the same efficiency is achieved both in fracturing, but with much lower costs.

In the Republic of Tatarstan at the end of the last century, almost all the methods of enhancing oil recovery and well stimulation used in the world were applied. Approximately 250 different technologies of enhancing oil recovery and bottomhole treatment of 30 basic methods were tested. A little more than 30 technologies are currently used for industrial implementation. Here, the main task is to ensure the selection of the most effective method of enhancing oil recovery and bottomhole treatment that are best suited to the specific geological and physical parameters of the deposits, based on the conditions for the effective application of specific method and their potential capabilities (Table 2).

It will make possible to test the stimulation system that is most adequate to the natural geological structure of the deposit. But all this should be done after choosing the optimal well spacing and operational objects of optimal size, providing a more complete drainage of the development facility. These are fundamental provisions, which can include the basic provisions of control and regulation, worked out in the fields over the past 50-70 years. And all the rest (horizontal, branched horizontal, multi-hole wells, sidetracking, dual completion, methods of oil recovery enhancement, bottomohole treatment, etc.) are the tools for rational production of hydrocarbon reserves.

The interests of the government in terms of filling the budget are more "short-term" in comparison with the "long-term" interests of society. For the subsoil user, high profits and a faster payback of costs are needed, and for the people – long-term earnings from the development of the field (greater oil recovery factor). Therefore, in general, optimization of production and maximization

Working agent	Increase in oil recovery, %	Critical factor of working agent application
Water + gas	5-10	Horizontal separation. Decreased productivity
Polymers	5-8	Salinity of water and reservoir. Decreased productivity
Alkalis	2-8	Oil activity
Micellar solutions	On to 8	The complexity of technology. Salinity of water and reservoir. Decreased productivity.
Gas methods of enhancing recovery	8-15 (Oil recovery factor for CO2 injection can grow up to 55-60%)	Loss of heat. Shallow depth. Removal of sand. Technical problems.
Steam	15-35	Loss of heat. Shallow depth. Removal of sand. Technical problems.
Air + water (VG)	15-30	Complications at initiation. Low coverage by burning. Technical problems. Unsatisfactory environmental protection.
Development systems with horizontal wells	20-30	Detailed study of the geological structure features
The newest physicochemical methods of enhancing recovery	8	Sufficient injectivity of injecting wells and permeability in producing wells.

Table 2

of oil recovery factor is needed. This should be done at the design and examination stage of documents for the development of the field on the principles of rationality (Muslimov, 2016b).

References

Ganiev R.F. Problems and prospects of wave machine building and wave technology in the fuel and energy complex. Advanced technologies on the threshold of the XXI century. Moscow: NITs Inzhener. 1998.

Gumarov N.F., Ganiev B.G., Romanov A.R. On the development of oil recovery control processes at a late stage of development. *Sbornik dokladov III-i nauchno-prakticheskoi konferentsii, posvyashchennoi pamyati N.N. Lisovskogo* [III Sci. and Pract. Conf., dedicated to the N.N. Lisovsky: Collected papers]. Almetyevsk. 2012.

Ivanova M.M. Dinamika dobychi nefti iz zalezhei [Dynamics of oil production]. Moscow: Nedra. 1976.

Kryukov V.A. Up-to-date knowledge and technologies for hydrocarbon production. *ECO*. 2013. No. 8. P. 4.

Malyshev A.G., Malyshev G.A., Kochetkov L.M. et al. Current state and improvement of works on hydraulic fracturing at the fields of OJSC «Surgutneftegas». *Neftyanoe khozyaistvo = Oil industry*. 2004. No.2. Pp. 38-42.

Morozov V.P., Korolev E.A, Kol'chugin A.N., Eskin A.A., Muslimov R.Kh., Shakirov A.N. Carbonate rocks of the Volga-Ural region as unconventional oil reservoirs. *Mat. Mezhd. nauchno-prakticheskoi konf. «Innovatsii v razvedke i razrabotke neftyanykh i gazovykh mestorozhdenii»* [Proc. Int. Sci. and Pract. conf. «Innovations in the exploration and development of oil and gas fields]. Kazan: Ikhlas. 2016. V.1. Pp. 147-151.

Muslimov R.Kh. Fundamental problems of the oil industry. *Neftyanoe khozyaistvo = Oil industry*. 2017. No.1. Pp. 6-11.

R.Kh. Muslimov The New Classification of Reserves and Resources of Oil and Combustible Gas – Movement Onward or Backward? Georesursy = Georesources. 2016. V. 18. No. 2. Pp. 80-87. DOI: 10.18599/grs.18.2.1

Muslimov R.Kh. Modernization of the Russian Oil Industry on the Way for Innovations and Global Trends. Georesursy = Georesources. 2016. V. 18. No. 4. Part 1. Pp. 246-255. DOI: 10.18599/grs.18.4.1

R.Kh. Muslimov. Ways to Improve the Efficiency of Horizontal Wells for the Development of Oil and Gas Field. Georesursy = Georesources. 2016. V. 18. No. 3. Part 1. Pp. 146-153. DOI: 10.18599/grs.18.3.1

Muslimov R.Kh. Nefteotdacha; proshloe, nastoyaschee, budeschee (optimizatsiya dobychi, maksimizatsiya KIN) [Oil recovery: past, present, future]. 2 Ed. Kazan: Fen Publ. 2014. 750 p. (In Russ.)

Muslimov R.Kh. Oil recovery: past, present, future. Kazan: FEN. 2012. 664 p.

Prishchepa O.M., Aver'yanova O.Yu, Il'inskii A.A., D. Morariu. Neft' gaz nizkopronitsaemykh slantsevykh tolshch – rezerv syr'evoi bazy uglevodorodov Rossii [Oil and Gas of Low-Permeability Shale Beds as a Reserve of Hydrocarbon Raw Materials Base in Russia]. St.Petersburg: VNIGRI. 2014. 323 p.

Zakirov S.N., Zakirov E.S., Indrupskii I.M. New ideas in 3D geological and hydrodynamic modeling. *Neftyanoe khozyaistvo = Oil industry*. 2006. No.1. Pp. 34-41.

Zakirov S.N., Indrupskii I.M., Zakirov E.S. et al. New principles and technologies of oil and gas fields development. Part 2. Moscow-Izhevsk: Institut komp'yuternykh issledovanii, NITs «Regulyarnaya i khaoticheskaya dinamika». 2009. 484 p.

Zakirov S.N., Muslimov R.Kh., Zakirov E.S., Indrupskii I.M., Kimelman S.A., Anikeev D.P., Lobanova O.A. Criteria of efficiency and rationality in oil and gas subsurface management. *Neftyanoe khozyaistvo = Oil industry*. 2016. No.3. Pp. 74-77.

Zakirov, S.N, Zakirov, E.S. Pseudo Horisontal Wells: Alternative to Horisontal and Vertikal Wells. Paper SPE 37085. *International Conference on Horisontal Well Technology*. Calgary. 1996.

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25-YEAR FORMATION EXPERIENCE OF DRILLING WELLS WITH HORIZONTAL END IN THE REPUBLIC OF TATARSTAN

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Abstract. The emerging problems of the long-term sustainability of the Russian oil industry, including Tatneft, in conditions of low world oil prices must be solved through more efficient use of costs, especially capital investments in the construction of new production wells. Along with various methods of increasing the oil recovery factor and intensification of oil production, one of the main ways to improve the profitability of wells is the construction of wells with horizontal end. Greater prospects for the use of horizontal wells are expected in the Timanian deposits of the Romashkino field. The use of a controlled valve (curtain) to open/close the inflow from the section of the horizontal trunk will significantly reduce the water cut of well and, accordingly, increase the share of oil per ton of produced liquid.

Keywords: horizontal wells, wells with horizontal end, oil flow rate, Tatneft
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The emerging problems of the long-term sustainability of the Russian oil industry, including Tatneft, in conditions of low world oil prices must be solved through more efficient use of costs, especially capital investments in the construction of new production wells. Along with various methods of increasing the oil recovery factor and intensification of oil production, one of the main ways to improve the profitability of wells is the construction of wells with horizontal end. Greater prospects for the use of horizontal wells are expected in the Timanian deposits of the Romashkino field. The use of a controlled valve (curtain) to open/close the inflow from the section of the horizontal trunk will significantly reduce the water cut of well and, accordingly, increase the share of oil per ton of produced liquid.

The current stage in the development of oil industry in Tatarstan is characterized by the introduction of active development of oilfields that are at different stages of development, characterized by high layer and zone heterogeneity, where effective production of oil reserves will be made using horizontal technology and advanced methods of enhancing the oil recovery factor. To achieve the predicted oil recovery coefficients, the most urgent for today, along with the use of hydrodynamic methods, is the use of horizontal technology. The use of horizontal technology will reduce the number of project vertical well stock, while not decreasing, but increasing the coverage factor for the production of oil reserves due to the spatial architecture of reservoirs drainage, which means raising the oil recovery factor and saving on infrastructure (Idiyatullina, 2015).

By the 1970s, more than 30 wells with a horizontal end were constructed under the leadership of A.M. Grigoryan in 13 regions of the former USSR (Tatarstan, Bashkortostan, Samara and Perm Regions, Western Ukraine, the Krasnodar Territory, etc.), including hundreds of curved branches, as well as a large number of wells with a single nominally horizontal trunk. Thus, the technology of drilling wells with horizontal end, having proved its high efficiency in various mining and geological conditions, was brought to the industrial level of application.

However, the discovery of highly productive fields in Western Siberia prompted the Ministry of Oil and Gas of the USSR to focus on the development of only these fields, and thus the interest in the development and improvement of horizontal drilling decreased. The drilling of wells with horizontal end was terminated for a period of more than 20 years before the implementation of the integrated branch program “Horizon”.

The company Tatneft much earlier than many oil companies has embarked on the industrial development of the horizontal technology. The development of horizontal technology in Tatneft PJSC began in 1977 with the drilling of three wells with horizontal end No. 1918, 1947 at the West-Sirenevsky site of the Sirenevsky field of the Oil and Gas Production Department Yamashneft proved to be the most productive, the accumulated oil production for them amounted to 68.7 thousand tons and 71.2 thousand tons at current average production rates of about 2.5-4.5 tons per day, which is 2-2.5 times higher than the average production

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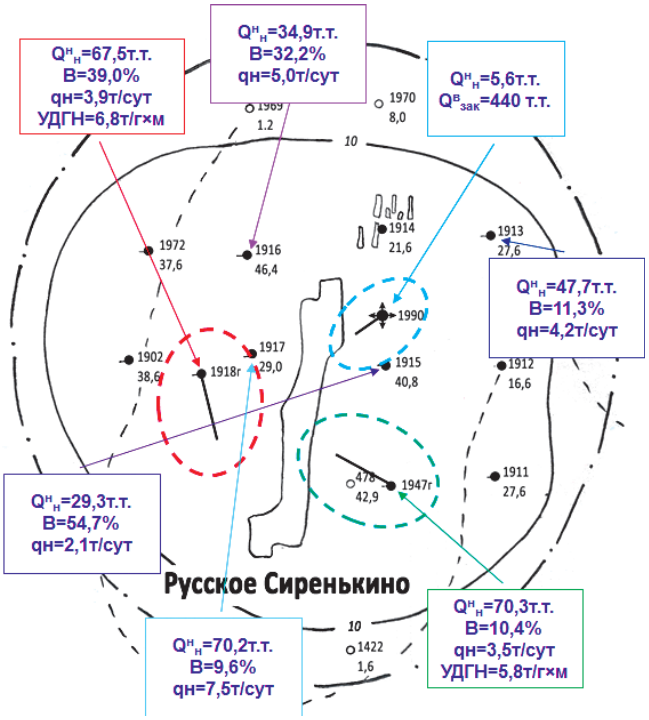

Fig. 1. Extract from the thickness map of the Zapadno-Sirenevsky section of the Sirenevsky oil field

rates of neighboring producing vertical wells. These wells are still in operation (Fig. 1).

Since 1978, the drilling of wells with horizontal end has been suspended and resumed only in 1992, which is still used instead of vertical drilling. As of January 1, 2017, 940 wells with horizontal end were drilled; the accumulated oil production for the whole period of exploitation was more than 6.5 million tons. The dynamics of drilling wells with horizontal end by years is shown in Fig. 2. Since 1990, the TatNIPIneft industry institute has compiled more than 80 design documents for the development of deposits using horizontal wells, according to which several thousand horizontal wells were to be drilled. Depths of occurrence of productive layers, penetrated by horizontal wells are from 800 to 2400 m.

Tatneft PJSC has been steadily increasing the number of wells with horizontal end, especially in the last 4 years. If from 1977 to 2012 the average number of horizontal wells drilled was 24 per year, from 2013 to 2016, on average, about 103 wells per year were drilled. In total, as of January 1, 2017, 940 horizontal wells were drilled in Tatneft PJSC. In addition, the company actively uses horizontal technology on deposits of super viscous oil. A striking example of using horizontal wells for the development of heavy oil objects is the Ashalchinsky field, where as of 01.01.2017 313 wells with horizontal end have been drilled (including 51 steam cycling and 138 production ones).

In general, according to oil fields of Tatneft PJSC, it is possible to distinguish five main objects that are developed using horizontal technologies (bottom-up):

- Timanian-Pashchian;
- Tournaisian;
- Tulian-Bobrikovian;
- Bashkirian-Protvinian;
- heavy oil deposits (Sheshminian horizon of the Ashalchinsky field).

The predominant part of wells with horizontal end was drilled to low-productivity carbonate deposits of the Tournaisian (36.8%) and Bashkirian-Serpukhovian (27.0%) stages of small deposits. 22.0% were drilled on the Tulian-Bobrikovian formations, 13.7% on the terrigenous Devonian and 0.5% of the wells on the carbonate Devonian (Fig. 3).

Geological and physical characteristics of reservoirs are given in Table 1.

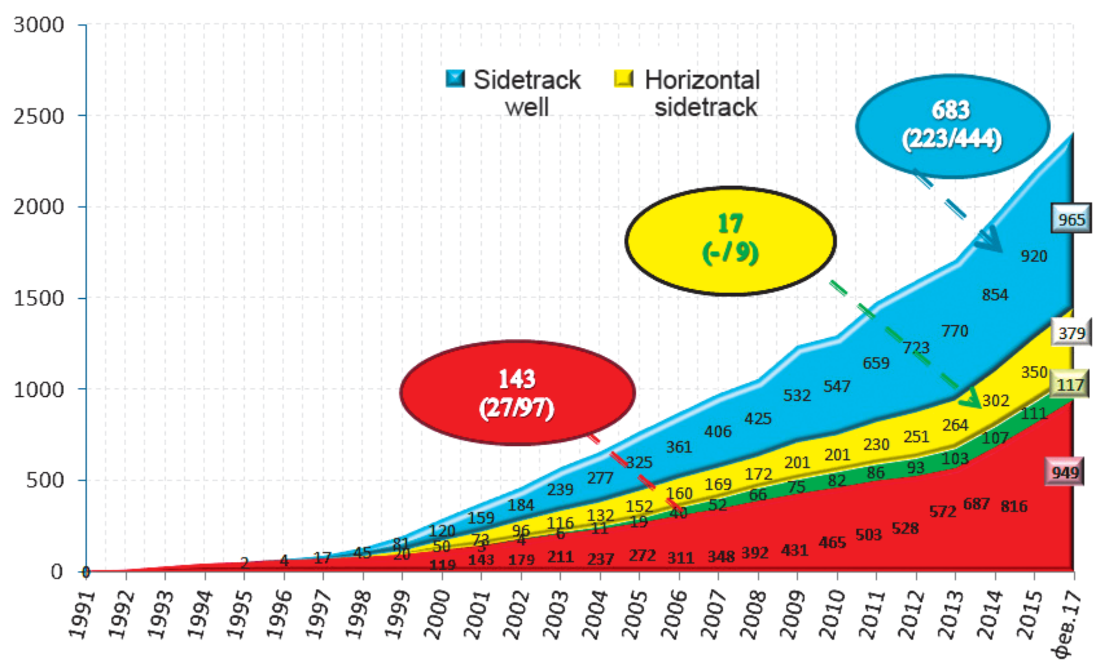

Fig. 2. The dynamics of drilling wells with horizontal end by Tatneft PJSC

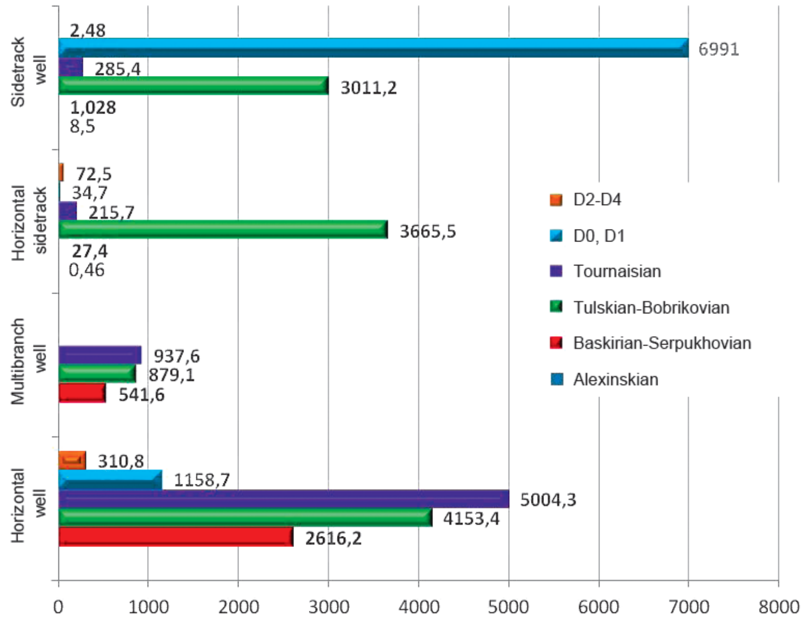

Fig. 3. Distribution of accumulated oil production by types of wells and development objects

Since 1990, the TatNIPIneft branch institute has compiled more than 80 design documents for the development of fields with the use of wells with horizontal end, according to which several thousand wells were to be drilled.

In connection with the increasing volume of directional drilling, the problem of monitoring the direction of the horizontal well trunk during its drilling becomes very relevant, therefore, since the end of 2010, the navigation systems "near-bit module of the measure while drilling" have become widely used in Tatneft PJSC, which allowed increasing annual oil production.

Greater prospects for the use of wells with horizontal end are expected in the Timanian deposits of the Romashkino field. The oil of the Timanian object differs little from the oil of the Pashian object (the viscosity of the oil is also 5-7 mPas-s), but the inhomogeneity of the productive formation D0, its lenticular-mosaic structure, does not allow the active development of the Timanian deposits. Drilling horizontal wells on the deposits of the Timanian age will allow the development of the full amount of oil reserves in lenses, water-oil zones and inaccessible areas under sanitary protection zones, populated areas, forests, floodplains and springs. The use of horizontal technology contributes to a more even production of reserves and, ultimately, an increase in the oil recovery factor. In addition, the use of wells with horizontal end is due to the geological structure of the Timanian reservoir, clamped from the roof and the bottom by thick intercalations of clays, which for a long time did not allow the Timanian site to be actively developed.

The mosaic spread of different lithotypes of rocks in the D0 reservoir does not allow uniform production of reserves. The solution of the problem also lies in the application of horizontal technology with the exit from one lithotype to another and by hydraulic fracturing with the connection to the development of far zone of the reservoir. In this regard, it is important to drill long trunks that replace the drilling of 3-4 wells and conduct multi-zone fracturing on them. Such a technology would allow a multiple reduction in the number of drilled wells and significantly reduce the mosaic effect on well productivity. Moreover, with long operation of wells with extended nominal horizontal trunks (350 ÷ 450 m and more), there are significant advantages.

Characteristic	Vereiskian-Bashkirian	Bobrikovian	Tournaisian	Dankovian-Lebedyanian	Pashian-Kynovian	D_{II}-D_{III}-D_{IV}
Average occurrence depth, m	911÷943	до 1099	1164	1466	1720	1773÷1811
Average net oil thickness, m	0,5÷25	0,8÷20	0,8÷45	1,8÷8,1	3,7÷16,6	2,3÷2,7
Permeability, μm^2	49	1,261	0,042	0,03	0,527	0,13÷0,258
Porosity, %	15	22,4	11,8	7,00	19,8	16,8÷18,7
Initial formation pressure, MPa	9,11	11,0	11,26	14,6	17,2	17,2
Viscosity mPa×s	15,5÷288	11,4÷220	6÷172	8,4÷46	1,9÷4,5	2,92÷7,55
Oil density, t/m^3	0,90	0,875	0,88	0,91	0,77÷0,82	0,79÷0,823
Gas-oil ratio, kg/m^3	2,34	11,37	17,66	12,40	46÷74,2	25,7÷54,5

Table 1. Geological and physical characteristics of objects

Such wells work stably with a lower rate of decline in productivity (Petrov et al., 2016). For example, well No. 4712G of the Bavlinsky field, which has the longest nominal horizontal trunk (637 m), is one of the most productive. The debit of oil in it in the first year of operation (2001) was 16-17 tons/day, for 2016 – 15.3 tons/day.

The carbonate layers of the Dankovian-Lebedyanian horizon and the Zavolzhskian horizon overlap up the section. As of 01.01.2017, 6 wells with horizontal end were drilled on the sediments of the Dankovian-Lebedyanian horizon, and 3 wells with horizontal end in the Zavolzhskian horizon. All the wells with horizontal end on the Dankovian-Lebedyanian horizon were drilled into 665 deposits of the Romashkino field. The average initial production rate for the wells with horizontal end for the Dankovian-Lebedyanian horizon was 2 tons/day (water cut 14.3 %), current – 6.9 tons/day (water cut 34.2 %). In total, since the beginning of the development of wells with horizontal end, 91.4 thousand tons were extracted from the deposits of the Dankovian-Lebedyanian horizon, with an additional production of 24.1 thousand tons.

3 wells with horizontal end on the Chegodaysky field were drilled on the sediments of the Zavolzhskian horizon. The initial oil production rate was 18 tons per day, the current production rate was 1.5 tons per day. In total, since the beginning of the development, 19.7 thousand tons of oil was extracted from the deposits of the Zavolzhskian horizontal as of 01.01.2017 (Petrov et al., 2016).

At present, in the Republic of Tatarstan the development of oil deposits, represented by carbonate reservoirs, enters the open phase. Horizontal technologies are particularly important in the development of carbonate reservoirs. Basically, this is due to the need to increase the productivity of wells and reduce their payback periods. As practice shows, wells with horizontal end are most effective for developing reserves in weakly drained areas, in low-permeability and cavernous-fractured reservoirs. Horizontal wells provide much greater opportunities for different methods of stimulating oil production than vertical or controlled directional wells.

The main share of wells with horizontal end in Tatneft PJSC was drilled on carbonate sediments of the Tournaisian stage. Korobkovsky area (6 block) of the Bavlinsky field (Fig. 4) is one of the most representative sites for the development of carbonate reservoirs by horizontal wells (Khakimzyanov, 2012).

Beginning in 2010, the amount of horizontal wells in the Korobkovsky area is about 40% of the total production stock, while providing 60% of the annual production of oil. The average debit for horizontal wells for the last three years was 7.1 tons/day with a water cut of 5.3%, for comparison, the performance of the controlled directional wells for the same period was 3 tons per day and 16.6 %, respectively.

In total, according to the Tatneft PJSC, 5377.5 thousand tons of oil were extracted from the sediments of the Tournaisian stage by horizontal wells as of 01.01.2017. The additional production from the beginning of the development of Tournaisian object by horizontal wells is 1758.3 thousand tons. The average initial production rate at the Tournaisian object by horizontal wells was about 3.4 tons/day (water cut 22%), current 4.8 tons/day (water cut 28%).

Terrigenous deposits of the Bobrikovian and Tulian horizons of the lower section of the Carboniferous system lie above the section. In general, the average initial production rate for the Tulian-Bobrikovian deposits in the Tatneft PJSC amounted to 7.5 tons per day with water cut of 50 %, the current one – 10.7 with water cut 59 %. Accumulated oil production as of 01.01.2017 was 4319.4 thousand tons (including 2739.2 thousand tons of additional production).

Tatsuksinsky field discovered in 2014 by exploration well No. 300 is an example for the efficiency of drilling horizontal wells on the terrigenous reservoirs of the Lower Carboniferous. As of the first half of 2017, 12 wells with horizontal end were drilled at the Tatsuksinsky field, one well with a horizontal profile is in drilling process. The average initial oil production rate was 40 tons per day with an average water cut of 8.2 percent, the current – 49 tons per day and 13 %, respectively (Petrov et al., 2016).

The next (upstream) development target, where horizontal wells are actively used, is the Protvinsky horizon of the Lower Carboniferous and the Bashkirian stage, the Vereiskian horizon of the middle section of the

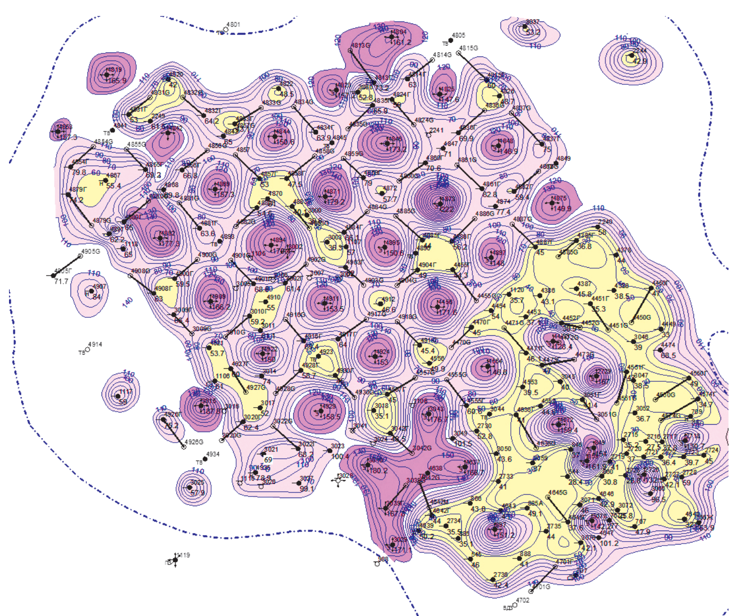

Fig. 4. Extract from the developmnet map of the Korobkovsky area (6 block) of the Bavlinsky oil field, January 1, 2017

Lower Carboniferous. Accumulated oil production as of January 1, 2017 for this development project amounted to 2584.4 thousand tons (including 1366.6 thousand tons of additional production). The average initial production rate for horizontal well was 2.5 tons per day with 47% water cut, current – 3.2 tons per day with 86.5 % water cut.

About half of the residual recoverable oil reserves of Tatneft PJSC are concentrated in carbonate reservoirs, a significant part of which is located in the Vereiskian horizon. The traditional well production rate here is 1 to 4 tons per day (Khakimzyanov, 2012).

An example of the successful application of horizontal technologies in the sediments of the Vereiskian horizon is well No. 4777G. A multi-stage hydraulic fracturing (5-stage) was produced in well No. 4777G of the Sokolkinsky field of Oil and Gas Production Department Elkhovneft in a horizontal wellbore of a small diameter that consists of five intervals (Fig. 5). The oil production rate was 40 tons per day. The experience of using a 5-stage acid fracturing in a horizontal borehole of a small diameter on the Vereiskian horizon of the Sokolkinsky oil field of Oil and Gas Production Department Elkhovneft is proposed to be distributed to other Oil and Gas Production Departments of Tatneft PJSC.

The highest development target, where oil production is carried out by horizontal wells, is the Sheshminskian horizon. As of January 1, 2017, 1 million 781 thousand tons of oil were extracted from the sediments of the Sheshminskian horizon of the Ashalchinsky field. The average initial oil production rate by horizontal wells was 9.8 t / day, the current one – 32.7 t/day.

It should be noted that the rate of annual production by horizontal wells has a tendency to increase – for example, in 2008 in horizontal well No. 2320 a total of 6.8 thousand tons of oil was produced per year (oil production rate oil was 19.4 tons /day), and in 2016 – already 23.1 thousand tons (oil production rate – 63.4 tons/day).

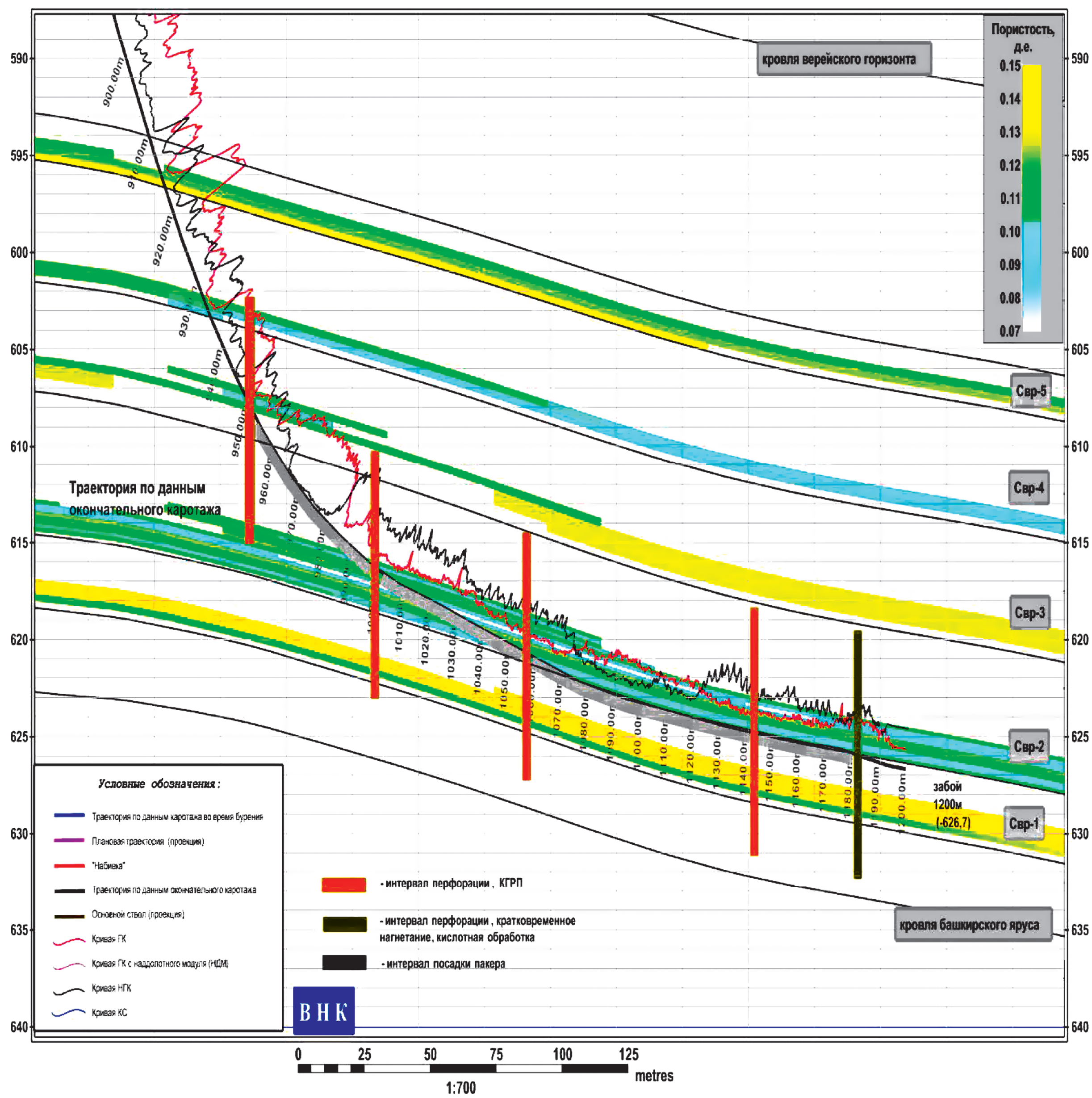

Fig. 5. The profile along the conditional-horizontal wellbore No. 8385G in the section on the porosity parameter

The same can be said for horizontal wells No. 232 and 240, which were put into operation in 2006 and 2008, respectively.

Beginning in 2010, Oil and Gas Production Department of Tatneft PJSC pays a lot of attention to the problem of geological justification for the selection of objects for drilling horizontal wells in carbonate and terrigenous reservoirs located at different stages of development. Oil deposits that are developed using horizontal technology require a detailed approach to the selection of points for drilling, operation objects and orientation of additional trunks.

Since 2012, the creation of sectoral geological and hydrodynamic models to justify the rational placement of horizontal wells has begun, which increased the efficiency and accuracy of installing conditional-horizontal trunks.

TatNIPIneft has developed a controllable valve (curtain) for opening/closing the inflow from the horizontal trunk section (Fig. 6). Increasing the effectiveness of dividing the horizontal trunk into sections is supposed to be realized by applying in the horizontal trunk downhole flow regulation valves, which allow limiting the volume of water during extraction from the sections. The curtains are installed on 5 wells of deposit No. 303 of the Romashkino field of Oil and Gas Production Department Leninogorskneft, in which the horizontal trunk is divided into 3 sections (Yartiev et al., 2016).

Figure 7 shows the scheme for completing the horizontal well using electro-controlled borehole valves (well No. 41502g of Oil and Gas Production Department Djalilneft).

Well No. 41502g has a horizontal trunk in the Bobrikovian-Radaevskian sediments of the deposit No. 12 of Romashkino field, and for the first time in Tatneft PJSC valves are installed that controlled from the surface by cable without stopping the operation of the well. With the operation of both sections of the trunk, the oil production rate was 12 tons per day with a water cut of 50 %, the production rate of the trunk sock was 21 tons per day with a water cut of 10 %, the production rate of the trunk sock was 7.5 tons per day, with a water cut of 65 %. Thus, by controlling the valves, the extraction from the well No. 41502g was optimized by reducing the water cut of production without stopping the exploitation of the well. Well No. 41502g has been in operation since 2012; the experimental equipment works reliably (Takhautdinov et al., 2013).

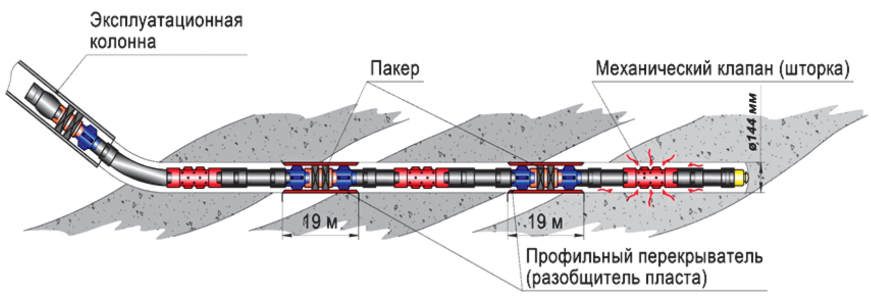

Fig. 6. Separation of the conditional-horizontal trunks into sections with the use of expandable pipes and mechanical valves (shutters)

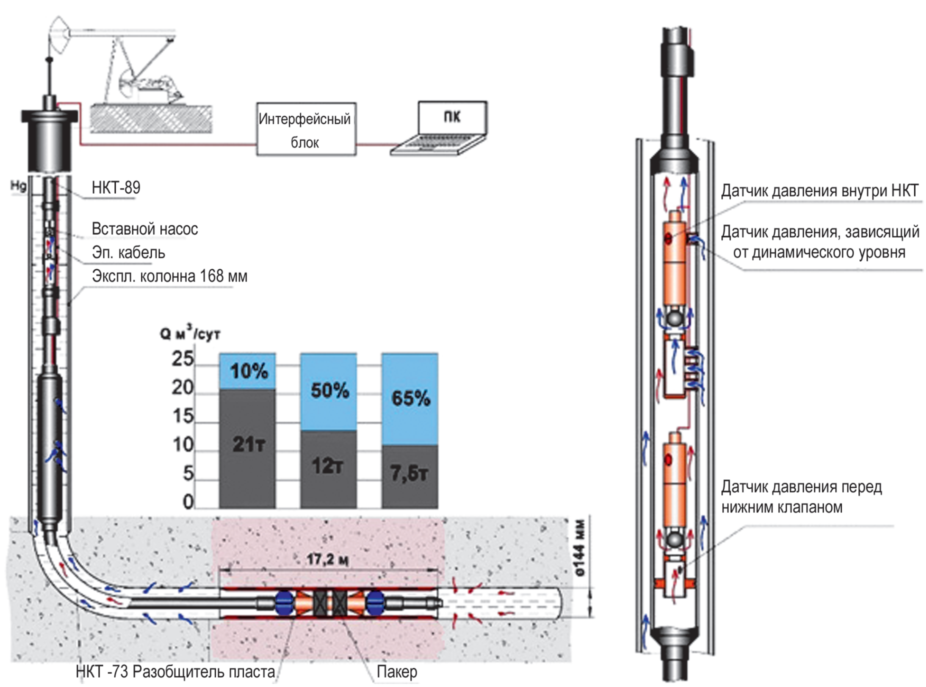

Fig. 7. Completion of the wells with horizontal end using electro-controlled borehole valves (well No. 41502g of Oil and Gas Production Department Djalilneft)

The effect from the use of horizontal technologies is particularly evident in the case of high lateral heterogeneity of reservoir rocks, which is more common for limestone. The horizontal wellbore increases the probability of penetrating sections with increased permeability of the reservoir, which has a high degree of heterogeneity both over the lateral and along the cut. In addition, due to the horizontal section, the area of contact between the well and the target reservoir increases, as a result, a more voluminous and complex drainage geometry arises as compared to the controlled directional wells. In general, the development of the Korobkovsky section by a system of horizontal wells is considered to be justified. With the current water cut, such a development system allows maintaining high rates of oil withdrawal from the initial recoverable reserves (6.8%).

In general, the efficiency of drilling horizontal wells in Tatneft PJSC was repeatedly confirmed in practice. However, the use of horizontal technologies does not always give the expected effect. The well-known factors of unsatisfactory efficiency of the use of wells with horizontal end in the fields of Tatneft PJSC are as follows (Idiyatullina et al., 2015; Khakimzyanov, 2012; Fazlyev, Mironova, 2005; Guidance document for the geological and technological feasibility ..., 2013):

- excessively high heterogeneity of the deposit section;
- probability of “swelling” and shedding of clay interlayers in the process of drilling and operation of wells;
- probability of crossing aquifers or layers in the inter-spacing interval because of the lack of information on the geological structure and saturation of the inter-wellbore interval;
- a rapid drop in oil production over time, caused by a pressure drop in the in the reservoir zone due to high heterogeneity and a difficult connection with the boundary zone.

Therefore, to ensure the maximum effect from the use of horizontal technologies, it is necessary to thoroughly study all stages of the horizontal wells design – from the idea to its implementation:

- when choosing the location of horizontal wells, it is necessary to apply a comprehensive approach – the study and analysis of seismic survey data (including the forecasting of reservoir properties), the construction of hydrodynamic models to justify the optimality of the horizontal well location and the calculation of technical and economic development indicators, studying the “best practices” of applying horizontal technologies both in Tatneft PJSC and in other companies;
- when drilling wells, constant monitoring of the curvature data (correspondence of the project placement of the trunk to the actual one), lithology and saturation of the formations in real time with the help of a near-bit module of the measure while drilling system;
- in the development of fields by horizontal wells, monitoring of the level of reservoir pressure and its maintenance at a sufficient level to ensure efficient development of the field.

References

Fazlyev R.T., Mironova L.M. Guidance document to the geological and technological feasibility study of horizontal, multistage and lateral horizontal wells drilling. No. RD 153-390-421-05. Bugulma: TatNIPIneft. 2005. 59 p. (In Russ.)

Guidance document for the geological and technological feasibility of the object selection and geological and hydrodynamic maintenance for drilling horizontal, multi-stage, lateral and lateral horizontal wells. No. RD 153-39.0-836-13. Bugulma. 2013. 54 p. (In Russ.)

Idiyatullina Z.S. The use of wells with a horizontal end to develop hard-to-recover oil reserves in carbonate reservoirs at the fields of Tatneft PJSC. Almetyevsk. 2015. 28 p. (In Russ.)

Idiyatullina Z.S., Mironova L.M. et al. Monitoring of the use of horizontal technology and cuttings of sidetracks, selection of sites for the implementation of new drilling and operation CDS technologies at the fields of Tatneft PJSC. Report. Bugulma: TatNIPIneft. 2015. (In Russ.)

Khakimzyanov I.N. Theory and practice of the oil field development by horizontal wells. *Diss. dokt. tech. nauk.* [Dr. engineer. sci. diss.]. Bugulma. 2012. 388 p. (In Russ.)

Petrov V.N., Mironova L.M. et al. Monitoring of the application of horizontal wells and wiring of additional tracks realized due to the implementation of new drilling and operation technologies at the fields of Tatneft PJSC. Bugulma: TatNIPIneft, LLC Nauka. 2016. 155 p. (In Russ.)

Takhautdinov Sh.F., Khisamov R.S., Ibatullin R.R., Abdrakhmanov G.S., Vakhitov I.D., Nizamov I.G. Controllable operation of horizontal wellbore intervals. *Neftyanoe khozyaystvo = Oil industry*. 2013. No. 7. Pp. 26-27. (In Russ.)

Yartiev A.F., Khakimzyanov I.N., Petrov V.N., Idiyatullina Z.S. Improving technologies for the development of oil reserves from heterogeneous and complex reservoirs of the Republic of Tatarstan. Kazan: Ikhlas. 2016. 192 p. (In Russ.)

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USING HORIZONTAL WELLS FOR CHEMICAL EOR: FIELD CASES

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Primary production of heavy oil in general only achieves a recovery of less than 10% OOIP. Waterflooding has been applied for a number of years in heavy oil pools and can yield much higher recovery but the efficiency of the process diminishes when viscosity is above a few hundreds cp with high water-cuts and the need to recycle significant volumes of water; in addition, significant quantities of oil are still left behind. To increase recovery beyond that, Enhanced Oil Recovery methods are needed. Thermal methods such as steam injection or Steam-Assisted Gravity Drainage (SAGD) are not always applicable, in particular when the pay is thin and in that case chemical EOR can be an alternative.

The two main chemical EOR processes are polymer and Alkali-Surfactant-Polymer (ASP) flooding. The earlier records of field application of polymer injection in heavy oil fields date from the 1970's however; the process had seen very few applications until recently. ASP in heavy oil has seen even fewer applications. A major specificity of chemical EOR in heavy oil is that the highly viscous oil bank is difficult to displace and that injectivity with vertical wells can be limited, particularly in thin reservoirs which are the prime target for chemical EOR. This situation has changed with the development of horizontal drilling and as a result, several chemical floods in heavy oil have been implemented in the past 10 years, using horizontal wells. The goal of this paper is to present some of the best documented field cases.

The most successful and largest of these is the Pelican Lake polymer flood in Canada, operated by CNRL and Cenovus which is currently producing over 60,000 bbl/d. The Patos Marinza polymer flood by Bankers Petroleum in Albania and the Mooney project (polymer, ASP) by BlackPearl (again in Canada) are also worthy of discussion.

Keywords: Heavy oil, Enhanced Oil Recovery, EOR, chemical EOR, polymer, Alkali-Surfactant-Polymer (ASP), field cases, horizontal wells

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Introduction

Primary production of heavy oil in general only achieves a recovery of less than 10% OOIP. Waterflooding has been applied for a number of years in heavy oil pools (Beliveau, 2009) and can yield much higher recovery but the efficiency of the process diminishes when viscosity is above a few hundreds cp with high water-cuts and the need to recycle significant volumes of water; in addition, significant quantities of oil are still left behind. To increase recovery beyond that, Enhanced Oil Recovery methods are needed. Thermal methods such as steam injection or Steam-Assisted Gravity Drainage (SAGD) are not always applicable, in particular when the pay is thin (Delamaide, 2017) and in that case chemical EOR can be an alternative.

The two main chemical EOR processes are polymer and ASP flooding. The principle of polymer flooding is to increase the viscosity of the injection water, thereby improving the mobility ratio. Polymer can also improve horizontal and vertical sweep efficiency, for instance by increasing pressure drops in high permeability layers thus diverting flow to less permeable layers. The principle of ASP (Alkaline, Surfactant and Polymer) is to achieve a reduction of interfacial tension between the water and the oil, which allows to reduce the residual oil saturation. In some cases when the oil is reactive, the addition of an alkaline agent such as NaOH can promote the formation of in situ surfactants, which allows to reduce the quantity of surfactant required. Alkali also allows to decrease surfactant adsorption.

The earlier records of field application of polymer injection in heavy oil fields date from the 1970's (Delamaide, 2014); however the process had seen very few applications until recently and indeed, screening criteria used to limit the oil viscosity to 150 cp for polymer flood applications (Delamaide, 2017). A major specificity of chemical EOR in heavy oil is that the highly viscous oil bank is difficult to displace and that injectivity with vertical wells can be limited, particularly in thin reservoirs which are the prime target for chemical EOR. This situation has changed with the development of horizontal drilling and as a result, several chemical floods in heavy oil have been implemented in the past 10 years, using horizontal wells; Table 1 presents a list of these projects. As can be seen from the table, most of these projects have been implemented at a large scale. The goal of this paper is to present some of the best documented field cases.

The most successful and largest of these is the Pelican Lake polymer flood in Canada, operated by CNRL and Cenovus which is currently producing over 60,000 bbl/d. The Patos Marinza polymer flood by Bankers Petroleum in Albania and the Mooney project (polymer, ASP) by BlackPearl (again in Canada) are also worthy of discussion.

Company	Field	Formation	Country	Dead oil viscosity (cp)	Process	Status
CNRL, Cenovus	Pelican Lake	Wabiskaw	Canada	1,500-2,500	P	Full field
BlackPearl	Mooney	Bluesky	Canada	255-400	P, ASP	Successful polymer pilot, ASP appears successful
Murphy	Seal	Bluesky	Canada	5,000-12,000	P	Large scale expansion
Bankers Petroleum	Patos Marinza		Albania	1,500	P	Large scale expansion
Northern Blizzard	Cactus Lake	Basal Mannville-Bakken	Canada	>500	P	Full field
PDO	Nimr		Oman	500?	P	Pilot
Enerplus	Medicine Hat	Glauconitic	Canada	1,000-1,500?	P	Successful pilot

Table 1. Recent chemical EOR field cases using horizontal wells

Projects description

Pelican Lake (CNRL and Cenovus, Canada)

The Pelican Lake field (sometimes called Brintnell) located approximately 250 km north of Edmonton, Alberta, Canada (Fig. 1) was discovered in 1978 and started producing in 1980 (Cenovus Energy…, 2013). Original Oil In Place is approximately 6.5 billion barrels.

The reservoir formation is the Wabiskaw "A" sand, a coarsening upward sheet sand interpreted as part of a prograding shoreface within the Clearwater formation of the Upper Mannville Group of Lower Cretaceous age (Fig. 2). It is deposited in a 35x60 km^2 NE-SW trending lobe thinning to the North, East and South and capped by the transgressive marine shale of the Clearwater formation. A water leg is found down-dip to the SW and a gas cap is found up-dip to the NE. Locally, small isolated gas caps may also be found. Immobile (highly viscous) oil is also found to the North-East (Cenovus Energy…, 2013). The reservoir is composed of unconsolidated sands which consist mainly of quartz and chert. Reservoir petrophysical properties are generally excellent with 28-32% porosity and a permeability that varies between 300 up to over 5,000 md. The main reservoir characteristics are summarized in Table 2 and a type log is provided in Figure 3.

The reservoir depletion mechanism is solution gas drive, but initial reservoir pressure was low and there is very little dissolved gas (Rs = 4-6 m^3/m^3) so there is little energy in the reservoir. As the oil is also viscous (from 800 to 80,000 cp) primary recovery is low, approximately 5 to 10% OOIP. In addition, the reservoir is thin (1 to 9 m, average 5 m) and as a result the first (vertical) wells drilled in 1980-1981 were not economic: low rates (less than 30 bbl/d usually declining rapidly to less than 10 bbl/d) and low cumulative productions (an average of 28,000 bbl total per well). This changed with the introduction of horizontal drilling in 1988; horizontal wells achieved much higher rates and improved the economics significantly, and as a result the whole pool was developed with horizontal wells (Delamaide et al., 2014a).

However, the recovery factor for primary production remained low even after the introduction of horizontal drilling. Thermal methods were tested but were not efficient due to the thin pay of the reservoir thus other methods were piloted. After a first – unsuccessful – polymer flood pilot in 1997, waterflood was also piloted. The waterflood managed to increase oil production but at the cost of high water-cut (Delamaide et al., 2014b).

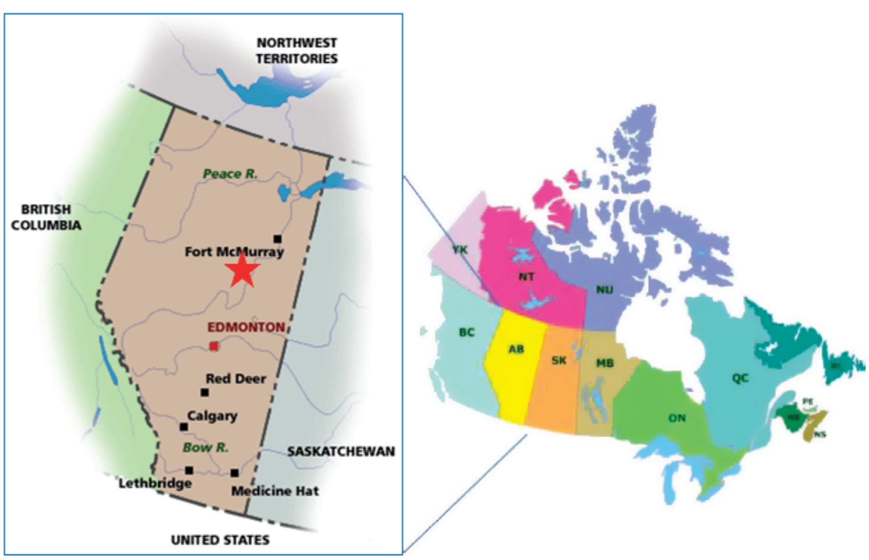

Fig. 1. Map showing location of Pelican Lake and Mooney pools (reproduced from (Delamaide et al., 2014b))

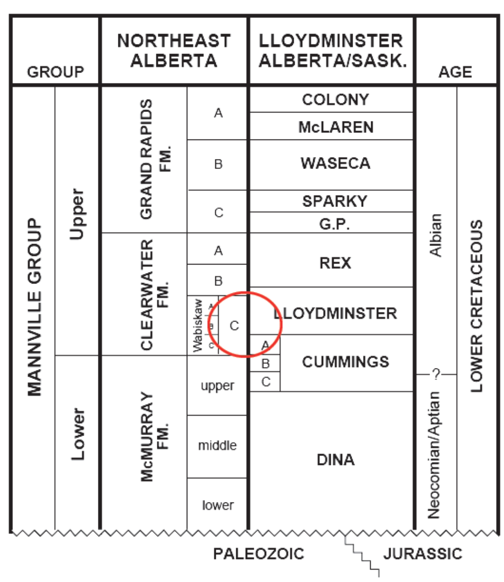

Fig. 2. Stratigraphic chart of the Mannville Group with Wabiskaw formation circled in red (reproduced from (Delamaide et al., 2014b))

Project	Country	Average depth (m)	Reservoir temperature (°C)	Average net pay (m)	Permeability (md)	API gravity	Live oil viscosity (cp)
Pelican Lake	Canada	300-450	12-17	1-9	300-5,000	12-14	800-10,000
Mooney	Canada	875-925	29	3-5	100-10,000+	12-19	100-250
Seal	Canada	610	20	8.5	300-5,800	10-12	3,000-7,000
Patos Marinza	Albania	1,200-1,300	40-42	4-12	100-2,500	8-10	600-1,600
Cactus Lake	Canada	850	27	6	500-1,500	15	500
Nimr	Oman		51	30-50	2,000-5,000	20	250-500
Medicine Hat	Canada	850	26	7	0-10,000		500-1,000?

Table 2. Main characteristics of selected projects

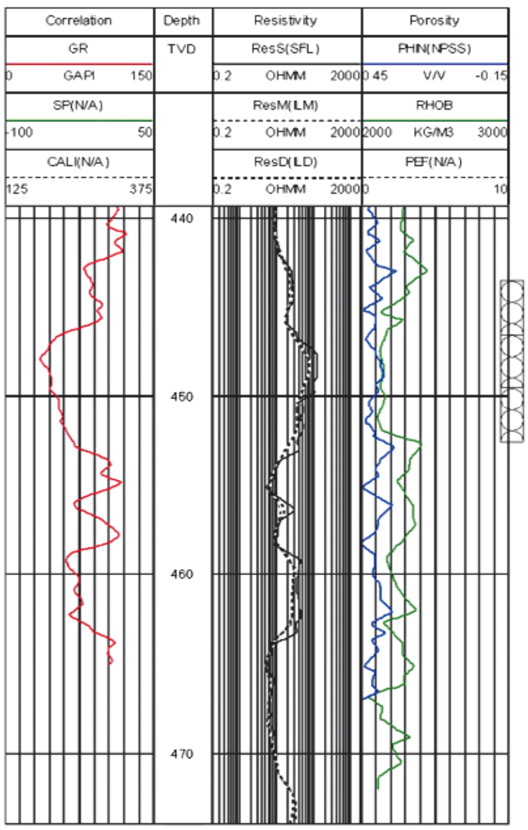

Fig. 3. Pelican Lake – Type log of well 1AD/11-09-081-22W4M (reproduced from (Delamaide et al., 2014b))

As a result, a second polymer pilot started in 2005.

This second pilot was composed of five 1400 m long horizontal wells (Delamaide et al., 2014a): three production wells (14-34, 15-34 and 16-34) and two injection wells in between (2/15-34 and 2/16-34), with a spacing of 175 m between the wells (Fig. 4). The wells had been drilled in 1997-1999. Viscosity in the pilot area ranges from 1,200 cp to 1,800 cp.

Polymer injection started in May 2005 with a target viscosity of 20 cp (corresponding to a concentration of 600 ppm initially), which was reduced to 13 cp at the end of August 2005 and later increased to 25 cp (Delamaide et al., 2014a). Initial injection rate was 930 bbl/d/well but it was later reduced as pressure increased in the pattern.

The response occurred in February 2006 in the central production well, and in April 2006 and September respectively in the two other producers (Fig. 5-7). As can be seen from the figures, the responses were excellent with oil rates increasing more than ten fold. On the contrary, the water-cut increased slowly and moderately in all three wells, especially compared to what was experienced in the waterflood pilot nearby, and after 10 years of constant polymer injection, is still in the 60-70% range.

Following that success, polymer flooding has been extended to significant portions of the field, with hundreds of wells under polymer injection (Fig. 8).

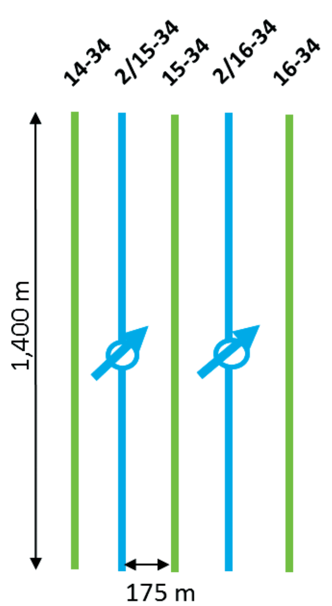

Fig. 4. CNRL HTLP 6 polymer flood pilot map (reproduced from (Delamaide et al., 2014b))

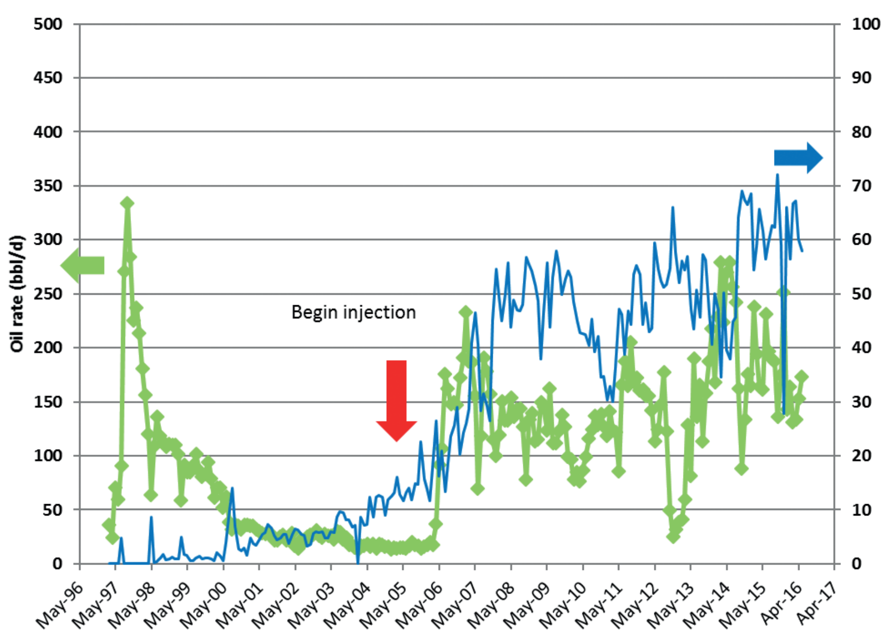

Fig. 5. HTLP 6 polymer flood pilot – Well 00/14-34-081-22W4 rate and water-cut (modified from (Delamaide et al., 2014b))

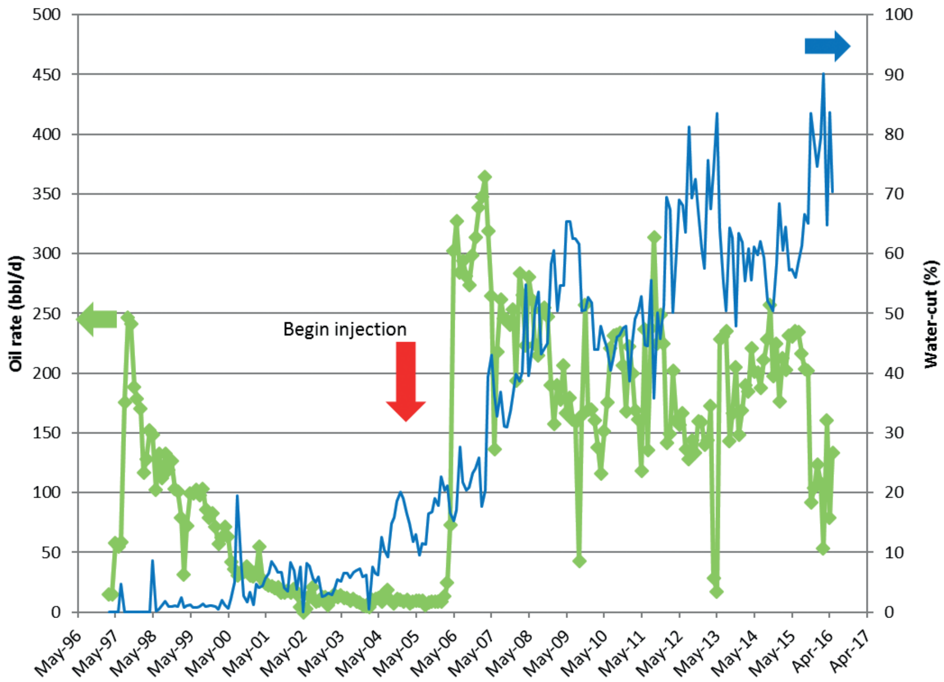

Fig. 6. HTLP 6 polymer flood pilot – Well 00/15-34-081-22W4 rate and water-cut (modified from (Delamaide et al., 2014b))

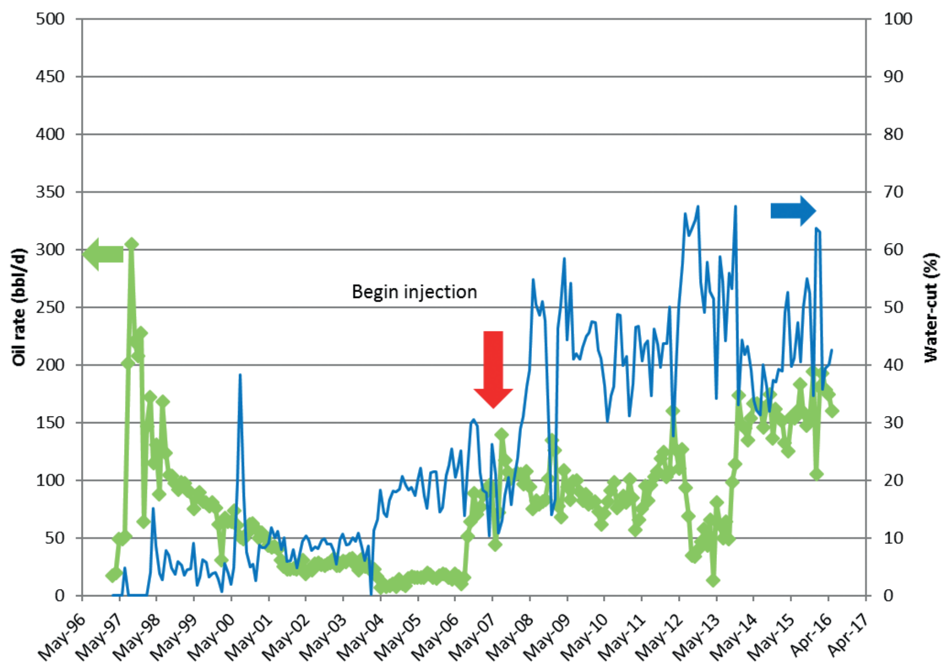

Fig. 7. HTLP 6 polymer flood pilot – Well 00/16-34-081-22W4 rate and water-cut (modified from (Delamaide et al., 2014b))

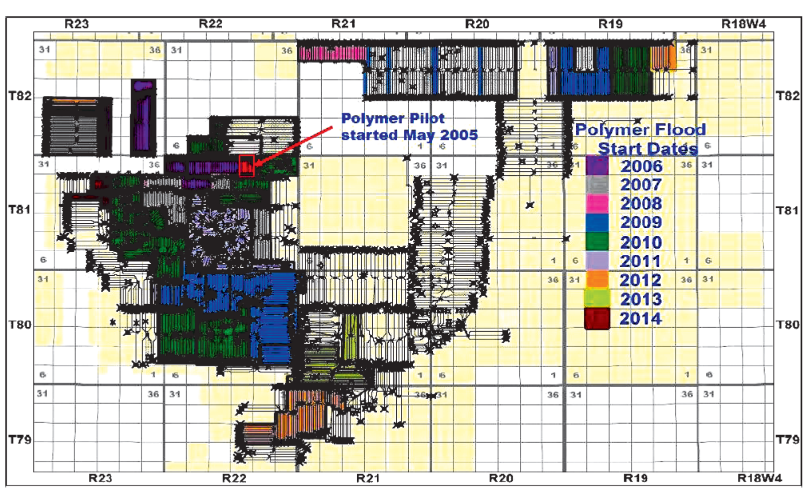

Fig. 8. Map of CNRL Pelican Lake pool with pilot location (in red) and polymer flood deployment (modified from (Delamaide et al., 2014b))

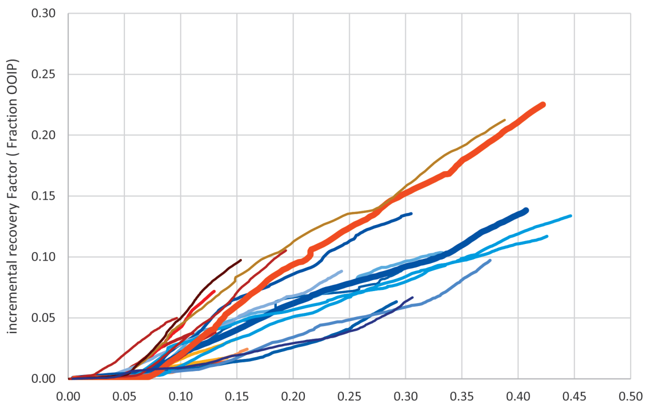

Fig. 9. Plot of Recovery vs. Cumulative injection for various wells in Pelican Lake. Each curve corresponds to a production well. Yellow-orange-brown colors correspond to secondary polymer flood while blue colors correspond to tertiary polymer flood (reproduced from (Delamaide, 2016))

The operators estimate that polymer flooding will increase the recovery factor to 20% OOIP to 30% OOIP, with the best pads achieving 38% OOIP.

A recent paper (Delamaide, 2016) reviewed the performances of primary, secondary and tertiary polymer flood in Pelican Lake. Figure 9 presents some of the results; they suggest that polymer flood is more efficient when applied in secondary conditions at least in Pelican Lake: recovery is accelerated and increased compared to waterflood, while water-cut is reduced. This first success allowed to demonstrate the potential for polymer flood in oil viscosities much higher than the ones recommended by the screening criteria, and opened the door for other field applications of the process.

Fig. 10. Location map of Patos Marinza field (reproduced from (Hernandez, 2016))

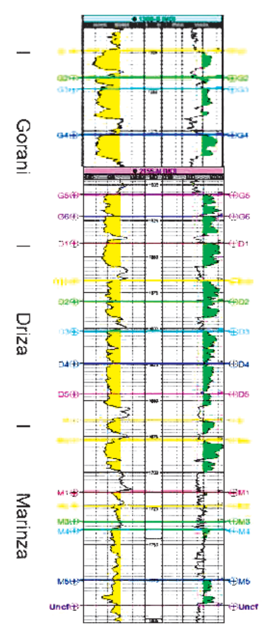

Fig. 11. Patos-Marinza type log (reproduced from (Hernandez, 2016))

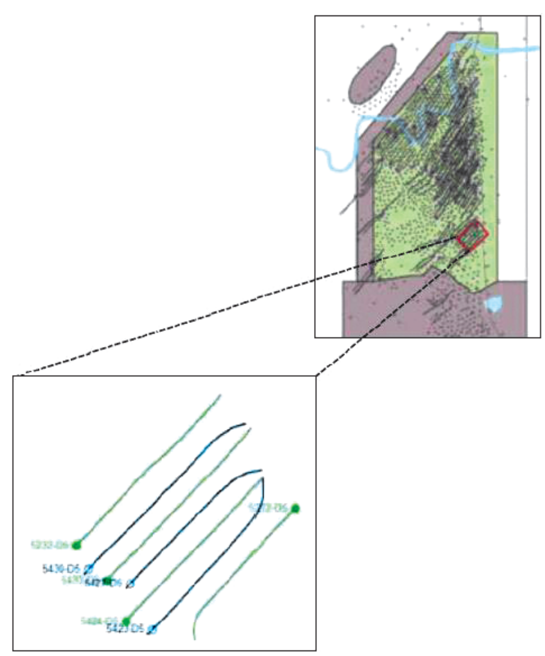

Fig. 12. Patos Marinza polymer flood pilot location and map (reproduced from (Hernandez, 2015))

Patos Marinza (Bankers Petroleum, Albania)

The Patos Marinza field is the largest onshore field in Western Europe and has been producing since 1928 (Hernandez et al., 2015). The reservoir is composed of several zones that consist in multiple stacked sands deposited during the Upper Miocene in a shallow marine environment at depth between 1,000 to 1,800 m. The main reservoir is the Lower Driza formation. Net pay is 4-12 m, and the petrophysical properties of the reservoir are good with a porosity of 21-26% and a permeability of up to 2,000 mD. The Lower Driza formation contains a heavy oil of 8-10 API with a live oil viscosity of 600 to 1,600 cp in reservoir conditions. OOIP is 5 billion bbl (Jacobs, 2015). A map of the field location is presented in Figure 10 and a type log in Figure 11.

The field was initially developed with vertical wells of which approximately 2,400 were drilled and produced by primary depletion (Weatherhill et al., 2005) with partial aquifer support but primary production only achieved a recovery of 6-10% OOIP. CHOPS (Cold Heavy Oil Production with Sand) was also tested in the field and horizontal wells were introduced since 2008: approximately 600 have been drilled so far. However, as in Pelican Lake, recovery remains limited even with horizontal wells and as a result EOR methods are required to increase recovery further.

The review of several polymer flood pilots in heavy oil – including Pelican Lake – led to the decision of piloting polymer injection in the field (Hernandez et al., 2015). A polymer flood pilot composed of 3 injection and 4 production wells, all horizontal, was initiated in 2013 (Fig. 12). The injection patterns consist of alternating injection and production wells. Following an initial success, the polymer flood was later expanded to over 59 patterns in total (Hernandez, 2016). The performances of the polymer flood are presented in Figure 13 and Figure 14. As in Pelican Lake, the increase in production is mainly due to the increase in reservoir pressure, but without polymer water-cuts would increase very rapidly.

Mooney Bluesky polymer flood and ASP (BlackPearl, Canada)

The Mooney field is located in north-western Alberta in Canada (Fig. 1). The reservoir formation is the shallow marine Bluesky (early Cretaceous), located at a depth of approximately 930 m.

The thin reservoir (up to 5 m thick, average thickness 2.5 m) is composed of semi-consolidated shoreface sandstone with excellent characteristics: average porosity of 26% (varying between 23% and 31%), average permeability of 3 darcies with a maximum of 10 darcies (BlackPearl Resources…, 2009). A type log is provided in Figure 15. The oil is heavy (12-19 API) and its viscosity at reservoir temperature (29^{0}C) varies between 300 to 1,500 cp. The main reservoir and PVT characteristics of the pool are summarized in Table 2.

The pool was discovered in 1986 and put on production with vertical wells in 1987 but due to the limited thickness and high oil viscosity productivity was low; in addition water was produced initially even though no fluid contact was visible on the logs. The initial production mechanism was solution gas drive. The pool was abandoned in 1997 due to low rates and high water-cut.

It was revived in 2005 through the use of horizontal wells (Fig. 16) but even though production rates were better than with vertical wells, the wells again produced water from the beginning (this has been attributed to the presence of mobile water in the reservoir (BlackPearl Resources…, 2009)). The lack of natural drive in the reservoir lead the operator to the conclusion that primary recovery would be very low (around 4% OOIP). Thus a waterflood pilot – one injection and two

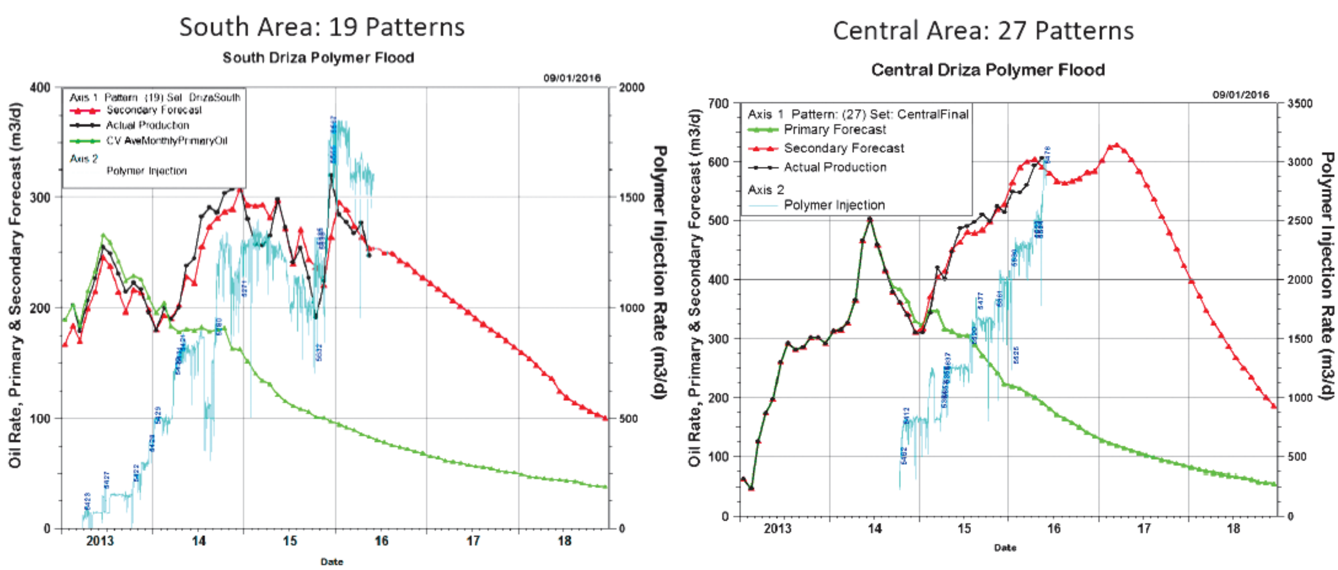

Fig. 13. Injection and production performances of polymer flood in Patos Marinza (reproduced from (Hernandez, 2016))

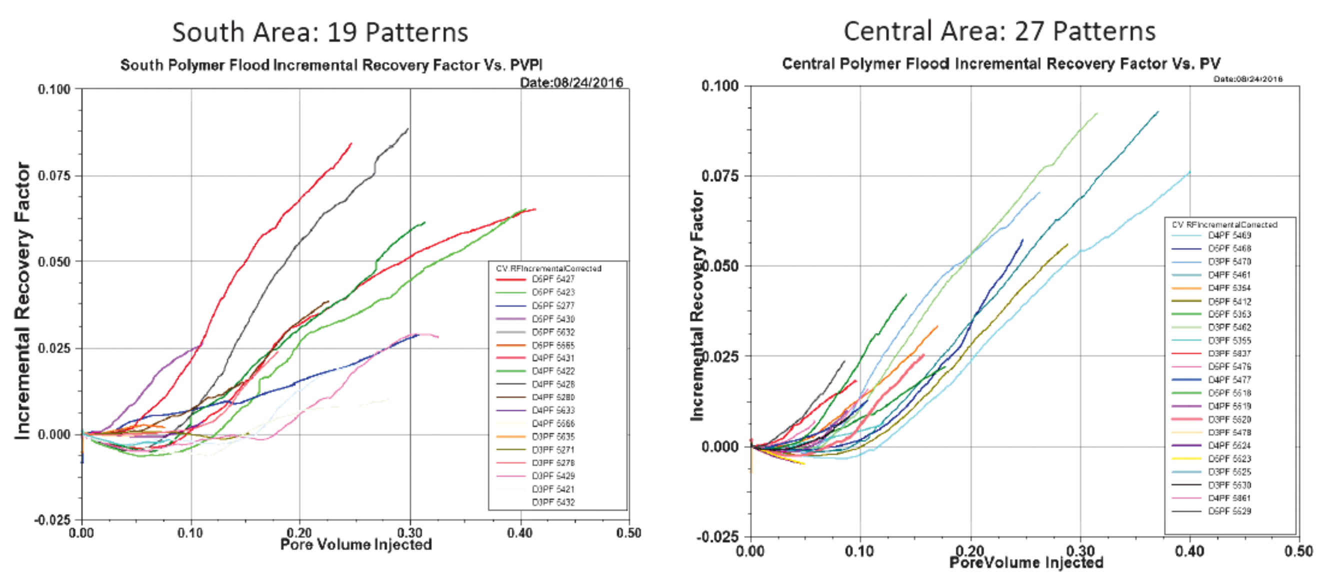

Fig. 14. Incremental recovery in Patos Marinza polymer flood (reproduced from (Hernandez, 2016))

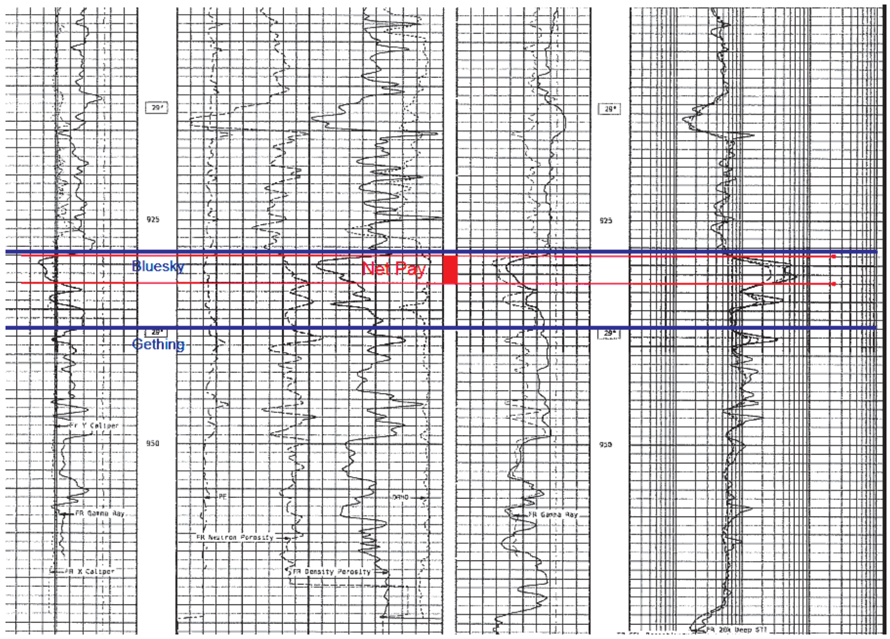

Fig. 15. Mooney – Type log of well 103/16-18-072-07W5

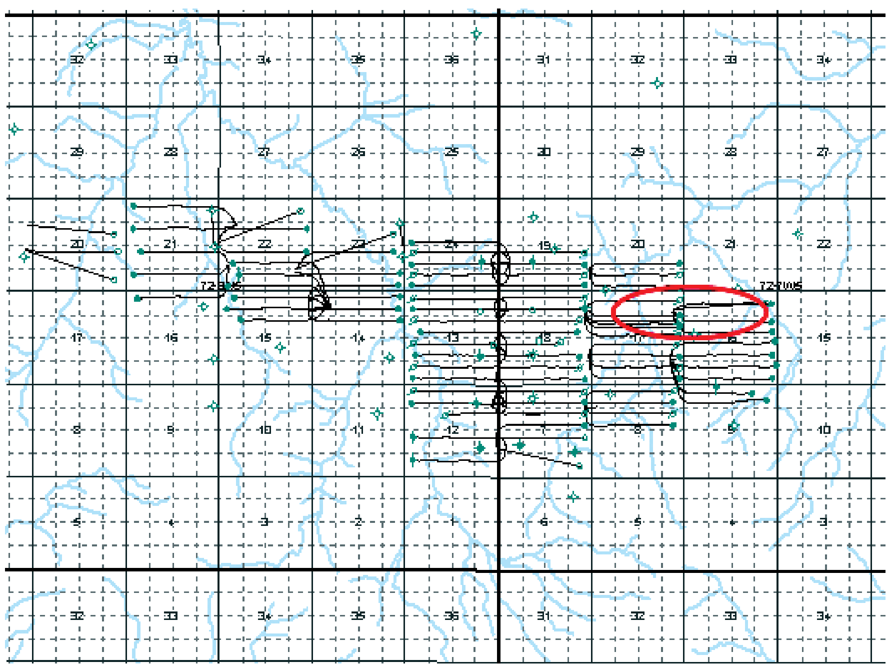

Fig. 16. Map of Mooney pool with pilot location (in red)

production wells, all horizontal – was implemented in 2006 but water breakthrough was quick and the oil rates dropped rapidly (BlackPearl Resources…, 2009). This quick breakthrough could be due to the presence of initial mobile water or to severe heterogeneity – or a combination of both.

This lead the operator to consider polymer flooding as a way to improve the sweep efficiency and reduce water production. A pilot composed of two injection wells and three production wells, all horizontal (Fig. 17) started in November 2008. Oil viscosity in the pilot area was approximately 300 cp. One of the specificities of this pilot is that it tested 3 different spacings between injection and production wells. Injected polymer concentration was approximately 1,500 ppm and

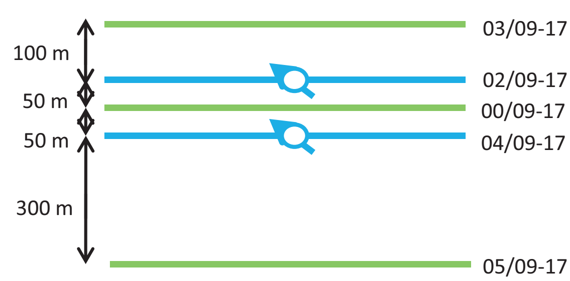

Fig. 17. Mooney polymer pilot map

viscosity ranged from 20 to 30 cp (Watson et al., 2014).

The polymer flood was able to increase production and maintain some kind of plateau for a few months in the two wells closest to the injection wells – a significant improvement over waterflood. However, water breakthrough still occurred within 4 months in the confined well and 6 months in the other well, and the water-cut increase was very sharp (Fig. 18, 19).

According to the operator, the polymer pilot ultimate recovery was estimated to be 18% OOIP (Watson et al., 2014).

In order to further increase recovery, the operator initiated an ASP flood in another part of the pool (Watson et al., 2014). The selected chemical formulation consisted of Na_2CO_3 at a concentration of 1.5% wt, a surfactant at a concentration of 0.15% wt and 2,200 ppm of associative polymer. Due to the hardness of the formation and injection water, water softening was required. This was done using a Weak Acid Cation exchanges unit.

ASP injection started in September 2011 in 23 injection wells. The production data is plotted in Figure 20; the response to the beginning of injection is clear. The response is first due to reservoir fill-up, as suggested by the increase in fluid production. The effect of the chemicals is difficult to discern; there was only a slight reduction in water-cut towards the end of 2013 then water-cut increased again while oil rate started to decrease. In cases such as this when ASP is injected in secondary conditions, it is difficult to differentiate

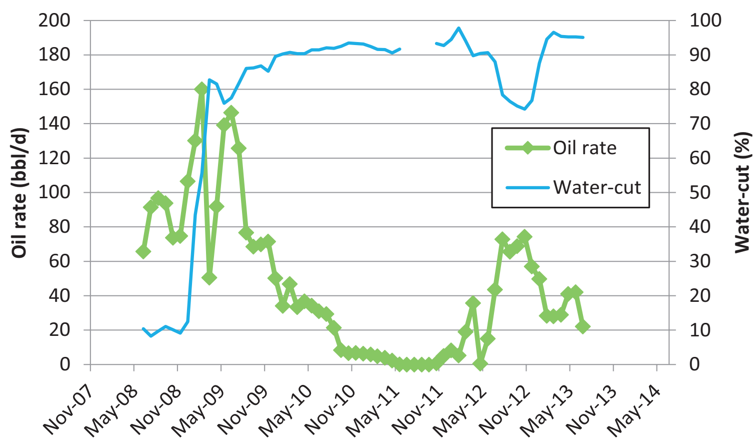

Fig. 18. Mooney polymer flood pilot – Well 09-17-072-07W5 rate and water-cut

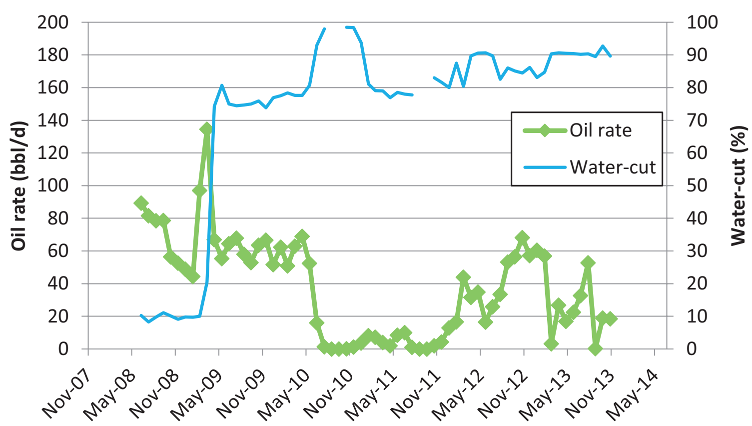

Fig. 19. Mooney polymer flood pilot – Well 03/09-17-072-07W5 rate and water-cut

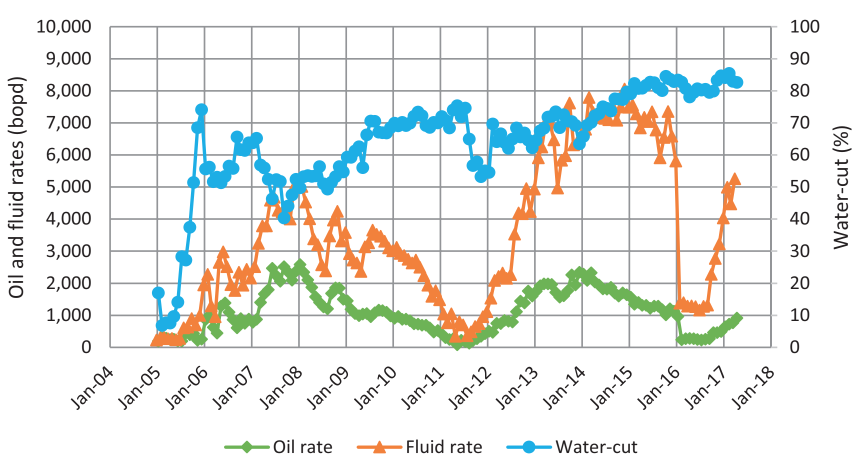

Fig. 20. Production data for Mooney ASP area

between the effect of the polymer and of the alkali and surfactant.

In 2016, the operator decided to suspend the injection in Mooney, citing high operating costs (BlackPearl…, 2012). At the end of 2016, cumulative oil production from the area was 5.2 MMbbl, which corresponds approximately to less than 9% OOIP; at that time approximately 15% PV of the ASP formulation had been injected. Clearly, these results are far below what was expected for the ASP flood, which targeted a recovery of 25% OOIP (BlackPearl press release, 2017) and even from the sole polymer flood which was expected to recover 18% OOIP. In early 2017 the company decided to reactivate the project, citing improved oil prices (Delamaide, 2017).

Discussion

The use of horizontal wells in conjunction with polymer has allowed to increase recovery and production in heavy oil fields where oil viscosity had long been deemed out of range. As showed in Table 1 there are now several ongoing large scale projects, with more in the works.

A recent paper (Delamaide, 2017) presents an analysis of the performances of polymer flooding in heavy oil, mostly using horizontal wells. The 3 examples from this paper are included in that study. Figure 21 reproduced from that paper presents the performances of a number of wells from 6 heavy oil fields (all of them horizontal except for 3) and shows the expected recovery vs. cumulative fluid injected. As can be seen from the figure, the range is relatively large which is not surprising given the variations in reservoir properties investigated, but there is a clear trend. Figure 22 from the same paper compares the performances of primary, secondary and tertiary polymer injection; as can be seen from the figure, primary and secondary polymer injection appear more efficient than tertiary polymer injection. This is confirmed by Figure 23 from the same paper, which compares the Water Oil Ratios for the 3 methods.

These results confirm the potential for polymer injection in heavy oil fields using horizontal wells. On the other hand, ASP has not yet been field proven for high viscosity oil; given the volumes of oil that cannot be recovered even with polymer, this represents a very significant – albeit challenging – target.

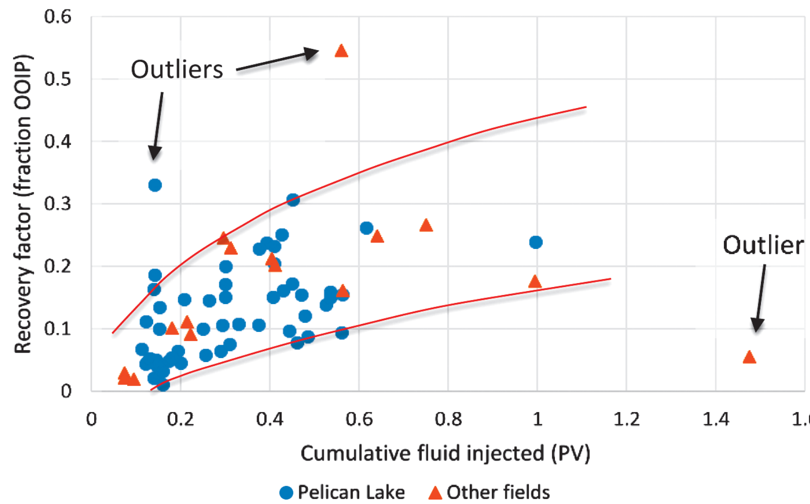

Fig. 21. Recovery factor vs. cumulative fluid injected (reproduced from (BlackPearl press release, 2016)). Each point represents a different well.

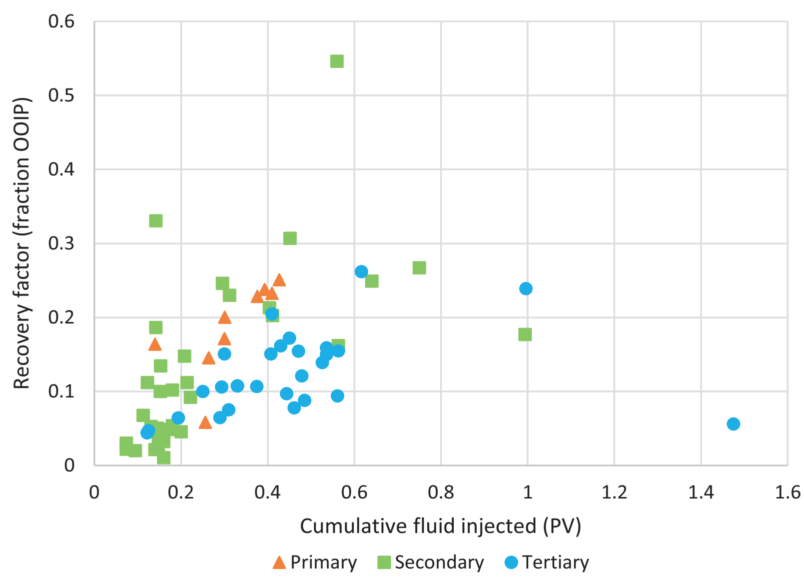

Fig. 22. Recovery factor vs. cumulative fluid injected for primary, secondary and tertiary polymer injection (reproduced from (BlackPearl press release, 2016)). Each point represents a different well.

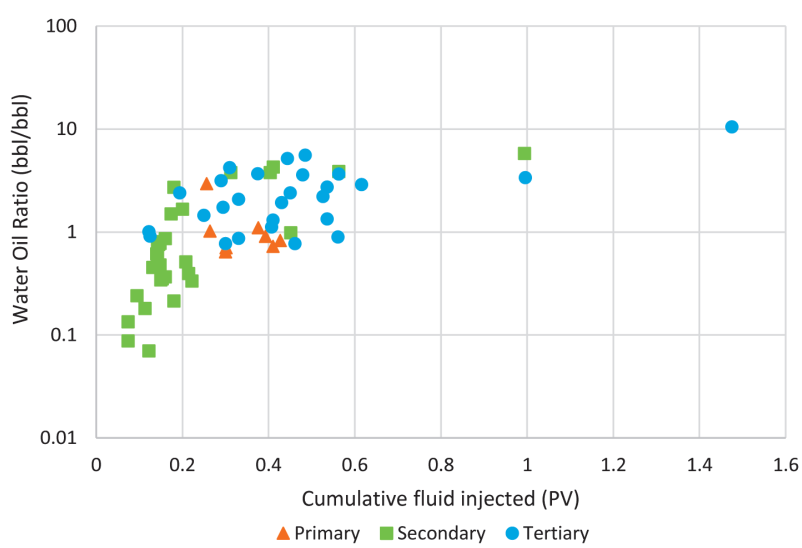

Fig. 23. Water Oil Ratio as a function of Cumulative fluid injected (reproduced from (BlackPearl press release, 2016)). Each point represents a different well.

Conclusions

The review of three chemical EOR projects in heavy oil which use horizontal wells – two polymer floods and one ASP floods – has led to the following conclusions:

• Polymer flooding is a viable solution to increase production and recovery in heavy oil. The process has been field tested for oil viscosity up to 7,000-10,000 cp and proven commercial for viscosity up to 5,000 cp.

• The Mooney case has showed that the process is still sensitive to factors such as heterogeneities and presence of initial mobile water, which can lead to early breakthrough;

• The ASP flooding process has not yet been tested at these high viscosities and its efficiency remains to be confirmed in the field.

References

Beliveau, D. (2009, October). Waterflooding Viscous Oil Reservoirs. SPE Reservoir Evaluation & Engineering, 12(05), 689-701.

BlackPearl press release, May 4, 2016. http://blackpearl.mwnewsroom.com/press-releases/blackpearl-announces-first-quarter-2016-financial-and-operating-results-tsx-pxx-201605041053399001

BlackPearl, June 2012corporate presentation. http://www.blackpearlresources.ca/i/pdf/2012_June_Presentation.pdf

BlackPearl press release, Feb. 23, 2017. http://blackpearl.mwnewsroom.com/press-releases/blackpearl-announces-fourth-quarter-and-full-year-2016-financial-and-operating-r-tsx-pxx-201702231086809001

BlackPearl Resources. (2009). Alkali Surfactant Polymer Flood Enhanced Recovery for the Mooney Bluesky "A" Pool.

Cenovus Energy. (2013, March 12). *Performance Review of In Situ Oil Sands Scheme Approval 9404T.* In Situ Progress Presentation, Calgary. Retrieved July 08, 2014, from Alberta Energy Regulator: http://www.aer.ca/data-and-publications/activity-and-data/in-situ-performance-presentations

Delamaide, E. (2017). Investigation on the Impact of Voidage Replacement Ratio and Other Parameters on the Performances of Polymer Flood in Heavy Oil Based on Field Data . *Paper SPE 185574 presented at the SPE Latin America and Caribbean Petroleum Engineering Conference.* Buenos Aires, Argentina, 17-19 May.

Delamaide, E. (2017). Comparison of Steam and Polymer Injection for the Recovery of Heavy Oil . Paper SPE 185728 presented at the SPE Western Regional Meeting. Bakersfield, California, USA, 23-27 April .

Delamaide, E. (2014). Polymer Flooding of Heavy Oil - From Screening to Full-Field Extension. Paper SPE 171105 presented at the SPE Heavy and Extra Heavy Oil Conference: Latin America. Medellin, Colombia, 24-26 September.

Delamaide, E., Zaitoun, A., Renard, G., & Tabary, R. (2014). Pelican Lake Field: First Successful Application of Polymer Flooding In a Heavy-Oil Reservoir. SPE Reservoir Evaluation & Engineering, 17(3), 340-354.

Delamaide, E., Tabary, R., Renard, G., & Dwyer, P. (2014). Field Scale Polymer Flooding of Heavy Oil: the Pelican Lake Story. Paper presented at the 21st World Petroleum Congress. Moscow, Russia, June 15-19.

Delamaide, E. (2016). Comparison of Primary, Secondary and Tertiary Polymer Flood in Heavy Oil - Field Results. Paper SPE 180852 presented at the SPE Trinidad and Tobago Section Energy Resources Conference. Port of Spain, Trinidad and Tobago, 13-15 June.

Hernandez, N., Estrada, C., Davis, G., Deren, S., & Hallman, T. (2015). Polymer Flooding in a Brown FIeld Re-Developed Heavy Oilfield. Paper PAMFC15-108 presented at the Pan American Mature Field Congress. Veracruz, Mexico, January 20-22.

Hernandez, N. (2016). Polymer Flooding in a Multi-Layered and Extra-Heavy Oilfield. Paper WHO16-903 presented at the World Heavy Oil Congress. Calgary, Alberta, Canada, September 6-9.

Jacobs, T. (2015, March). Reviving Europe's Largest Onshore Field. Journal of Petroleum Technology, 67(03), 70-74.

Weatherhill, B., Seto, A., Gupta, S., & Cobo, L. (2005). Cold Heavy Oil Production at Patos-Marinza, Albania . Paper SPE 97992 presented at the SPE International Thermal Operations and Heavy Oil Symposium. Calgary, Alberta, Canada, 1-3 November.

Watson, A., Trahan, G., & Sorensen, W. (2014). An Interim Case Study of an Alkaline-Surfactant-Polymer Flood in the Mooney Field, Alberta, Canada. Paper SPE 169154 presented at the SPE Improved Oil Recovery Symposium. Tulsa, Oklahoma, USA, 12-16 April.

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EXPERIENCE IN NORTH AMERICA TIGHT OIL RESERVES DEVELOPMENT. HORIZONTAL WELLS AND MULTISTAGE HYDRAULIC FRACTURING

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The accelerated development of horizontal drilling technology in combination with the multistage hydraulic fracturing of the reservoir has expanded the geological conditions for commercial oil production from tight reservoirs in North America. Geological and physical characteristics of tight reservoirs in North America are presented, as well as a comparison of the geological and physical properties of the reservoirs of the Western Canadian Sedimentary Basin and the Volga-Ural oil and gas province, in particular, in the territory of Tatarstan. The similarity of these basins is shown in terms of formation and deposition.

New drilling technologies for horizontal wells (HW) and multistage hydraulic fracturing are considered. The drilling in tight reservoirs is carried out exclusively on hydrocarbon-based muds The multistage fracturing technology with the use of sliding sleeves, and also slick water – a low-viscous carrier for proppant is the most effective solution for conditions similar to tight reservoirs in the Devonian formation of Tatarstan. Tax incentives which are actively used for the development of HW and multistage fracturing technologies in Canada are described.

Key words: North America, tight oil, sandstone, carbonate, horizontal wells, multistage fracturing

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There is the rapid growth of the new technics and technologies in the development of unconventional hydrocarbon reserves in the last decade. Among them are drilling of horizontal and multilateral wells, as well as technology, equipment, and reagents for multistage hydraulic fracturing (MSF) for tight oil and shale oil. This has opened new opportunities for effective industrial development of the vast unconventional resources in shale and tight reservoirs.

These technologies are most effectively used in North America, where hydrocarbons in tight and shale reservoirs are extended over a large territory (Fig.1).

The most rapidly developing area in the United States in the last three post-crisis year is the Permian basin. This basin is located in the country's south, where is the third US active drilling rigs for oil (over 300 units) and about half of the total US rig count. Hydrocarbon deposits of the Permian basin are located at depths of 2500-3000 m in the shales within area's porosity value above 5%.

In Canada, similar resources are located in the Western Canadian Sedimentary Basin (WCSB), a brief description of which is presented in table 1.

Upper Devonian sediments in WCSB were formed mainly under conditions of shallow coastal sedimentary environments, including reef sediments of Leduc. Their location is shown (Stacy C. Atchley, Lawrence W. West, Jeff R. Sluggett, 2006) in the center, and also in the right of part B (Fig. 2). In the 30-s of the last century, the discovery of these reserves marked the beginning of the oil boom in Canada, similarly to Sakmara-artinsky reef sediments of the Ishimbay oil field which was opened in Bashkortostan, Russia at the same time. The counterpart of these carbonate reservoirs in Tatarstan in reservoir characteristics are Dankovo-Lebedyansky, the Zavolgsky and Yeletsky deposits of the South-Tatar arch of the South-East of Tatarstan (Table 2), and for the Cardium sandstone it is Kynovsky formation of the Devonian age (Table 3).

Development of oil reserves in tight reservoirs and shales in the United States and in Western Canada in the last 5-7 years is dramatically intensified on the basis of new highly efficient technologies for horizontal wells and MSF.

These technologies have created a new investment policy with large upfront capital costs and an accelerated return due to the large initial production rate. The difference of the tight reservoir development in comparison with conventional reservoirs arises due to the emergence of significant short-term fracturing impact in the case of the tight reservoir. It should be noted, that comparable changes in pressure drop will be observed: for a tight reservoir at distances up to ten meters from the fracture, but for conventional reservoirs in hundreds of meters. This explains the presence of two legs on the decline curves on a logarithmic scale (Fig. 3). The initial hyperbolic part of the curve describes a reaction of the near-fracture zone, and further is the effect of the boundary energy (a remote area). The decline curves are applied for the recoverable oil reserves assessment widely, so the using only an initial dependence in the

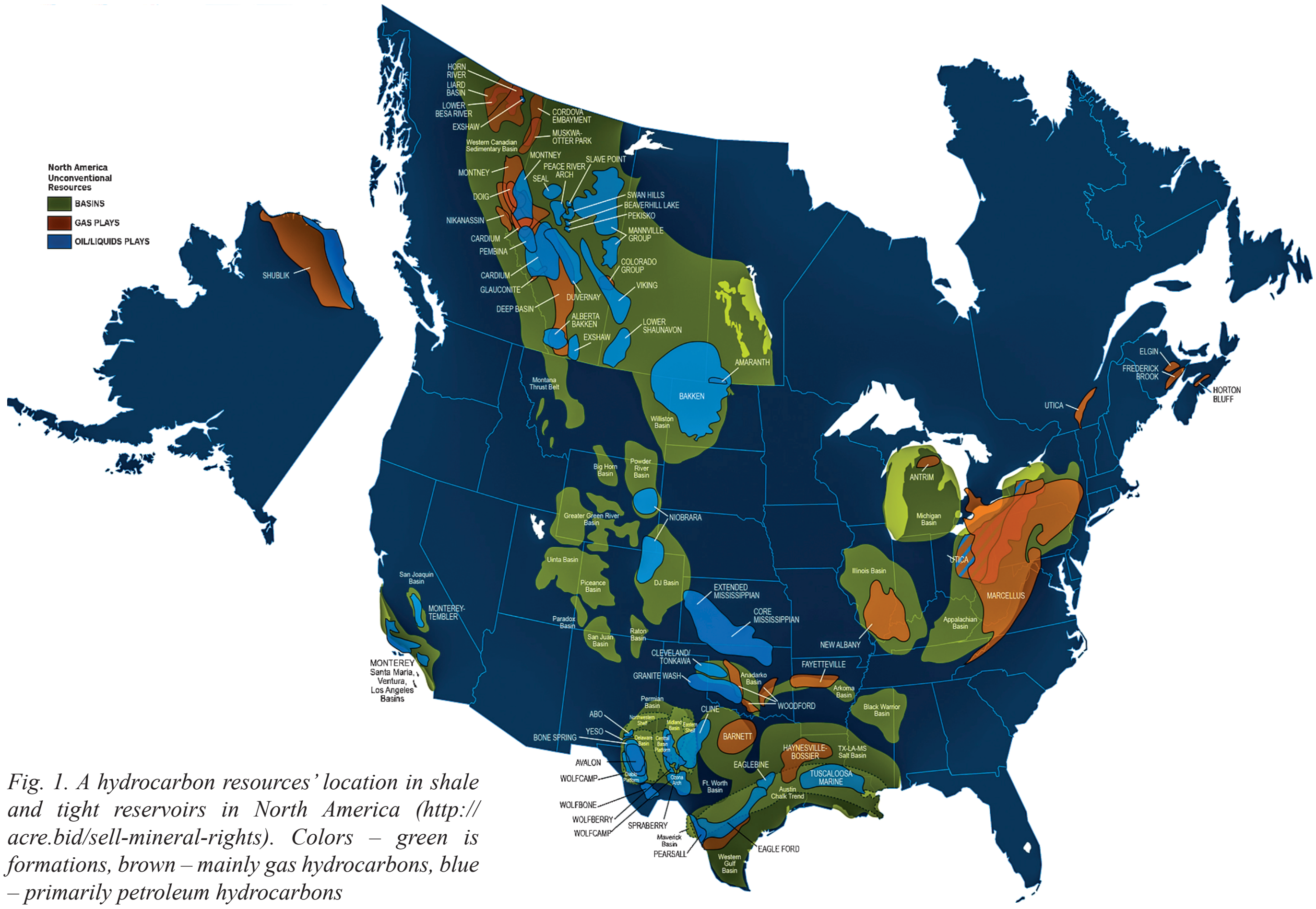

Fig. 1. A hydrocarbon resources' location in shale and tight reservoirs in North America (http://acre.bid/sell-mineral-rights). Colors – green is formations, brown – mainly gas hydrocarbons, blue – primarily petroleum hydrocarbons

Formation (Canadian Province)	Reservoir type/Age	Typical depth, m
Bakken/Exshaw (Saskatchewan, Manitoba)	Sandstone/Devon	900-2500
Cardium Formation (Alberta)	Sandstone / upper Cretaceous	1200-1600
Viking formation (Alberta, Saskatchewan)	Sandstone /low Cretaceous	600-900
Lower Shaunavon (Alberta)	Limestone mixed with shale and minor sandstone /middle Jurassic	1300-1600
Montney/Doig (Alberta, British Columbia)	Sandstone / low and middle Triassic	800-2200
Duvernay/Muskwa (Alberta)	Carbonate /middle Devon	2000+
Beaverhill Lake (Alberta)	Carbonate / middle Devon	2000-2900
Slave Point (Alberta)	Carbonate / upper Devon	1200-1500

Table 1. Characteristics of the tight reservoirs and shale plays in the Western Canadian Sedimentary Basin

continuation of a trend (the graph shows a solid line) will lead to overestimating of reserves.

In the recent low hydrocarbon price environment, a drastic cost reduction of services in North America was achieved while increasing the technological efficiency of HW drilling and hydraulic fracturing.

There is the presence, often significant, of clay components in tight reservoirs and shales. To protect swallowing and the collapse of the borehole rocks the hydrocarbon based drilling muds ("invert") are used only. This kind mud significantly reduces complications during drilling and the subsequent installation of the sophisticated completion tool for MSF.

The important reserve of the cost reduction is also cheaper equipment and maximizing the runtime of the expensive and limited of hydraulic fracturing fleet. One of the latest innovation in this field was the NCS company's (Canada, USA) fracturing technology named as the "sliding" sleeves. This technology allows conducting high-speed MSF (e.g. for 9-11 hours at 1500 m horizontal leg 30 fractures with the injection of up to 50 tons of proppant in each) by using a coiled tubing and the straddle packer system.

High formation pressure can limit coil tubing using because of its flexibility. In this case, the successive opening of fracturing stage valves by balls is mostly used technology. To mill balls and valve seats are necessary at the end of such process. To exclude these steps materials are developed which dissolved in acids or disintegrated in the salt solutions at high temperatures for acid-free systems. An example of the latter is packed compound of fiberglass, cyanate ether of resin, and a crosslinker.

Another widespread shift of the modern fracture technology for tight reservoirs and shales is "slick" water as fracturing fluid. The viscosity of such fracturing

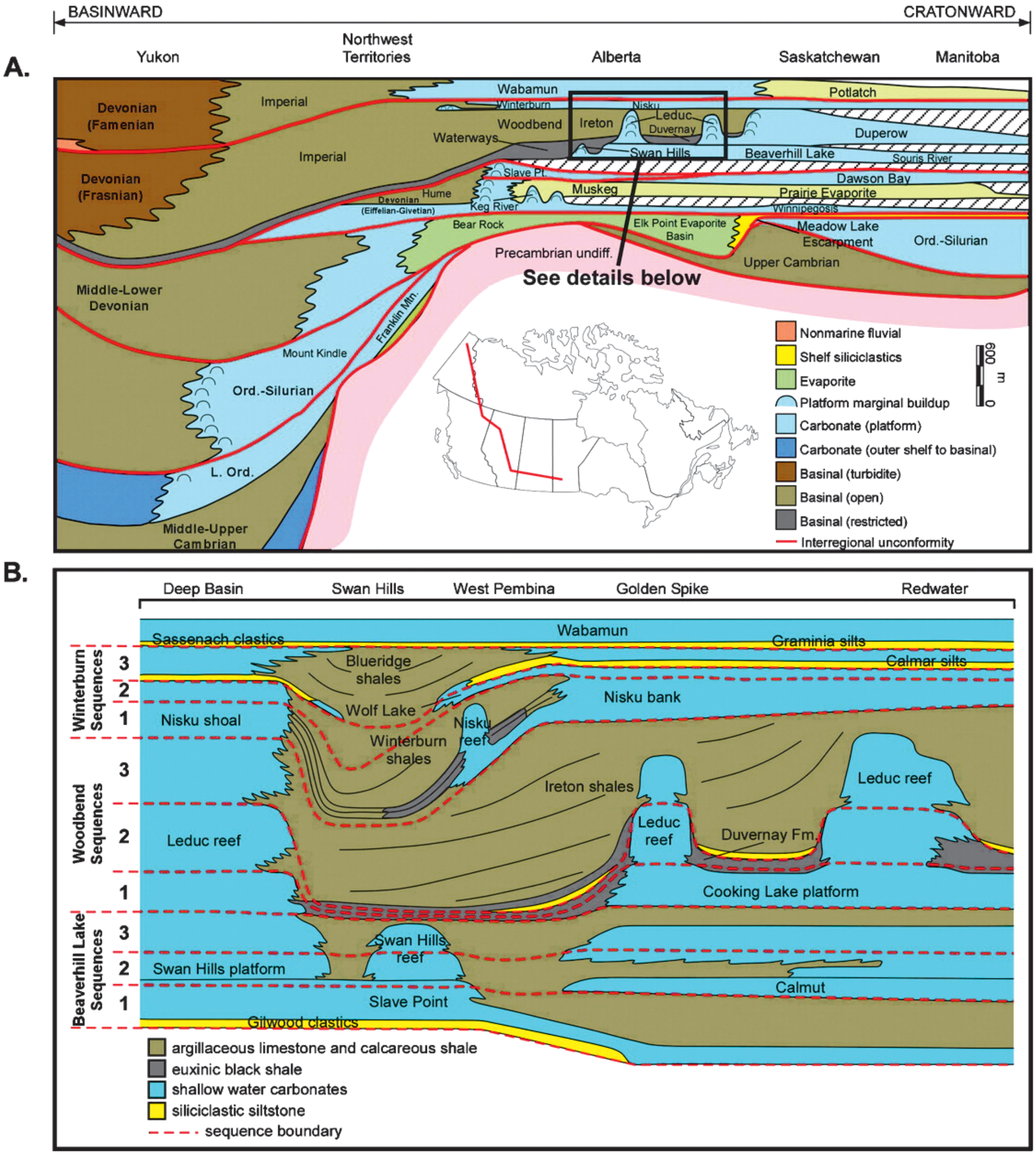

Fig. 2. Crossection of the Western Canadian Sedimentary Basin in the territory of Alberta (Stacy C. Atchley, William Lawrence West, Jeff R. Sluggett, 2006)

Parameters	Red Earth и Sawn Lake	Devonian formations in Tatarstan		
Age, formation	Upper, middle Devon, Beaverhill Lake	Zavolgsky	Dankovo-Lebedyansky	Yeletsky
Depth, m	1380	1100	1300	1500
Total thickness, m	<30	< 93	< 200	< 138
Net thickness, m	12-18			
Porosity range, %	4-15	0,5-18,7	0,3-10,9	2,2- 15,5
Average porosity, %	6			
Permeabiliy, md	0,1-10	0,01-97,3	0,01-96,6	0,09-22,5
Water saturation, %	35			
Formation temperature, °C	34	25-29	25-35	30-31
Initial pressure, MPa	9-14	10-15	9,4-13,6	14,2-15,2
Oil density, kg/m^3	840	859-942		

Table 2. Comparison of the tight carbonate reservoirs of the South-East of the Republic of Tatarstan and WCSB's Red Earth and Swan lake fields parameters

Oil field	Pembina	Romashkinskoye
Age, formation	Cretaceous, Cardium	Devon, Kynovsky
Typical depth, m	1200-1600	1700-1800
Total thickness, m	<20	<20
Net thickness, m	3-6	3-8
Porosity range, %	5-15	< 15
Permeability, md	0,1-5	< 200
Formation temperature, °C	34	
Initial pressure, MPa	12-17	17-19
Oil density, kg/m^3	830	

Table 3. Comparison of the Kynovsky Devonian formation of the Romashkinskoye oil field and Cardium formation of the Pembina field characteristics

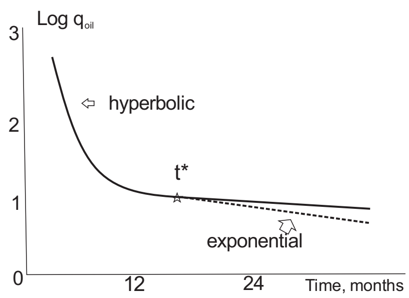

Fig. 3. The time dependence of the oil production rate for HW with MSF in semi-logarithmic coordinates (the continuous black line shows hyperbolic dependence, the dashed one is an exponential line), t is a time of transition from the predominantly fracture inflow to the predominant inflow due to the boundary energy*

fluid is lowered to 5 MPa*s while saving the retaining properties to keep the proppant (sand) in the suspended condition by using a low concentration polymer solution. On this basis, you ensure that the sand will penetrate easy into the fracture space for tens of meters by a standard fracturing fluid injection procedure.

The evolution of MSF technology shows that the efficiency for tight, predominantly hydrophobic reservoirs, grew chronologically in the following sequence of used fluids: oil-based gels, water-based gels, and, finally, “slick” water. Wide field experience approves higher efficiency of “slick” water fracturing technology for tight reservoirs and shales.

The volatility of oil prices leads to implement more “aggressive” technology of hydraulic fracturing, which consists of a larger number of fractures per horizontal length, the volume of proppant injected, and an injection rate of fracturing fluid. In addition, there is compacted wells’ spacing in modern projects.

The pilot fracturing optimization by the density of fractures and proppant mass per HW length (Jaripatke, Samandarli, McDonald & Richmond, 2014), was held by Pioneer Natural Resources (PNR) in the Eagle Ford oil field in Texas (Table 4, fig. 4). The true vertical depth is about 3500 m, porosity near 5-6%, and rock material is carbonate with permeability less 0,01 md. MSF was performed according to the “Plug and Perf” method by applying clusters of fractures. A cluster is a group of perforations/fractures formed by one perforating tool in one run.

The results of the pilot fracturing optimization in the object B has been assessed by four different methods (Jaripatke, Samandarli, McDonald & Richmond, 2014):

1. Normalized production rates;
2. Decline curves;
3. Rate Transient Analysis -RTA;
4. Reservoir modeling.

Table 5 summarizes all the pilot results assessment obtained by the mentioned authors.

Pioneer has continued MSF optimization in 2017 in more “aggressive” manner. The distance between the clusters is reduced from 15.2 m to 9.1 m, and the proppant specific consumption is increased from 810,8 kg/m to 1351,3 kg/m.

PNR has led the modification of the MSF and field development plans in the Permian Basin also. Generally, the evolution of the MSF parameters over the years is presented in table 6 (Pioneer Natural Resources, 2017). The depth of the lower Permian deposits (Wolfcamp

Pilot objects (number of wells)	**Parameters**		
	Proppant mass per HW length, kg/m	**Distance between clusters, m**	**Combination (2)+(3)**
1	2	3	4
A	(4 wells)	(4 wells)	(4 wells)
B	(3 wells)	(3 wells)	(3 wells)
Values for regular/pilot	540,5 / 810,8	21,3 / 15,2	

Table 4. Pilot MSF parameters in the Eagle Ford field to assess the effectiveness of multistage characteristics by using increasing specific proppant mass per HW length and the density of fracture clusters (regular/pilot)

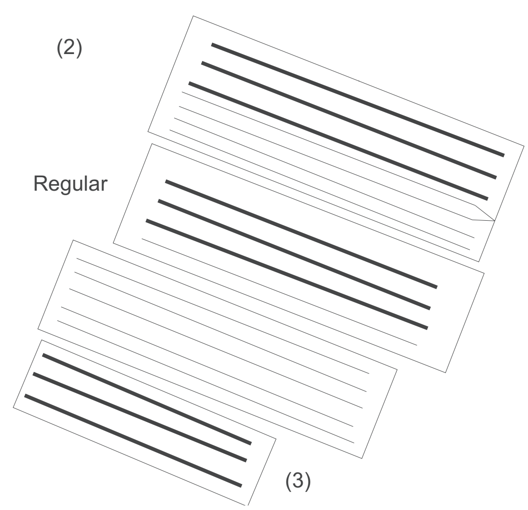

Fig. 4. PNR pilot groups’ location on the object B of the Eagle Ford field. Assigned increased thickness of the pilot wells’ projection from the table 4: (2) – increased the proppant specific consumption (810,8 kg/m); regular – the specific proppant consumption 540,5 kg/m, the distance between clusters -21,3 m; (3) increased specific consumption proppant (810,8 kg/m) and decreased distance between clusters (15.2 m)

MSF optimization method	Assessment methods			
	Normalized production rates	**Decline curves**	**Rate Transient Analysis**	**Reservoir modelling**
Increased proppant specific consumption	For 4 months 7% For 12 months 11%	21%	13%	11%
Increased proppant specific consumption and decreased distance between clusters	For 4 months 37%	42%	71%	49%

Table 5. The results of the pilot MSF optimization. Increase in cumulative production compared to the baseline method, % (Jaripatke, Samandarli, McDonald & Richmond, 2014)

MSF parameters	Years		
	2013-2014	**2015-2016**	**2016-2017**
Proppant specific consumption, кг/м	676	946	1149
Specific injection rate of fracturing fluid, m^3/m	15,64	18,76	26,05
Distance between clasters of fractures, m	18,28	9,14	4,57
Distance between fracturing stages, m	73,15	45,72	30,48

Table 6. Evolution of the MSF parameters which realized by the company Pioneer Natural Resources in the Permian Basin in 2013-2017

and Spraberry formations) is 1500-3000 m, MSF was performed by the method Plug and Perf.

In order to realize such advanced technology more powerful fracturing equipment with high run time is applied, thereby reducing time to reach production. Today's horizontal well pad under multistage fracturing is similar to a large plant with a maximum concentration of technologies and equipment with minimal time for the moving and installation/dismantling.

The waterflooding is effectively used at some tight reservoir conditions. Comparison with the classical waterflooding of conventional reservoirs demonstrates that tight reservoir pressure maintenance effectively assists oil displacement from the hydrophilic matrix, but does not allow to conduct direct oil displacement because of low permeability. Tight carbonate reservoirs and shales are frequently overpressed that stimulates a high initial oil rate just after fracturing, and in such case, they are mostly hydrophobic thus rarely waterflooded.

An important factor in the sustainability of the oil industry in Canada is tax incentives for new HW and fracturing technologies, which is based on a single well oil production recording system, with the lowered royalty rates to provide a certain coverage of costs for drilling the HW and fracturing. The value of the low royalty rate production depends on the depth of the reservoir, the length of the HW and the volume of proppant injected.

A reduced royalty rate of 5% is introduced in Alberta from 1st January, 2017 for oil produced by new HW with MSF for the certain value of the total revenue calculated based on the following equations (Alberta Energy Regulator, 2016):

For instance, this value for wells with true vertical depth shallower than or equal to 2 km is a following:

$$C^*\,(C\$) = ACCI^*((\,1170^*(TVD_{MAX} - 249)) + (Y^*800^*TLL) + (0.6{*}TVD_{AVG}{*}TPP)). \qquad (1)$$

Where:

C($)* – The Drilling and Completion Cost Allowance (C$);

ACCI – Alberta Capital Cost Index, and custom government of Alberta on an annual basis to maintain the competitiveness of investments and growth in drilling and fracturing efficiencies, which adopted by 2017 equal to 1.0. For future years, an estimation is expected the rate of 3% per year;

TVD_{MAX} – The deepest True Vertical Depth (m);

TVD_{AVG} – The average True Vertical Depth (m) for all legs (non-reported legs included as zero);

TLL – Total Lateral Length (m);

TPP – Total Equivalent Proppant Placed (tonnes);

TMD – Total Measured Depth (m) (i.e. Combined total length for all legs);

Y – a cost adjustment for multileg wells to better reflect actual costs – Y = 1 if the ratio of $TMD/TVD_{AVG} < 10$, otherwise Y equals the greater of 0.24 and $[1.39 - 0.04^*(TMD/TVD_{AVG})]$.

To estimate the value of the Alberta province support will take the modern data for HW and MSF for the Pembina field. Let's calculate according to the equation (1) for a single-leg horizontal well with 35 hydraulic fracturing stages and 20 tons of proppant in each, with the following parameters:

TVD_{MAX} – 1600 m;

TVD_{AVG} – 1600 m;

TLL – 1600 m;

TPP – 700 tons;

TMD – 3400 m.

The resulted marginal revenue covered by 5% royalty is 3.53 million C$. Assume the cost HW with MSF for mentioned conditions above was about 2 million C$. In order to obtain the specified revenue at an oil price of 55 C$/bbl (43,8 USD/bbl in according to the exchange rate on 15.07.2017) will need to produce approximately

64,000 barrels of oil. With average production rate up 100 bbl/day, it takes near 2 years. When operating costs are 20 C$/bbl net revenues is 2.2 million C$. So, the incentive royalty rate allows the company to generate revenues to cap full cost of the new well in relatively short time.

After reaching the marginal revenue for incentive taxation, the regular rate comes into effect where the royalty rate depends on the production rate and world market oil prices (the marginal rate for high flow rates and highest prices – up to 40%).

A similar approach is implemented in Alberta regarding enhanced oil recovery projects, as well as projects with high geological risks, from 1st January 2017.

Conclusion

1. The high efficiency of modern technologies for the development of unconventional resources in North America along with the tax incentives allows providing sustainable development of the previously marginal resources even in conditions of low hydrocarbon price environment.

2. The new MSF technologies are aimed to minimize costs and achieve maximum production rate in a very short time. This is provided by a higher density of fractures, the increase the specific volume of the injected proppant per fracture, and the high flow rate of the fracturing fluid.

3. The tax regulation for hydrocarbon production in Alberta allows achieving payback for HW and MSF projects in low royalty rate borders. The same approach is adopted for projects of enhanced oil recovery, as well as the development of reserves in uncertain geological conditions. This promotes to reduce risks and facilitate the loans for business development.

4. The Volga-Ural oil and gas basin’s substantial resources of light hydrocarbons in tight reservoirs can be an important engine for oil and gas industry in the nearest future.

References

Alberta Energy Regulator. About Royalties. 2016. http://www.energy.alberta.ca/Org/pdfs/MRFCstar.pdf

Jaripatke, O.A., Samandarli, O., McDonald, E., & Richmond, P. L. Completion Optimization of an Unconventional Shale Play: Implementation of a Successful Completion Design Optimization Plan and the Results. *Society of Petroleum Engineers*. SPE Paper 170764. 2014. doi:10.2118/170764-MS

Pioneer Natural Resources. Investor Presentations. http://investors.pxd.com/phoenix.zhtml?c=90959&p=irol-presentations

Stacy C. Atchley, Lawrence W. West, Jeff R. Sluggett. Reserves growth in a mature oil field: The Devonian Leduc Formation at Innisfail field, south-central Alberta, Canada. *AAPG Bulletin*. 2006. V. 90. No. 8 Pp. 1153-1169. doi:10.1306/03030605193

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UNCONVENTIONAL OIL RESERVES DEVELOPMENT IN THE VIKING PLAY (WESTERN CANADA) USING HORIZONTAL WELLS AND HYDRAULIC FRACTURING

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Abstract. Oil production from the Viking play in Saskatchewan province started in the 1950s and continues since that time. Horizontal drilling and multistage fracturing have caused resurgence in development of this play. Based on the production data from several fields, the comparative results of the Viking play development using vertical and horizontal wells are presented. Horizontal wells drilling made it possible to increase oil production in those formation zones that were previously considered predominantly gas-saturated, as well as in the zones affected by water injection using vertical wells in order to maintain reservoir pressure. Infill drilling combined with longer lateral completion length also positively affected the development of oil reserves from the Viking play.

Keywords: Viking play, horizontal wells, Saskatchewan province
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The Viking play ranges from east-central Alberta to west-central Saskatchewan with most activity concentrated in Dodsland and Kindersley fields in Saskatchewan and Halkirk-Provost fields in Alberta. According to Canadian experts, original oil in place in this play ranges from 3-4 to 6 billion barrels of oil. Oil production from this play was started in the early 1950s but was revived with the improvement of horizontal drilling technology combined with multistage hydraulic fracturing.

This play, which actually covers most of Saskatchewan, consists of interbedded fine sandstones, siltstones and mudstones, bracketed by two shales. The upper layer is two to three meters thick while the lower is three to nine meters thick.

The distinctive factors of geological structure of this play are the following:

Net to Gross reservoir ratio is difficult to determine using log evaluation because of the rock characteristics; geophysical well logs not advanced enough to accurately quantify net pay.

Reservoir consists of cm-scaled parallel-laminated and bioturbated oil-bearing sands and interbedded tight shales.

Porosity ranges 15 to 20%, permeability varies from 20 to 80 μm^2 from conventional core analysis and oil density is about 36 degrees API (845 kg/m^3).

Understanding the reservoir in area is paramount to developing a successful horizontal drilling and stimulation program. Combining the best reservoir quality and thickest net pay areas focuses horizontal drilling to the most prospective areas.

As noted above, initially oil production from the Viking play began in the 1950s and its production through vertical wells, mainly from the upper zone, has continued since then. Horizontal wells drilling combined with multistage hydraulic fracturing revived the development of this play as the lower zone became economically more attractive. In the Dodsland and Prairiedale fields, the Viking play lies at a relatively shallow depth – less than 800 meters – which reduces drilling costs; on the other hand low reservoir pressure limits production.

As of mid-2017, more than 35,000 oil wells have been drilled in the Viking play; approximately 27,800 of those wells are vertical or deviated and the remaining approximately 7,500 are horizontal. More than half of all wells (about 20,000) were drilled within Alberta province and the remaining slightly more than 15,000 wells – in Saskatchewan. This proportion is completely different for horizontal wells – almost 80% of all those wells (about 5,800) were drilled within the fields in Saskatchewan province. The main factor that determined such development was that, as noted earlier, the depth of the play within this province is less than 800 meters, which significantly reduces drilling and completion costs for horizontal wells.

The Table 1 shows the main parameters and production data for all analyzed fields. It is worth noting that the total number of horizontal wells drilled in these fields is about 45% of all horizontal wells drilled in the Saskatchewan province targeting Viking play.

Several areas were identified within each of the reviewed fields with different vertical and horizontal wells patterns in each area and for each area several typical production performance profiles for both vertical and horizontal wells were generated.

Characteristics	Unit	Field			
		Dodsland	Kerrobert	Prairiedale	Plato North
Beginning of production	year	1957	1981	1984	1978
Total well	pcs.	4,314	1,807	1,318	876
Vertical wells	pcs.	3,060	1,179	1,147	333
Horizontal wells	pcs.	1,254	628	171	543
Total producing well	pcs.	3,815	1,657	1,318	850
Vertical wells	pcs.	2,597	1,032	1,147	318
Horizontal wells	pcs.	1,218	625	171	532
Total injection well	pcs.	499	150	-	26
Vertical wells	pcs.	463	147	-	15
Horizontal wells	pcs.	36	3	-	11
Initial oil reserves	Million barrels	424.55	238.52	565.24	171.62
Cumulative oil production	Million barrels	113.49	28.99	11.60	18.39
From vertical wells	Million barrels	88.90	20.24	10.13	7.88
From horizontal wells	Million barrels	24.64	8.74	1.47	10.51
Average depth of occurrence	Ft	2,201	2,343	2,438	2,313
Field area	Acre	61,171	41,247	35,966	19,042
Average thickness of play	Ft	8.01	6.50	17.78	8.63
Average porosity	%	22.40	23.00	23.00	23.00
Density of oil	API	36.60	36.60	31.10	32.10
Current oil recovery factor	%	26.7%	12.2%	2.1%	10.7%
Due to vertical wells	%	20.9%	8.5%	1.8%	4.6%
Due to horizontal wells	%	5.8%	3.7%	0.3%	6.1%
Spacing	Acre/well	14.2	22.8	27.3	21.7
Vertical wells	Acre/well	20.0	35.0	31.4	57.2
Horizontal wells	Acre/well	48.8	65.7	210.3	35.1

Table 1

Dodsland Field

This is one of the very first fields where oil production began from the Viking play and at the same time it is the largest field in this play. The first well was drilled on December, 1957 and over the next 30 years it produced just over 30,000 barrels of oil. More than 4,300 wells, including over 3,000 vertical and 1,250 horizontal, have been drilled to the date of the analysis. In some areas of the field, water injection into the reservoir has been implemented to maintain reservoir pressure – and, in particular, water injection has been started also in a number of horizontal wells. The Figure 1 shows vertical and horizontal wells location within Area 1.

Type wells oil production profiles are shown in the Figure 2 for two areas selected, one of which is located in the central part of the field and has approximately the equal number of vertical and horizontal wells (Area 1). The second area is located closer to the southern limit of the field and the results of vertical wells production in this area are significantly worse than those of the

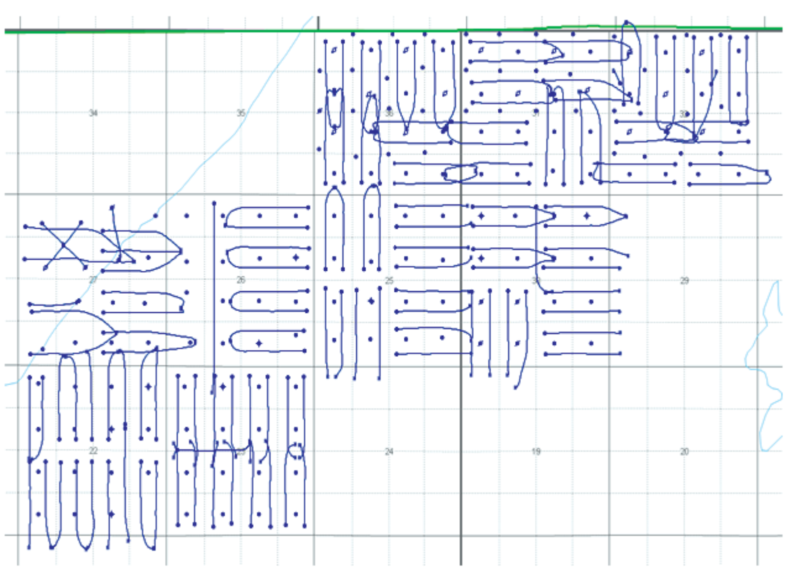

Fig. 1. Layout of vertical and horizontal wells within plot 1

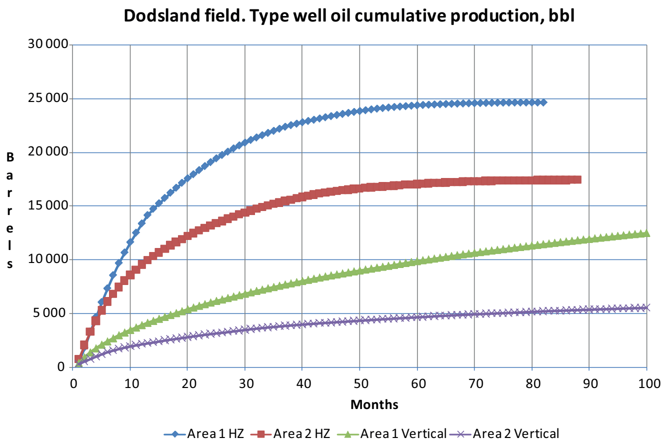

Fig. 2

Area 1. At the same time, for both areas, the results of comparative analysis (Fig. 2) indicate that the horizontal wells are much better than the vertical ones, and the total accumulated oil production for comparable time intervals is 2.5-3 times higher.

Kerrobert Field

The first well in this field was put into operation in May, 1962 and after three years it produced slightly more than 4,500 barrels of oil. The active development of the field began in the first half of the 1980s and to date more than 1,800 wells have been drilled from which a little less than 1,200 are vertical and more than 600 are horizontal wells. For the purposes of this analysis, two areas were selected within the field, one of which (Area 1) was drilled only by vertical wells and there is no water injection within it. In addition to vertical wells, horizontal wells were drilled within the boundaries of the second area and, in addition, injection of water into the play was implemented to maintain reservoir pressure. The Figure 3 below shows cumulative oil production from a typical vertical and horizontal well for each of the selected areas.

As can be seen from the plot, water injection within the second area slightly improved oil production performance from a typical vertical well; however,

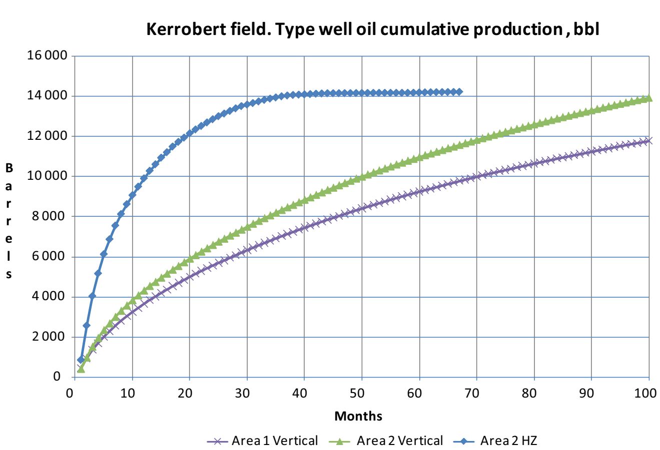

Fig. 3. Cumulative oil production from a typical vertical and horizontal well for each of the selected areas

the horizontal well production profile is significantly higher than the production from vertical wells in both areas. The available data do not allow us to unambiguously assess the degree of influence of the recently implemented water injection into the reservoir to improve the oil production efficiency from horizontal wells.

Prairiedale Field

Development of this field began later than all of other fields analyzed in the present paper – in the mid-1980s – and to date more than 1,300 wells have been drilled with about 1,150 wells to be vertical and more than 150 wells are horizontal. The proportion of horizontal wells as seen from this data is the smallest among all other fields. Three areas were identified within the field, two of which, located in the northern and southern zones of the field, were drilled both vertically and horizontally, while the third one, located between the two previous ones, was drilled only by vertical wells. Another distinguishing feature is the fact that the water injection within the field has not been started until now. The Figure 4 below shows the cumulative oil production over time from typical vertical and horizontal well within each of the selected areas.

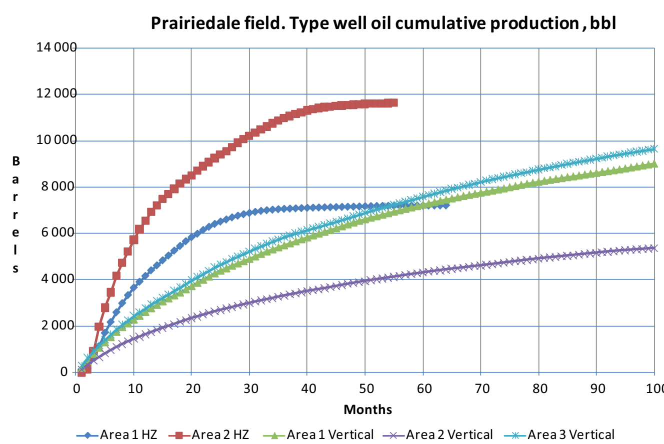

Fig. 4. Cumulative oil production over time from typical vertical and horizontal well within each of the selected areas

The oil production performance for these wells clearly illustrates the earlier statement that the main factor in the effectiveness of horizontal drilling (as well as vertical) and the stimulation methods applied to the reservoir within the Viking play is the geological characteristics and net pays of the formation within the analyzed area.

PlatoNorth Field

The first wells in this field were drilled in the late 1970s, but the active drilling of the northwestern part of the field began in the first half of the 1980s and during 1982-1986 period the entire vertical wells count was drilled. Some efforts to drill vertical wells

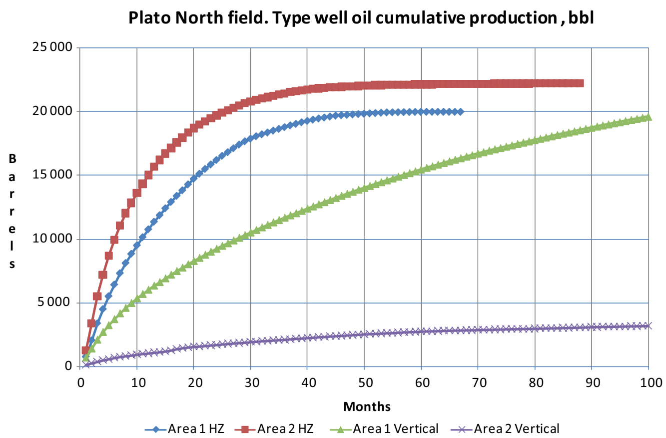

Fig. 5. Cumulative oil production and a typical vertical and horizontal well performance for each of the selected areas

in the southeast direction within the field have not been reasonably successful. Having said that, two areas were selected within the field, one of which was drilled both by vertical and horizontal wells (Area 1) and it covers the northwestern part. The second area is located in the southeastern part where only seven vertical wells were drilled but it did not lead to any noticeable results. In the same time drilling of horizontal wells within this area was much more successful and gets better results. Similar to other fields reviewed before, Figure 5 below shows the cumulative oil production and a typical vertical and horizontal well performance for each of the selected areas.

As can be seen from this data, horizontal wells drilling within Area 2 allowed increasing 7-8 times of recoverable oil volume per well.

In conclusion, it should be noted once again that the development of horizontal well drilling technology in combination with multistage hydraulic fracturing allowed the previously considered low-productive areas and development zones of the Viking play within the Saskatchewan province to be actively developed and recovered. Horizontal wells drilling made it possible to increase oil production in those formation zones that were previously considered predominantly gas-saturated, as well as in the zones affected by water injection using vertical wells in order to maintain reservoir pressure. Infill drilling reducing horizontal wells spacing to 200 meters between wells combined with the longer lateral length (up to 1,500 meters) also positively affected the oil reserves recovery from the Viking play.

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TECHNOLOGY OF MULTISTAGE HYDRAULIC FRACTURING IN HORIZONTAL WELLS: DEVELOPMENT EXPERIENCE OF SHALY CARBONATES IN THE US AND ITS OPTIMIZATION FOR THE FIELDS OF THE REPUBLIC OF TATARSTAN

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Abstract. The paper considers efficient development of Domanic reservoirs in Tatarstan using multistage fracturing technology in horizontal wells, based on the analysis of developing Shaly Carbonates in the United States, which are the closest in terms of geological and physical characteristics. Simulation in the software product GOHFER was carried out. Three types of multistage fracturing were considered: acid, proppant, and combined. Calculations show that practically all types of multistage fracturing with 5 stages are either not profitable, or are on the verge of profitability. Acid and combined multistage fracturing are the most effective at 10 stages; net discounted income for 5 years of operation is 90-100 million rubles. All three types of multistage fracturing are effective at 20 stages; acid and combined multistage fracturing are also characterized by the biggest net discounted income of 240-280 million rubles.

Keywords: Domanic reservoirs, multistage fracturing, horizontal wells, acid, proppant, net discounted income

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1. Introduction

For a long time it was believed that production of hydrocarbons in tight and shale reservoirs is economically unprofitable. Significant improvements in horizontal drilling, completion and stimulation technologies have led to a change in this view.

In the last decade the interest of US oil companies in shale and tight reservoirs has intensified, production reached a maximum in 2014. After the crisis and the decline in oil prices in 2015, the volume of hydrocarbon production from such reservoirs has significantly decreased. Nevertheless, after that, the companies managed to reduce the cost of a well with multistage hydraulic fracturing twice, optimizing costs. In 2016-2017 at an oil price of about $50/bbl. US oil companies have resumed development of shale and tight reservoirs. The production from these sediments is currently growing, which is due to the relatively high economic efficiency of their development. It is expected that unconventional hydrocarbon resources, especially shale and tight, will provide the main growth in oil and gas production, and also attract significant investment in their development.

Studies conducted by Tatneft PJSC show that oil source reservoirs (shale and tight) are distributed throughout the territory of the Republic of Tatarstan, their reserves significantly exceed the reserves of conventional oil. Therefore, taking into account the positive experience of the USA, the issue of similar development of oil deposits in the Republic of Tatarstan, with the exception of previous mistakes made by national and foreign companies, is of great interest.

The purpose of this paper is to show how to efficiently develop oil source Domanic reservoirs in Tatarstan using multistage fracturing technology in horizontal wells, based on the analysis of developing Shaly Carbonates in the United States, which are the closest in terms of geological and physical characteristics.

2. Geological and physical characteristics of Domanic deposits and Shaly Carbonates

Fig. 1 shows the scheme of three main types of rocks – sandstone, limestone and shale. In nature, the ratio of these rocks in different proportions is more common. Characteristics analysis of different types of rocks shows that the Shaly Carbonate reservoir in the United States are fairly close to the carbonate Domanic deposits of Tatarstan. A comparison of the main geological and physical characteristics of these reservoirs is given in Table 1. The main difference is in two-fold lower reservoir temperature and two-fold higher viscosity of oil of the Domanic deposits, which undoubtedly influences the oil filtration, which lowers the rate of its withdrawal in comparison with the Shaly Carbonates.

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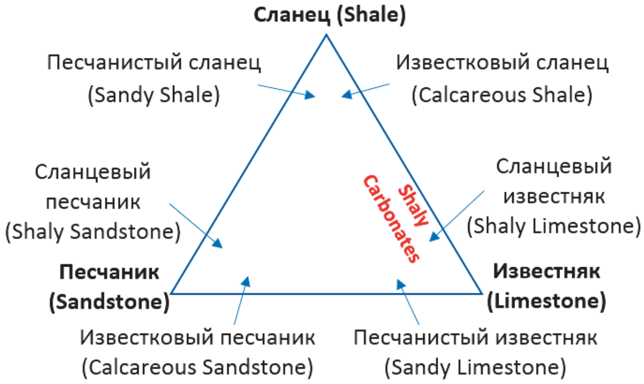

Fig. 1. Oil and gas provinces of shale and tight reservoirs of US fields

The largest oil deposits in the Shaly Carbonates in the United States belong to the provinces of EagleFord, Utica, Haynesville (Fig. 2). The rocks consist mainly of limestone, dolomite, clays, partially carbonate siltstones, siliceous and calcareous mudstones, sometimes sandstone impurities

3. Multistage hydraulic fracturing in horizontal wells

There are two fundamental and critical properties of unconventional reservoirs – low permeability and extremely small pore sizes compared to conventional

Characteristic	Unit	Domanic deposits	Shaly Carbonates
Reservoir depth	m	1700-1800	1600-1700
Net oil thickness	m	7-35	9-21
Reservoir temperature	^0C	35	70
Permeability	mD	0.001-1	0.001-0.2
Viscosity of oil	mPa*s	20-35	1.3-10
Gradient pressure in depth	MPa/m	0.0094	0.0094-0.01
Initial reservoir pressure	MPa	16-17	15-16
Initial oil saturation	%	60-90	40-80
Porosity	%	6-15	6-10
T_{max}	^0C	420-433	427-440
TOC	%	2-20	4-12
Clay content	%	2-18	4-25
Kerogen type	-	I, II	I, II

Table 1. Basic geological and physical characteristics of Domanic deposits in Tatarstan and Shaly Carbonates in the USA

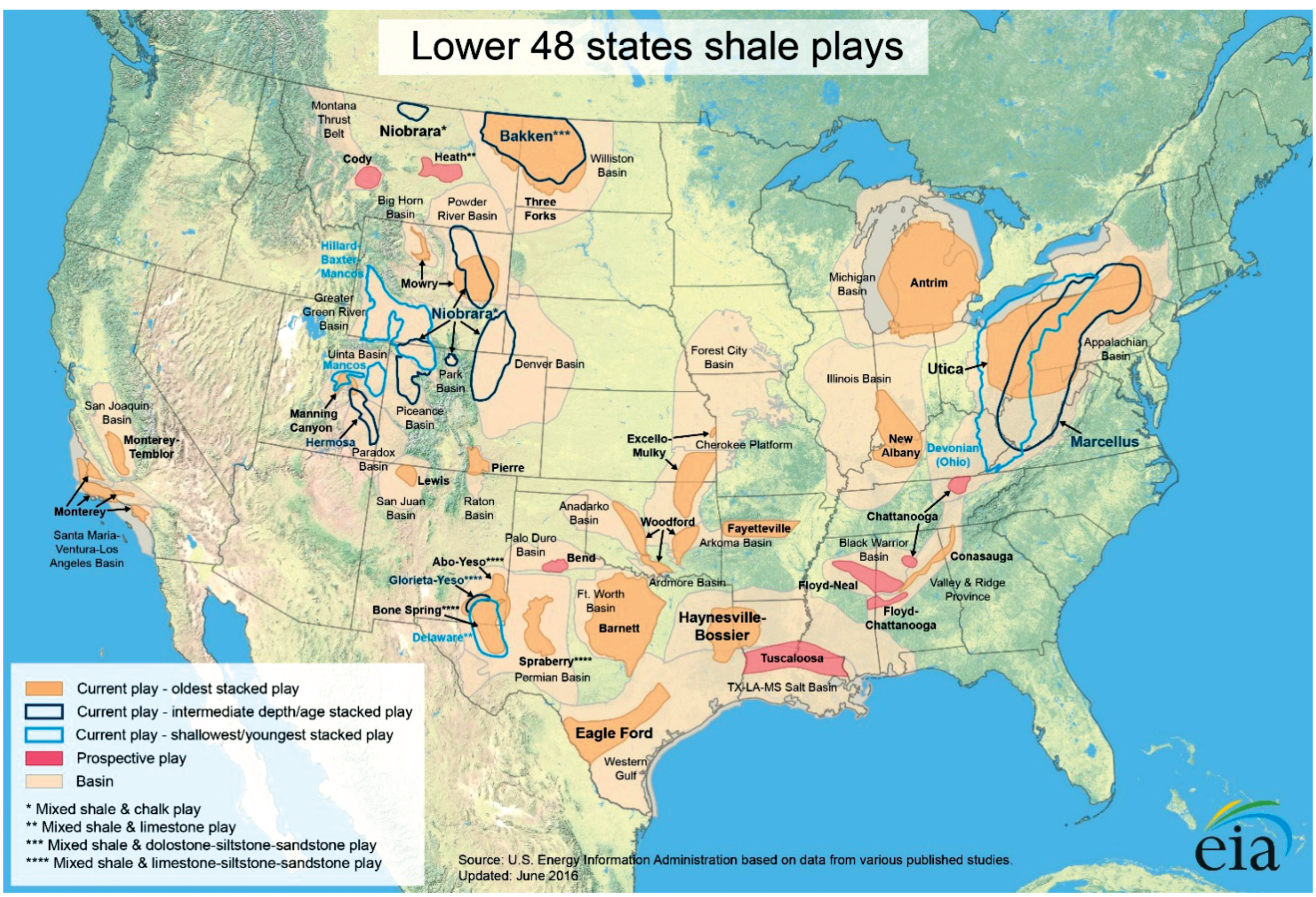

Fig. 2. Oil and gas provinces of shale and tight reservoirs in the US (according to Energy Information Administration – Agency for the collection, analysis and distribution of information on energy and energetics)

reservoirs. Very low permeability significantly hinders the filtration of hydrocarbons within the reservoirs. This means that hydrocarbons can be extracted only by natural or artificial fracturing of the formation. The main method for this is hydraulic fracturing.

An analysis of the works that are carried out in the USA before the modeling and design of the multistage fracturing showed that the standard set of studies includes:

1. SEM-Scanning Electron Microscopy. It determines the composition and structure of the rock at the pore level. Particular attention is paid to clay inclusions.

2. Thin section petrography. It describe in detail texture, rock skeleton, pore systems and minerals.

3. X-Ray Powder Diffraction. It determines the composition and structure of the rocks and inclusions.

4. Test for the content of TOC – Total Organic Carbon.

5. Test for determining VRo – Vitrine Reflectance. It determines the maturity of kerogen.

6. RCA – Routine Core Analysis. The properties of core samples are measured and used to construct petrophysical models.

7. Test for proppant embedment into the rock (Proppant Embedment Test). It determines the most effective fraction and proppant material. For rocks with high clay content, a larger fraction of the propane is used.

8. A complex of studies on migration of clay particles and determination of the critical salinity of working agents (Critical Salinity Test, Capillary Suction Time Test, Roller Oven Shale Stability Test, Erosion Test). It is necessary to select the optimal working agents for completion of the well and hydraulic fracturing, to prevent a significant decrease in the permeability of the reservoir.

9. Determination of capillary pressures.

10. Determination of the Young's triaxial modulus, Poisson's ratio, vertical and horizontal stresses of the formations.

In addition, it is possible to conduct special or additional studies.

In general, the complex of these studies, modeling, design of the multistage hydraulic fracturing, selection of working fluids and equipment allows to significantly reduce technical and technological risks, increase the economic efficiency of the project. The results of the works carried out in the USA on Shaly Carbonates are impressive. With a horizontal trunk length of 1600-3200 m, 20-40 stages of multistage fracturing, an initial oil production rate of about 130-200 t/d is obtained. The bulk of oil is extracted in the first 1.5 years. During this time, the reservoir pressure and, accordingly, the oil production rate drop rapidly. After 2.5-3 years, a second multistage fracturing is carried out, which allows extending the economically viable life of the well by another 2-2.5 years. All this allows, with an average drilling cost of $ 4 million (about 240 million rubles), to recoup capital costs for 6-12 months. In this case, after 3-5 years after putting the well into operation, the profitability index is 2.0-2.5 currency units.

A comparison of these indicators with the multistage fracturing conducted in 2015 in well 2917G for the Domanic deposits (Dankovo-Lebedyanian horizon) of the Bavlinsky oil field is given in Table 2. With a horizontal trunk length of 300 m, 4 stages of the multistage fracturing, an initial oil production rate of 12 tons/day was obtained. Capital costs for drilling, completion of wells and conducting acid multistage fracturing amounted to approximately $1.5 million (about 90 million rubles), the expected payback period is 5-10 years.

Thus, if we calculate the oil production rate of one well in Shaly Carbonates for a length of 270 m and 4 stages of the multistage fracturing, we will get 20-25 tons/day, which can be taken as potential production rate of well 2917G for Domanic deposits. To achieve this rate, it may be necessary to use large amounts of acid, as well as proppant, additional research and careful selection of working fluids. However, this issue requires additional study.

It should be noted that in spite of the vast experience of the USA in the field of multistage hydraulic fracturing

Parameter	Unit	Domanic deposits (well 2917G)	Shaly Carbonates (mean values)
Trunk length of the horizontal well	m	270	1600-3200
Stage numbers of multistage hydraulic fracturing	pcs.	4	20-40
The initial oil production rate	t/day	12	130-200
The main oil production period	years	-	1.5
Time through which multistage hydraulic fracturing is repeated	years	-	2.5-3
Period of well operation after repeated multistage hydraulic fracturing	years	-	2-2.5
The total life of the well	years	-	3-5
Capital costs per 1 well (drilling + completion + multistage hydraulic fracturing)	$ mln	1.5	4
Payback period	month	60-120	6-12
Cost-benefit index	cur.un	-	2-2.5

Table 2. Indicators comparison of multistage hydraulic fracturing conducted in well 2917G in the Republic of Tatarstan and on an average of Shaly Carbonates in the USA

in oil source deposits, Russia is also carrying out pilot commercial development. However, a review of the literature shows that most of the works relate to conventional low-permeability reservoirs (0.1-5 mD). The largest oil companies, such as Rosneft PJSC NK, Gazpromneft PJSC, Lukoil PJSC, Surgutneftegaz JSC, as well as their divisions, have been carrying out since 2013 in tight reservoirs both acid and proppant multistage fracturing in average of 4-8 stages per well. Comparison with vertical unstimulated wells shows that the oil production rate of horizontal wells with multistage fracturing is 4 times higher on average.

4. Computational simulation of multistage hydraulic fracturing in the Domanic deposits of the Republic of Tatarstan

Simulation in the software product GOHFER was carried out to assess the potential of the multistage hydraulic fracturing in the Domanic deposits of Tatarstan. The basis was a well Stoler-21-3N (North Dakota, USA) that penetrated Shaly Carbonates reservoir. The reservoir has similar mineralogy, depth of occurrence, and also petrophysical parameters, contains 30-45% limestone, 15% anhydrides, 35% dolomite, 1-10% clay. The average geological and physical characteristics correspond to the Domanic deposits in Tatarstan, the values are given in Table 1.

Three types of multistage fracturing were considered: acid, proppant, and also combined that includes cracks fixation by proppant after acid multistage fracturing. In each of the three types of multistage fracturing, three options are calculated, differing in the number of fracturing stages and, respectively, in the length of the horizontal well trunk. The length of the horizontal trunk for 5 stages is 300 m, for 10 stages – 550 m, for 20 stages – 1050 m. SlickWater (a fluid with additives for reducing friction) and Guar- 20 (guar-based resin fluid) were used as fracturing fluids. Ceramic proppant of low density was used, of CARBOECONOPROP and CARBOLITE grades, 20/40 mesh fraction, concentration 0.0275 kg/m^2. The acids were applied with 15% HCl and 2% KCl. The results of the calculations are given in Table 3.

Calculations show that practically all types of multistage fracturing with 5 stages are either not profitable, or are on the verge of profitability. Acid and combined multistage fracturing are the most effective at 10 stages; net discounted income for 5 years of operation is 90-100 million rubles. All three types of multistage fracturing are effective at 20 stages; acid and combined multistage fracturing are also characterized by the biggest net discounted income of 240-280 million rubles.

5. Conclusion

Taking into account the existing amendments to the tax legislation of the Russian Federation, which have exempted the Bazhenov, Abalak, Khadum and Domanic formations from taxation of mineral extraction tax for 15 years, it is necessary to accelerate the process of studying oil reservoirs and conduct pilot commercial development by the technology of horizontal wells with multistage hydraulic fracturing. The experience of foreign experts in this can significantly reduce the risks of developing such reservoirs. Nevertheless, it is unlikely that all the works

Characteristic		Acid multistage fracturing		Proppant multistage fracturing		Combined multistage fracturing	
		1 year	5 years	1 year	5 years	1 year	5 years
Volume of injected fluids per 1 stage of multistage fracturing, tons	SlickWater	114		127		132	
	Guar-20	-		170		-	
	15%HCl	132		-		132	
	2%KCl	19		-		-	
	CMHPG#35	57		-		106	
Mass of injected proppant per 1 stage of multistage fracturing, tons	CARBOLITE	-		59		-	
	CARBOECONOPROP	-		-		21	
Initial oil production rate, t/d	5 stages	34.0		33.5		56.3	
	10 stages	71.6		73.7		112.6	
	20 stages	143.2		147.4		225.2	
Accumulated oil production, thousand tons	5 stages	1.7	4.1	1.2	2.1	1.8	4.9
	10 stages	3.5	8.5	2.5	4.4	6.2	9.7
	20 stages	7.0	17.1	5.1	8.8	8.9	19.4
Total capital costs, mln rub.	5 stages	151.6	151.6	135.2	135.2	163.7	163.7
	10 stages	177.8	177.8	162.3	162.3	203.5	203.5
	20 stages	255.0	255.0	217.8	217.8	283.6	283.6
Net discounted income, mln rub.	5 stages	-41.8	-10.2	-40.9	-25.8	-49.0	16.1
	10 stages	-10.2	91.4	-21.0	14.6	-2.4	104.1
	20 stages	32.2	239.0	13.9	88.7	63.4	280.1

Table 3. Indicators comparison of multistage hydraulic fracturing conducted in well 2917G in the Republic of Tatarstan and on an average by Shaly Carbonates in the USA

and operations of the horizontal wells with multistage fracturing will be copied completely due to the presence of some distinctive features of the Domanic deposits in Tatarstan and Shaly Carbonates in the USA. First of all, this is the lower reservoir temperature and higher oil viscosity. Therefore, it is necessary to create our own modification of the multistage hydraulic fracturing technology for the development of Domanic deposits.

The main recommendations that can be learned from the development of Shaly Carbonates in the US and which can be recommended for Domanic deposits in the Republic of Tatarstan:

1. Use of proppant. In the USA, multistage fracturing is rarely used with acid injection, even in purely carbonate rocks. Many studies by US scientists show the closure of the multistage fracturing cracks in a short time. If an acid is used, the proppant is injected into the formed "wormholes".

2. Shank cementing. Statistics on the wells completion in oil source deposits in the United States shows that the number of wells with an open trunk is decreasing annually and now most of the new wells are completed with cementing and perforation.

3. Large length of horizontal trunk. A number of studies conducted for horizontal wells in Tatarstan shows that the effective length of the horizontal trunk is much less than the actual one and drilling horizontal trunks longer than 300-400 m can be economically not profitable. However, firstly, the research data include mainly open-hole wells, and secondly, do not include wells in tight reservoirs. Therefore, it is necessary to carry out additional studies for the drilling of wells above 1 km.

4. More stages of the multistage fracturing. The oil production rate is directly proportional to the number of fracturing stages, which in turn depend on the length of horizontal trunk. Therefore, in the US, less than 20 stages are rarely used. For the Domanic deposits, the main obstacle to increasing the stages is the technical side – the need for more expensive equipment.

Application of chemicals and temperature. The viscosity of oil in reservoir conditions of 20-35 mPa*s for conventional reservoirs is not a problem. However, filtration is greatly complicated for Domanic deposits with ultra low permeability. Therefore, it is recommended to carry out research and pilot commercial development on the use of chemicals during the multistage fracturing, or the use of heated working fluids.

Maintenance of the reservoir pressure. In the US, water injection is used in a reservoir with a permeability of up to 1 mD. For permeability with lower values, research is currently conducted on injecting CO_2.

Thus, for the successful development of Domanic deposits in the Republic of Tatarstan with the use of multistage hydraulic fracturing in the horizontal well, it is necessary to conduct full-scale research, starting with the study of the formation and structure specifics of these reservoirs, geochemistry, geophysics, geomechanics, etc., the collection and analysis of all geological and geophysical information, creation of geological, hydrodynamic, geomechanical and other models, horizontal well designing and its completion, design of the multistage hydraulic fracturing, and finishing with the selection of working fluids and equipment for drilling, opening and multistage hydraulic fracturing. All this, according to the experience of the United States, allows minimizing all risks and, accordingly, obtaining economically efficient oil production from oil source deposits.

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EXPENDABLE TUBULARS AND CONTROLLED OIL AND WATER WITHDRAWAL INCREASE OIL FIELDS PROFITABILITY

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Abstract. The article describes the achievements of Tatneft PJSC in the field of isolating water inflow zones in horizontal wells by expandable cross-sectional profile pipes. An example of the isolation of water inflow zones on a well that left the production for three years due to 100% water cut is given, and the dynamics of its operation for 16 years after insulation by two expandable profile packers is shown. Technologies and technical means for regulating oil and water flows in horizontal wells, multi-channel well designs for simultaneous targeted impact and operation of different sections of the reservoir (deposit) are presented. An example is given of the separation of a horizontal well into two segments controllable from the surface and graphs are shown of the dynamics of bottomhole pressures in segments obtained during the well operation. The most promising directions of science development are shown to simplify well designs and improve the quality of their fixation by cardinally solving complications emerged during the drilling process, as well as to increase the productivity of wells by controlling the flow rates of liquids that are extracted from several heterogeneous zones of oil deposits.

Keywords: isolation of water inflow zones, expandable casings, inflow control valves, multi-channel well design, multi-channel lift pipes, well designs, lateral horizontal trunks, profile packers, profile uncoupler, electrical isolator, wireless communication, production rates and water cut of individual areas
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One of the most serious negative factors of the late stage of development in oil deposits is an increase of water cut, which is accompanied not only by a decrease in oil production rates, but also by the occurrence of extensive network of water-saturated channels (reservoirs) between production and injection wells, as well as between aquiferous and oil-bearing interlayers. When drilling wells with horizontal end, the probability of crossing these channels increases, which leads to a rapid flooding of the horizontal trunk.

Well 11251 (Fig. 1) of the Sarapalinsky field was drilled at the end of 1991 into the productive carbonate deposits of the Tournaisian. A year later, the well was flooded to 100%, which led to well decommissioning from production for three years. It took 8 months to find the point of water inflow by geophysical methods and packers (Abdrakhmanov et al., 2003). Then the intervals of water inflow were isolated by two expandable cross-sectional profile packers, and the well was returned to production with an oil production rate of 18-12 tons/day for 16 years (Fig. 2).

Important results for field development were obtained during research and controlled operation of horizontal well 41502g of the Romashkino field (Takhautdinov et al., 2013), drilled in the Bobrikovian horizon and divided into 2 segments using an expandable profile uncoupler (Fig. 3). For 2,5 years of operation of the nearby field, with the highly watered far segment turned off, the accumulated oil production amounted to 12,000 tons, water production – 9,000 tons, and if the horizontal trunk operated along the entire length (i.e. without valves), oil production would be 2 times less, water – 1.7 times more.

On the well 41502g, the dynamics of bottomhole pressures were studied during the operation of two segments simultaneously, and separately – the far and near sections, ***without stopping the operation of the well.***

According to the study, after 15 months of operation (Fig. 4), it can be seen that:

- when the two segments are operated together, the difference in the bottomhole pressure between them is 0.06 MPa;
- when the far segment is operated with the near one turned off, the pressure drop between the segments is 0.25 MPa;
- when the lower valve is choke restricted, the pressure drop is almost the same as for the simultaneous operation of two segments, but the water cut is reduced by 11% and the oil production rate is increased by 1 ton/day.
- with a fully closed lower valve and operation of the near segment, the pressure difference between the sections is 0.75-0.85 MPa, the bottomhole pressure in the near segment decreased by 0.6-0.8 MPa, while the

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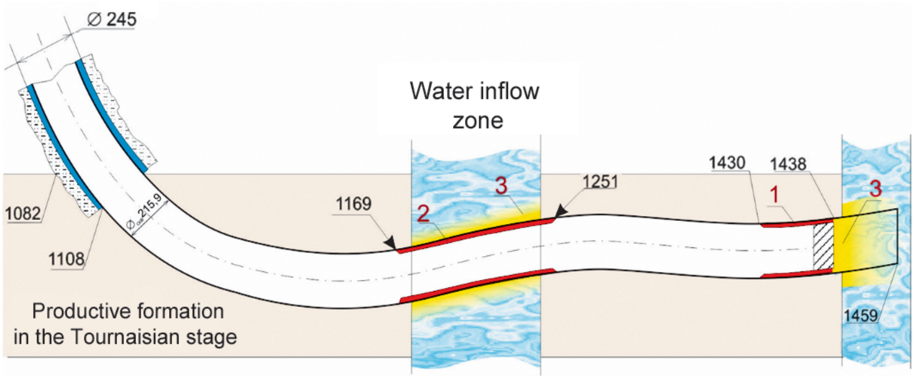

Fig. 1. Isolation of water inflow zones in a horizontal well 11251 with two profile packers of 8 m and 82 m in length

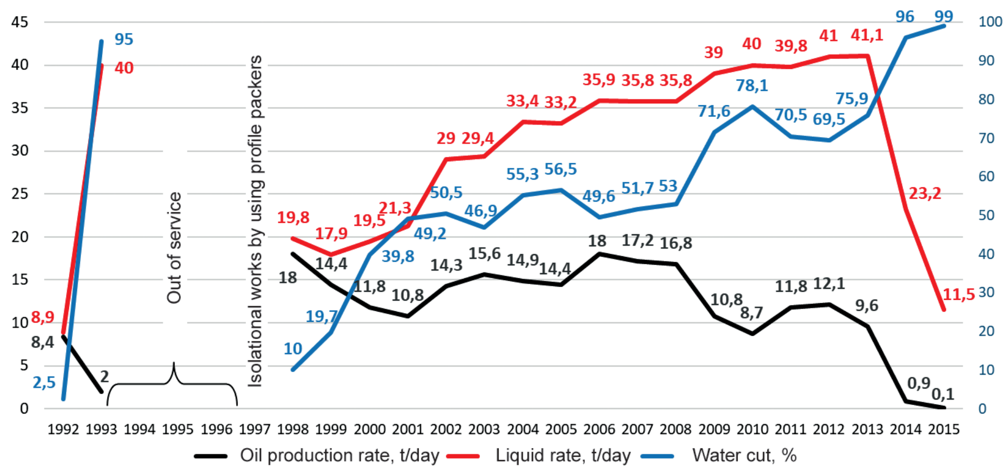

Fig. 2. Dynamics of production rate of well 11251g of the Sarapalinsky field after isolation of the water inflow zones by profile packers

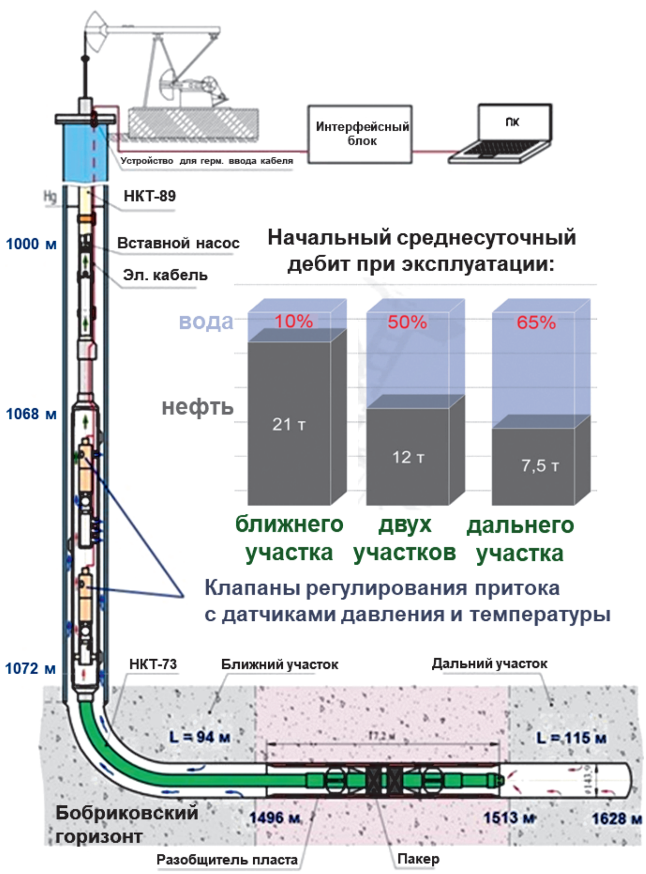

Fig. 3. Schematic location of the equipment for controllable from the surface operation of a horizontal well divided into 2 segments (well 41502g)

water cut decreased by 50 %, and the oil production rate increased by 10 tons/day.

Thus, the disconnection from the production of a highly watered interval allows not only to reduce the volume of produced water, but also to increase the difference between reservoir and bottomhole pressures in other oil-bearing intervals, which substantially increases the oil flow rate of the horizontal well.

Interesting data on the dynamics of bottomhole pressures in this well occur when the injection well is switched on and off (Fig. 5). In spite of the fact that the curve of bottomhole pressure change in the near segment is 7-8 hours ahead of the same graph of the pressure change in the far segment, the difference in bottomhole pressures in the range of 0.73-0.77 MPa between segments of the horizontal trunk is preserved regardless of the increase and decrease in the reservoir pressure. That is, even in the same reservoir in a horizontal well, decompressed intervals, separated by impermeable or low-permeable rocks during separation and targeted impact, work independently with different water cut and different oil rates.

Based on the results obtained for the wells given above, a large number installed in the wells of expandable casing pipes instead of intermediate casing strings (more than 1650 wells), we propose the following ways (italicized in the paper) to develop expandable

Fig. 4. Dynamics of bottomhole pressures and liquid production rates after switching flow regulation valves for well 41502G

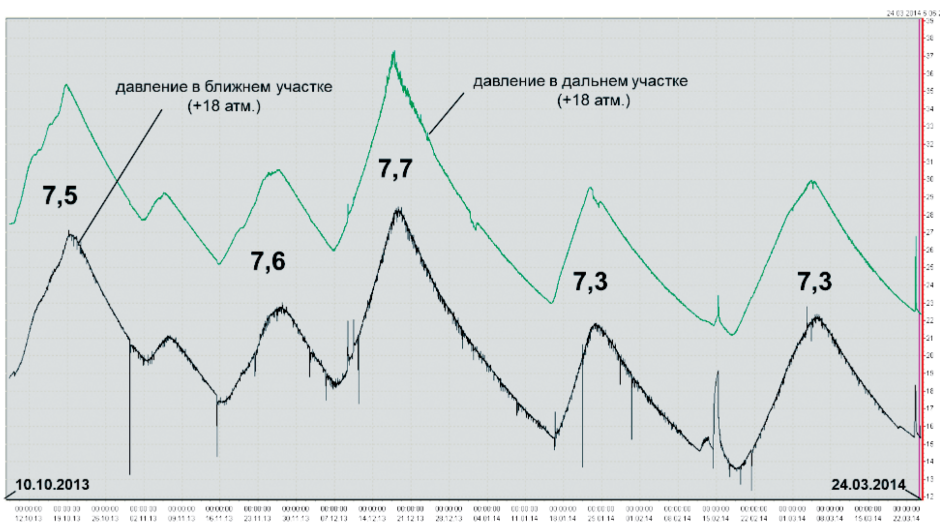

Fig. 5. Effect of cyclic operation of the injection well on the dynamics of bottomhole pressures in well 41502G in the process of oil production from the near segment.

tubulars and technologies for controlled oil and water withdrawal.

Development of technology and technical means for regulating oil and water flows in horizontal wells is shown in Fig. 6.

The specified technology will allow:

1. Withdraw fluid from different segments of the horizontal well and cut out highly watered intervals without interrupting oil production;

2. Apply a cyclic operating method;

3. Increase the current oil recovery factor;

4. Perform continuous monitoring of bottomhole pressure of each site.

Within the framework of this technology it is planned to create:

- cut-offs with wired and wireless communication;

- technology and equipment for installation in a horizontal trunk of any number of uncouplers for a single tripping operation;

- packer elements, triggered on a single technological operation, regardless of their number.

Creation of multi-channel well designs for simultaneous targeted impact and operation of different sections of the reservoir (deposit)

With long-term exploitation of oil fields, when production of small volumes of oil from the reservoirs becomes unprofitable, it is especially important to create special technical and technological solutions to separate and simultaneously operate several inhomogeneous productive zones, opened by one well.

The creation of multi-channel well designs for simultaneous targeted impact and operation of different sections of the reservoir (deposit) will significantly

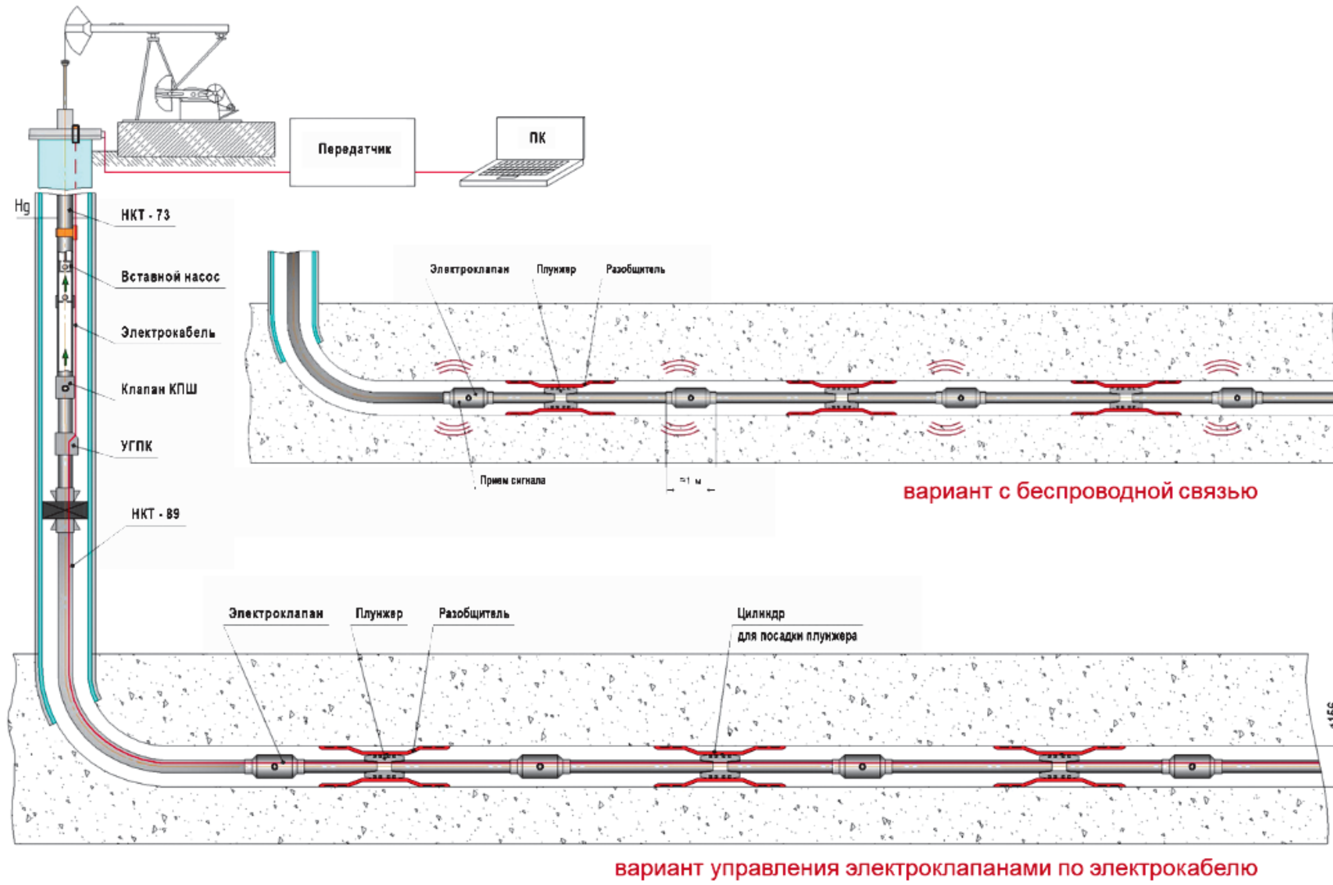

Fig. 6. Layout of the equipment for oil and water flow control in horizontal wells

reduce capital investments in the development of deposits and increase the profitability of oil production.

The technology is based on the separation of the horizontal trunk into segments and the use of multi-channel lift pipes and individual pumps for each segment of a horizontal well, operating from a single hydraulic drive equipped with a flow switch (Fig. 7).

The production rate of the well will be equal to the sum of the production rates of the individual productive intervals. Options of multi-channel lift pipes can be quite different. For example, they can consist of a set of tubes or a six-beam profile pipe sealed between two cylindrical pipes, and also of a package of lightweight hoses. The connection of individual multi-channel pipes is carried out with the help of special multi-channel clutches and

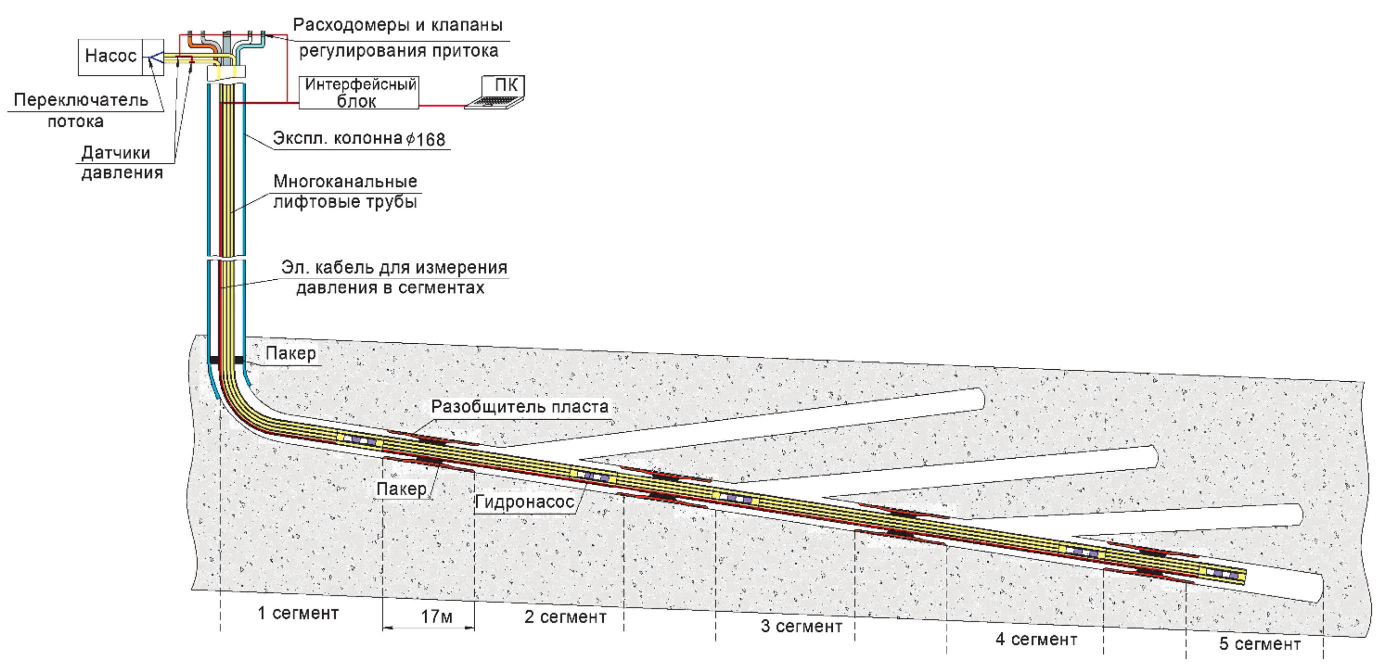

Fig. 7. Schematic diagram of the well designed for simultaneous controlled oil withdrawal from all the trunks of a multihole well

locks, triggered by axial movement of one part of the coupling into the other, i.e. without rotation.

The hydraulic pump consists of a hydraulic drive and a pump part. The capacity of each pump is adjusted from the surface by means of cranes installed at the output of all channels. Pumps operate independently from each other. By switching the flow direction of fluid in the pump installed at the wellhead, a constant computed fluid withdrawal takes place from each interval.

An even greater effect can be obtained from the application of this technology in multi-trunk wells.

The advantages of this method allow to:

1. Increase the production rate of oil by simultaneously withdrawing fluid from each trunk of multihole well or each segment of horizontal well using separate pumps.

2. Continuing the operation process, reduce the water cut of the production and conduct the bottomhole treatment in the required intervals.

3. Manage the profile of oil inflow in the zone of the horizontal trunk, due to differentiated effects on different **intervals** of the reservoir.

This method is being developed for the first time in the international practice of well construction and will be of great interest not only for Russian but also for foreign oil companies.

The creation of such equipment will be the beginning of a new more rational approach to the development of oil fields – with the exception of withdrawal of huge water amounts, with simultaneous increase in the oil recovery factor and a significant reduction in its cost.

Simplification of well designs with a simultaneous increase in the quality of fastening

To ensure work safety and environmental protection in the process of drilling and operation of wells, all intervals with different reservoir pressures, rock falls and shedding should be covered by casing pipes. However, in complex mining and geological conditions, the well crosses a large number of such formations, and the worldwide fastening technology with telescopic arrangement of intermediate casing strings does not always allow meeting these requirements.

For example, in a foreign reference book of an oil engineer (Spravochnik inzhenera-neftyanika ... [Guide book of an oil engineer], 2014), one of the options of the conventional design of a deep well is given (Fig. 8, a), which provides for the separation of formations by ten casing strings with a ratio of diameters at the beginning and end of drilling 10:1. Seven of them are intended for overlapping of multi-pressure strata and landslide zones. In the process of drilling, such a telescopic structure cannot be changed and if additional complications arise, the well will need to be re-drilled, providing additional intermediate casing strings.

No.	Length of profile packers, m	Time required for their installation, hours	
1	128,6	58	Installation of six profile packers using punches with simultaneous drilling and expansion - 9.5 days
2	157	48	
3	88	37	
4	140	34	
5	51,5	28	
6	70,6	22	
7	120	264	Installation of profile packers with additional expansion and dispensing of expanders - 11 days

Table 1. Data on the length of profile packers and the time required for their installation in well 18

Drilling of well 18 was carried out in the particularly difficult mining and geological conditions of the Aleksandrovsky field of JSC Tatneft-Samara, using ten casing strings, including seven columns of expandable profile pipes to block the absorption zones of the drilling mud and rock falls under the patent of Tatneft PJSC (Fig. 8, b). In this case, the sixth string is installed over five casing strings already installed in the well, as the hope of isolating this zone by the filler overwash was not justified, that is, the technology of local fastening of wells allows changing the design even during drilling. The table gives data on the length of profile packers and the time required for their installation in well 18. Thus, even in difficult mining and geological conditions, a well can be built on a schedule without complications with significant savings in casing, cement and time. That is why the technology of local fastening of the well walls by expandable pipes has gained worldwide recognition.

A big impact on the world economy is the drilling of wells offshore, which is a global multi-billion dollar business with great prospects. The offshore drilling challenges a difficult task – to ensure the profitability of all production processes, while fulfilling strict requirements for safety and environmental protection.

All this is mainly related to well designs (Fig. 9). According to conventional designs, the deeper the well, the longer intervals it takes to drill without casing, and the higher the likelihood of complications. In addition, many problems in the process of exploitation are closely related to the complications in drilling. For example, inter-casing flows or cement stone of a poor quality behind the casing in the intervals of large caverns and others.

Therefore, when developing deep-water productive deposits, the quality and timeliness of fastening wells during drilling significantly affects the economy and profitability of the project.

Fastening wells with expandable tubulars fundamentally solves this problem in combination with

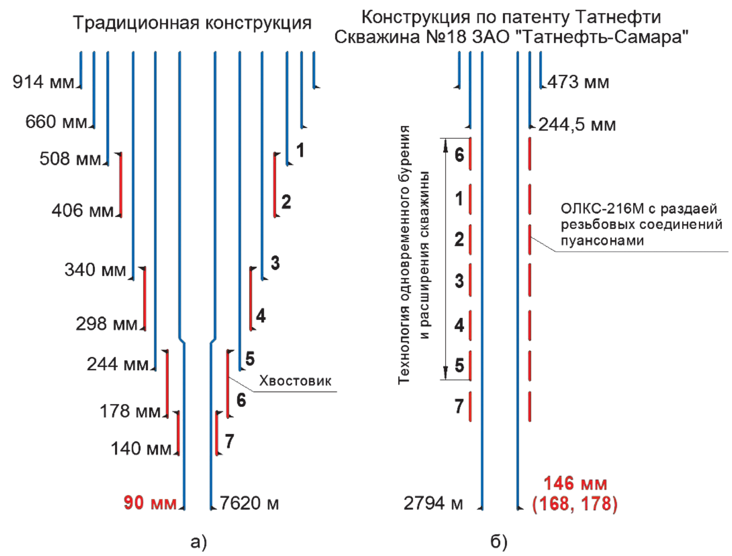

Fig. 8. Designs of oil and gas wells crossing a large number of formations requiring overlapping by casing pipes during drilling. OLKS-216M – the modernized equipment for local fastening of well walls with a diameter of 215.9 mm

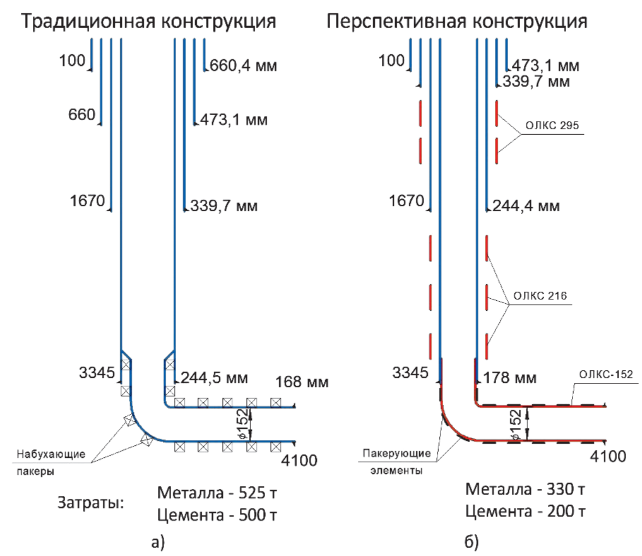

Fig. 9. Examples of offshore structures: The conventional design is the construction of wells with the elimination of complications by pumping plugging material into the well; a promising design is the construction of wells with the use of expandable tubulars

intermediate casing strings, which will only be used in the presence of high pressure formations.

A perspective diagram of offshore well designs shows the possibility of drilling according to the schedule without complications. All the zones of absorption of drilling mud, shedding and rock falls are overlapped immediately after opening. At the same time drilling in these intervals is conducted with simultaneous expansion of the wellbore and logging.

The advantage of this design is the ability to overlap by casing pipes of all multi-pressure formations and landslide zones with simultaneous reduction of metal and cement costs and an increase in the quality of fastening of intermediate and production columns.

Expandable tubular technologies of Tatneft PJSC are currently applicable in the development of such a project for any oil and gas producing company first on experimental wells and then on a large scale.

Conclusions

1. The operation of multi-segment and multi-hole wells controllable from the surface makes it possible to increase the oil recovery factor and to substantially limit the inflow of water from the reservoirs.

2. The use of multi-channel lift pipes and individual hydraulic pumps for simultaneous oil production from heterogeneous sections of deposits will lead to a significant reduction in capital investments in the development of oil fields.

3. Experience in the use of profile packers shows that one of the most promising areas of development of science and practice in the field of well construction is the concept of drilling with a simultaneous increase in the diameter of the trunk and subsequent overlap with expandable tubulars of all zones of possible complications immediately after their opening, except formations with anomalously high pressure, which are overlapped by intermediate casing strings.

Such a technology, apart from the elimination of many complications and accidents in the drilling process, will bring significant revenue in the development of oil and gas fields due to improved quality of fastening wells, and hence the period of their maintenance-free operation.

References

Abdrakhmanov G.S. Fixing wells with expandable pipes. 2 ed. Moscow: VNIIOENG. 2014. 267 p. (In Russ.)

Abdrakhmanov G.S., Yusupov I.G., Orlov G.A. et al. Isolation of water inflow zones in directional and horizontal wells. *Neftyanoe khozyaistvo = Oil industry*. 2003. No. 2. Pp. 44-46. (In Russ.)

Spravochnik inzhenera-neftyanika [Guide book of an oil engineer]. V. 2. Inzhiniring bureniya [Drilling engineering]. Ed. Larri Leik; Roberta Mitchella; Eng. Ed. A.G. Shatrovskii, S.O. Borozdin. Moscow-Izhevsk: Institute for Computer Research. 2014. 1033 p. (In Russ.)

Takhautdinov Sh.F., Khisamov R.S., Ibatullin R.R., Abdrakhmanov G.S., Vakhitov I.D., Nizamov I.G. Controllable operation of horizontal wellbore intervals. *Neftyanoe khozyaistvo = Oil industry*. 2013. No. 7. Pp. 26-27. (In Russ.)

Takhautdinov Sh.F., Ibragimov N.G., Ibatullin R.R., Abdrakhmanov G.S., Akhmadishin F.F., Khamit'yanov N.Kh. Development of expandable technique and technology for trouble zones isolation. *Neftyanoe khozyaistvo = Oil industry*. 2008. No. 7. Pp. 34-38. (In Russ.)

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ROLE OF HORIZONTAL WELLS AND HYDRAULIC FRACTURING IN INCREASING THE EFFICIENCY OF OILFIELD DEVELOPMENT USING THE EXAMPLE OF OIL AND GAS PRODUCTION DEPARTMENT «AZNAKAYEVSKNEFT» TATNEFT PJSC

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Abstract. At a late stage of development, with deterioration in the structure of reserves, the use of advanced technologies and development principles helps to maintain the level of oil production and fully develop reserves. Technologies such as drilling horizontal wells and hydraulic fracturing are undoubtedly technologies with a wide range of applicability at various sites and in different mining conditions. It is especially important to use development systems with horizontal wells in fields with high geological heterogeneity, stratification, presence of numerous replacement zones of reservoirs, zones of wedging, sections of thin reservoirs. Such complex objects include terrigenous sediments of the Bobrikovian horizon of deposits No. 2,3,33 and carbonate sediments of the Kizelian horizon of deposits No 281, 292 of the Romashkino field.

Horizontal technologies for the purpose of involving reservoirs of the Bobrikovian horizon have been actively used since 2015. More than 40 wells with an average increase of more than 15 tons per day have been drilled, this is one of the main factors of production growth in the upper horizons. In 2016, a horizontal well No. 3745G with an input rate of 10.9 tons per day was built on the Kizelian horizon, which is 7 times higher than the production rate of vertical wells.

Main results and achievements of Oil and Gas Production Department «Aznakayevskneft» Tatneft PJSC in the field of horizontal drilling and hydraulic fracturing are considered. According to the strategy of Oil and Gas Production Department, it is projected to drill 55-60 horizontal wells and carry out 20-30 fracturing processes in horizontal wells every year until 2025.

Keywords: horizontal wells, hydraulic fracturing, oil recovery, low-permeability reservoir
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The most rational direction of increasing the oil recovery factor of hard-to-recover reserves is the transition to fundamentally new systems of field development. Horizontal wells, having a large penetration area, reduce the filtration resistance and are an effective method of not only increasing the productivity of wells, but also the oil recovery of reservoirs.

It is especially important to use development systems with horizontal wells in fields with high geological heterogeneity, stratification, presence of numerous replacement zones of reservoirs, zones of wedging, sections of thin reservoirs.

Such complex objects include terrigenous sediments of the Bobrikovian horizon of deposits No. 2,3,33 and carbonate sediments of the Kizelian horizon of deposits No 281, 292 of the Romashkino field. The annual production of the Bobrikovian horizon is increased due to the drilling of horizontal wells. With one of the highest annual rates in the company (11.9% per annum), the efficiency of the geological and technical measures allows to restrain the water cut of the extracted products. Designed oil recovery factor is 0.359, actual – 0.260 (Fig. 1, 2).

Horizontal technologies for the purpose of involving reservoirs of the Bobrikovian horizon have been actively used since 2015. More than 40 wells with an average increase of more than 15 tons per day have been drilled, this is one of the main factors of production growth in the upper horizons (Fig. 3, Table 1).

Increase in drilling volumes for carbonate reservoirs in 2015-2016 allowed to increase production. Production growth in 2016 was 30% (Fig. 4).

Deposits of carbonate reservoirs of Oil and Gas Production Department Aznakaevskneft have small dimensions and small oil-saturated thickness (4-6 meters). The development of such reservoirs by conventional methods is ineffective, in the current economic conditions it is unprofitable.

In 2016, a horizontal well No. 3745G with an input rate of 10.9 tons per day was built on the Kizelian horizon, which is 7 times higher than the production

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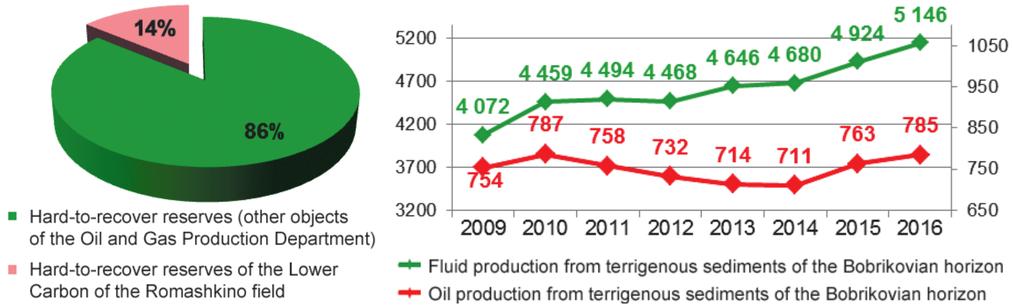


	2009	2010	2011	2012	2013	2014	2015	2016
Hard-to-recover reserves production rate	6,4	7,1	7,4	7,7	8,1	8,8	10,4	11,9
Water cut, %	81,5	82,4	83,1	83,6	84,6	84,8	84,5	84,8
Produced from initial recoverable reserves, %	47,6	51,3	54,9	58,4	61,7	65,1	68,7	72,4

Fig. 1. Dynamics of development indicators for the Bobrikovian horizon of the Romashkino field of the Oil and Gas Production Department Aznakaevskneft

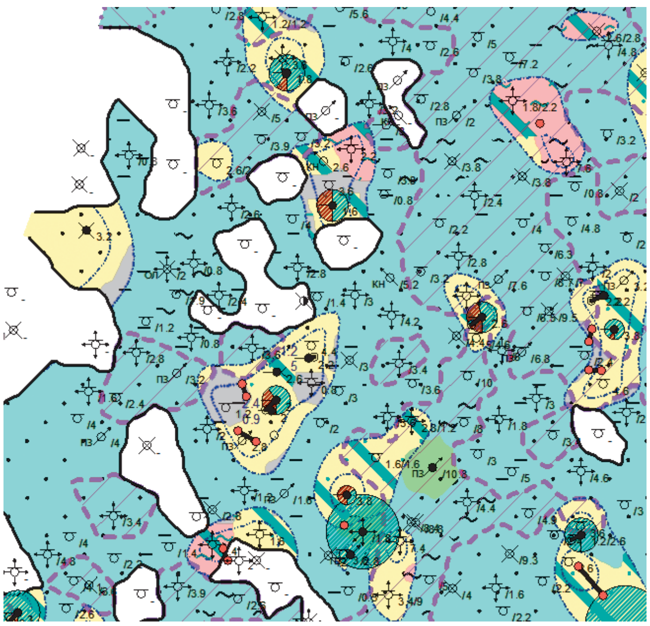


Fig. 2. Compilation of the development map of deposit No. 3 of the Romashkino field

rate of vertical wells. The construction of wells on the Kizelian horizon of deposits No. 281, 292 is actively developing. In 2017, it is projected to drill 15 horizontal wells on carbonate sediments (Fig. 5). 10 wells were put into operation with a current production rate of 6.5 tons per day. However, even penetration of the carbonate reservoir with a horizontal trunk does not always ensure economically justified production rate.

Because of the natural inefficiency of carbonate sediments, an essential condition for intensification is the conduct of bottomhole treatment to create cavernous zones along the trunk, caverns of storage. In recent years, the implementation of hydrochloric acid treatment in the bottomhole zone using a jetting nozzle has been widely used. The technology consists of a hydromonitor treatment with the help of coiled tubing along the entire length of the trunk with the intermittent injection of acid. The treatment of horizontal trunks due to the "excision" in the rock of additional oil supply channels

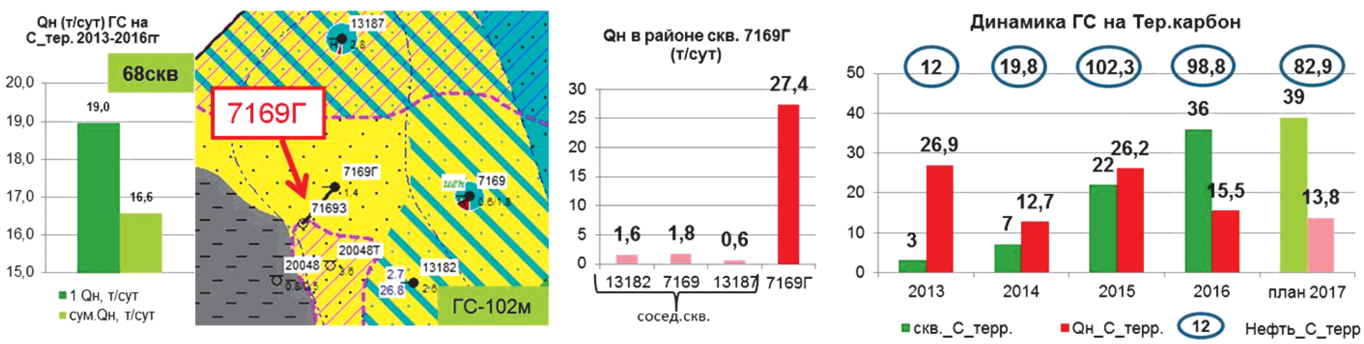
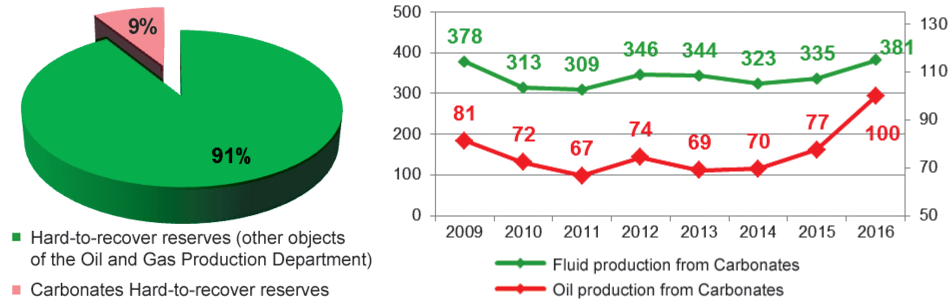


Fig. 3. Application of horizontal drilling on the objects of the Bobrikovian horizon

	2015		2016		2017	
	Number	Production, tons	Number	Production, tons	Number	Production, tons
Drilling of horizontal wells on Bobrikovian horizon	6	18720	18	55414	17	22854
Cutting off the sidetrack, horizontal sidetrack along the Bobrikovian horizon	3	1898	28	38668	6	5926
Drilling of horizontal wells on carbonate sediments	0	0	2	1815	14	20042

Table 1. Dynamics of drilling, cutting of lateral and horizontal holes on Bobrikovian, Kizelian, Dankovo-Lebedyanian horizons



	2009	2010	2011	2012	2013	2014	2015	2016
Hard-to-recover reserves production rate	1,9	1,7	1,6	1,9	1,7	1,8	2,0	2,6
Water cut, %	78,5	76,9	78,4	78,5	80,0	78,5	76,9	73,8
Produced from initial recoverable reserves, %	42,2	43,2	44,1	45,1	46,0	46,9	48,0	49,3

Fig. 4. Dynamics of development indicators for carbonate deposits of the Romashkino field of the Oil and Gas Production Department Aznakaevskneft

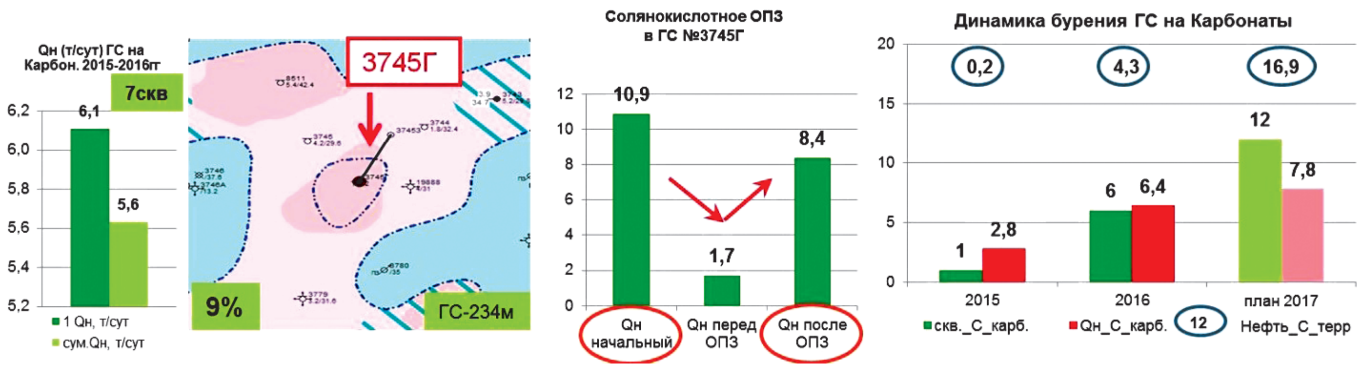


Fig. 5. Application of horizontal drilling on the objects of the Kizelian horizon

(cracks) makes it possible to increase the efficiency of acid treatment. In addition, periodic acid treatments with a constant feed through the "tubes" without lifting the downhole pumping equipment should allow maintaining the production rate during operation.

With the current depletion of reserves, much attention is paid to the search for oil in the transit horizons. Such deposits include the Aleksinskian horizon. Attention to these deposits was inadequate due to the extremely complex geological structure: lace, head-shaped forms of the deposit, often represented by lenses and a rare oil occurrence during drilling. Lithological heterogeneity and substitution are characteristic. At core sampling, oil saturation signs were detected only in one of 18 wells.

After delineating the deposit, the location of five horizontal wells with small diameter was chosen, two of which were drilled this year. According to the results of development, the well has no flow. After the hydraulic fracturing, an inflow was obtained. The current flow rate of the liquid is 10 m3/day, Qoil = 6.1 t/day, water cut = 31%. As a result, the further drilling of the well section No. 18318G with the hydraulic fracturing was continued (Fig. 6).

The process of building horizontal wells is constantly evolving. One of the directions is the development of Russian-made near-bit modules, which will allow to abandon the final logging. In the horizontal well No. 6110G of the East Leninogorsk area, a LWD logging tool was used while drilling by the VNIIGIS-ZTK company. The bottomhole assembly included a near-bit module with gamma-ray sensor, and a downhole telesystem with inductive electro-magnetic, gamma-ray, neutron-neutron sensors. The current production rate of 40 t/day is provided by the involved interval (Fig. 7).

It is not possible to achieve significant indicators, without the constant search for the technology that involves reserves of various horizons and taking into account the depletion and reservoir characteristics. The Pashian deposits of the Romashkino field are no exception. Beginning in 2012, 12 horizontal wells drilled with an initial average oil production rate of 12 tons/day for the development purpose of the washed oil zones of the terrigenious Devonian. In 2016 horizontal well No. 4619G was drilled in Aznakayevsk area, oil production rate of which is 2-5 times higher than the adjacent vertical wells. In order to extract hard-recoverable oil reserves 48 horizontal wells have been drilled with average oil production rate of 10 t/d (Fig. 8).

The increased interest in hydraulic fracturing is explained by the fact that it can be considered as an element of a system for developing reserves of low-permeability reservoirs (the share of which has grown

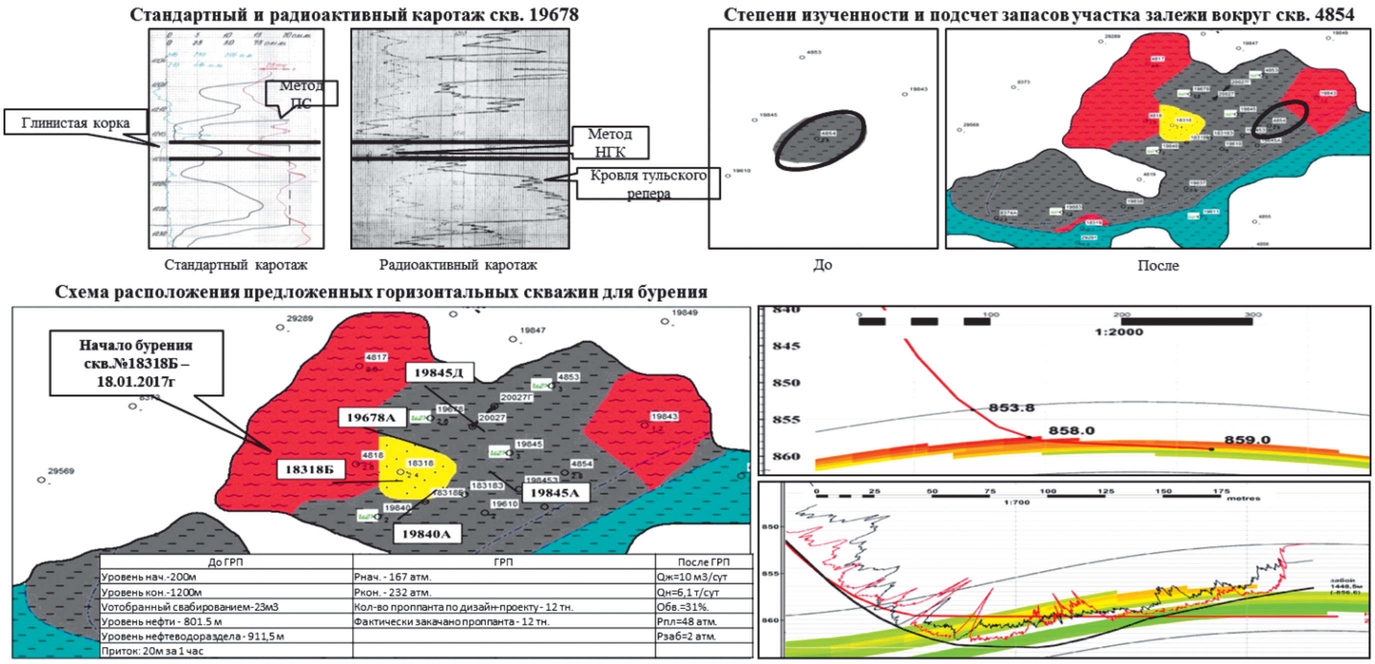


Fig. 6. Involvement in the development of reserves of the Aleksinskian horizon

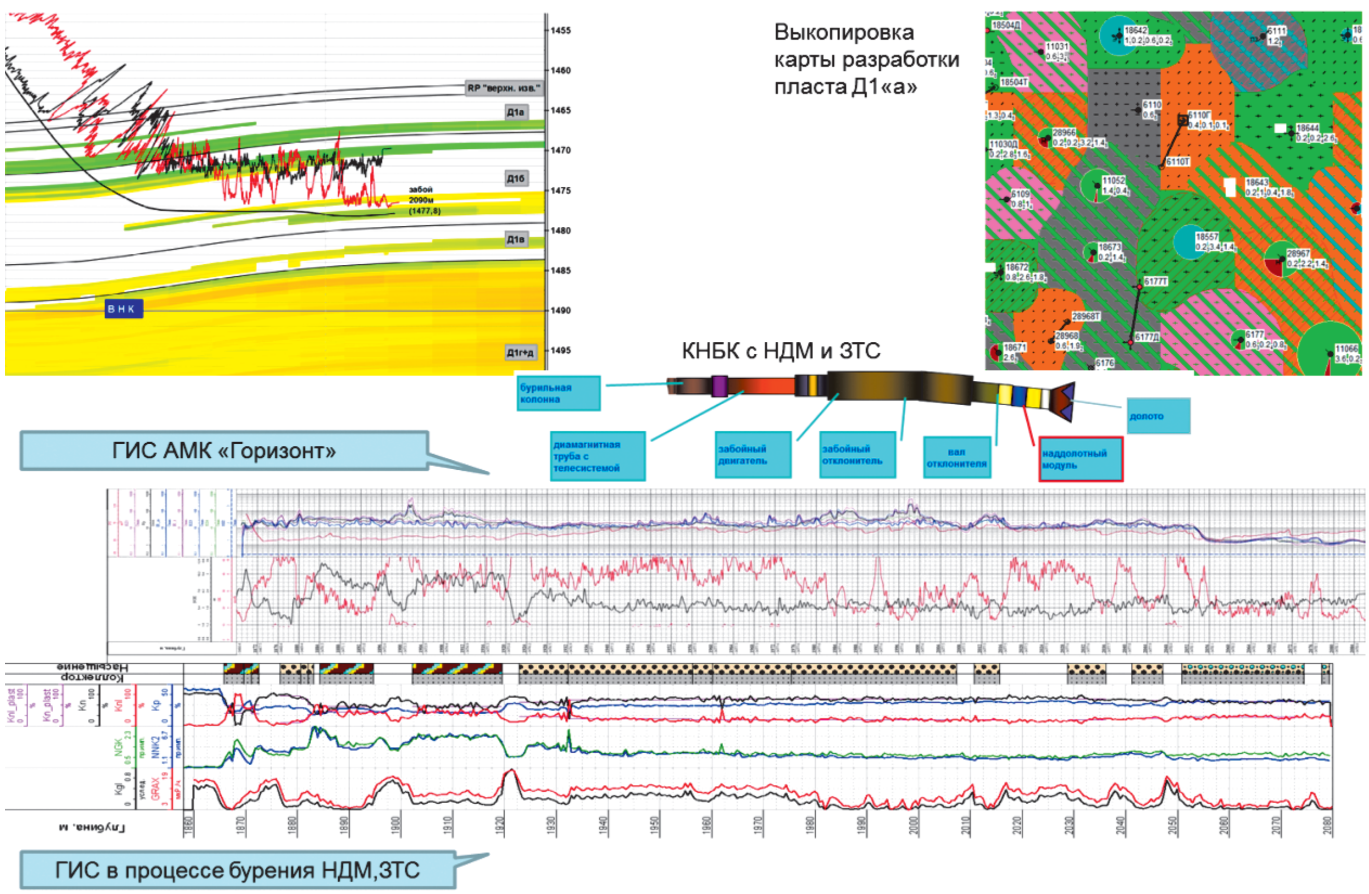


Fig. 7. Logging while drilling well No. 6110G of the East Leninogorsk area

significantly). Hydraulic fracturing affects not only the bottomhole zone, but also the remote sections of the reservoir, and thereby contributes to enhanced oil recovery. In addition, the hydraulic fracturing method is the most powerful method for treating the bottomhole zone, which is capable of creating artificial channels in the reservoir with sufficiently large length.

Hydraulic fracturing in Russia in recent years is being revived on a new technological and technical basis. The reason is mainly due to the fact that for many development facilities with low-permeability reservoirs, there are simply no alternative methods. Only hydraulic fracturing allows intensifying low-productive wells, including weakly draining zones of the reservoir. Of

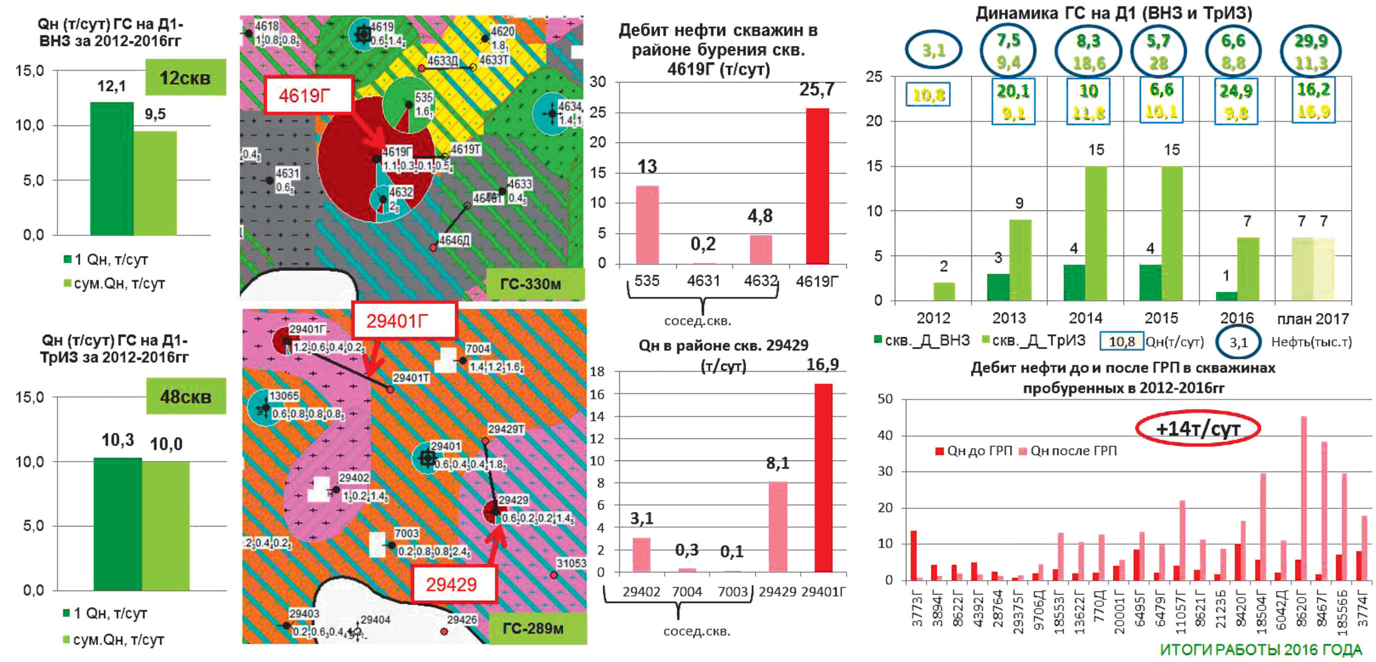


Fig. 8 *Drilling of horizontal wells as a method (technology) for the development of reserves from washed zones and hard-to-recover reserves of the terrigenous Devonian*

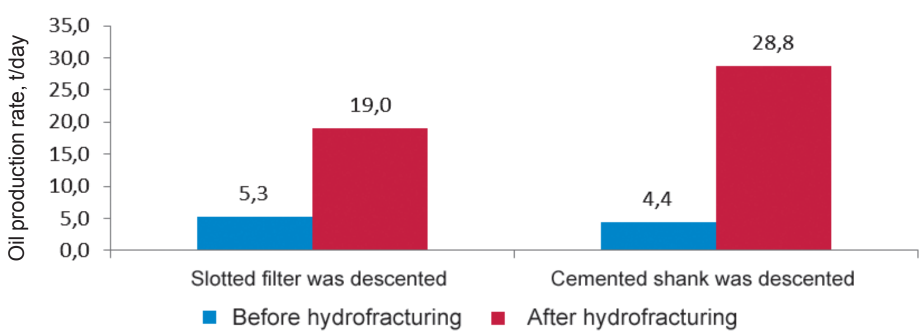


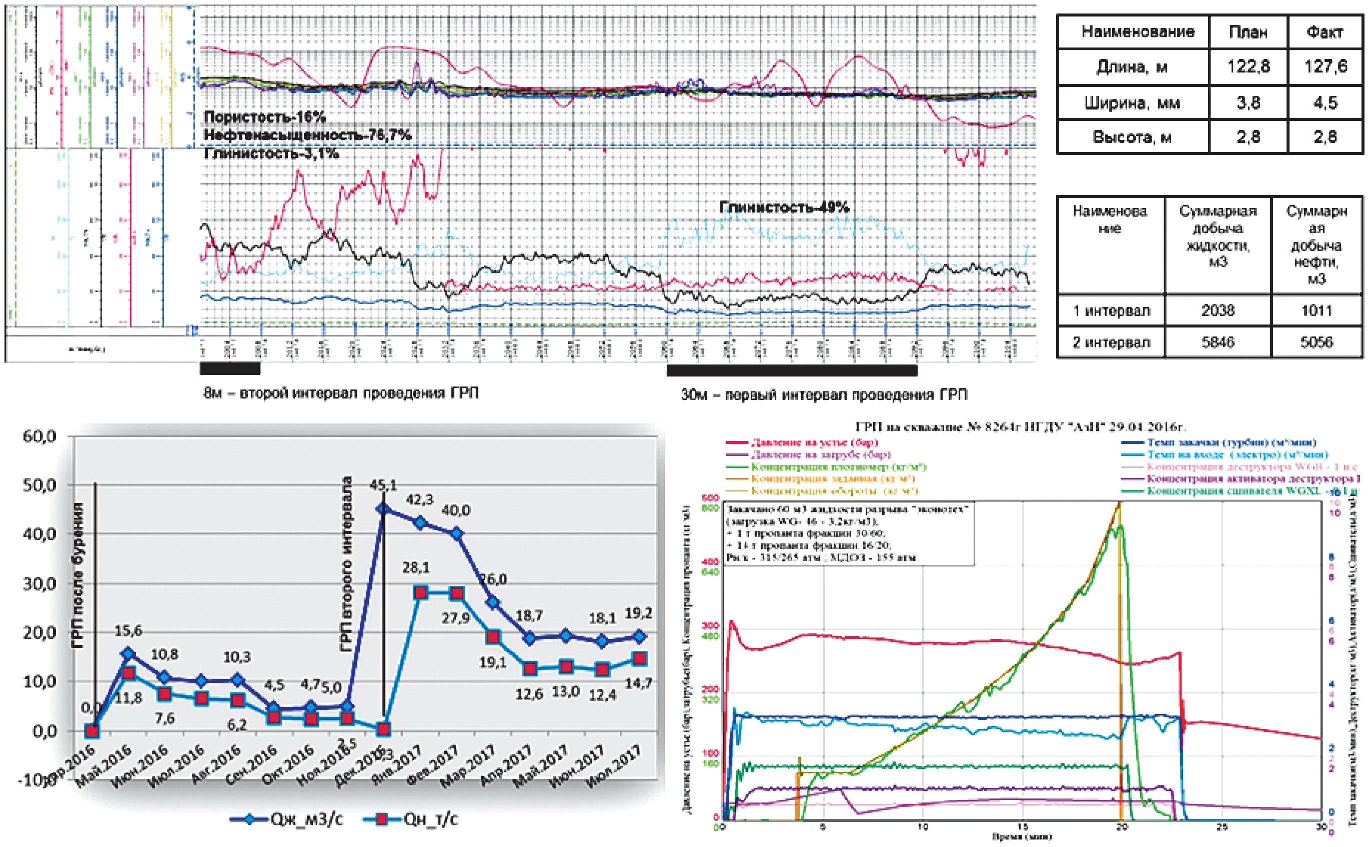
Fig. 9. Efficiency of hydraulic fracturing on horizontal wells of the terrigenous Devonian

course, this applies to horizontal wells, in which not the entire horizontal trunk is involved in the operation due to the considerable heterogeneity of the lateral strata. Since 2012, more than 70 wells have been drilled into the Devonian terrigenous sediments. In order to fully involve the reserves of the entire length of the trunk, fracturing processes are carried out.

The hydraulic fracturing is carried out in two options, depending on the method of completion of the well during construction: 1) by a common filter during descent, 2) intervally during descent of the cemented shank. The results of the hydraulic fracturing in horizontal wells of the terrigenous Devonian are presented in Figure 9.

The upper layer of the terrigenous Devonian strata is a complex reservoir, represented by the interlayering of clays and sandstones both along the lateral and along the strike. The construction of horizontal wells with subsequent hydraulic fracturing allows efficient development of these reservoirs. An example of the impossibility of extracting reserves from highly clayed reservoirs without integrating horizontal wells and fracturing technologies is well No. 8264G of Pavlovsk area. A 30 m long sock was perforated on the well. According to the logging data, the reservoir in this interval consists of clay with no flow. The oil production rate after the hydraulic fracturing was 11.8 tons/day with a gradual decrease in production rate; in December 2016 it was decided to conduct hydraulic fracturing on a second interval. The increase was 28 tons/day (Fig. 10).

At a late stage of development, with deterioration in the structure of reserves, the use of advanced technologies and development principles will help maintain the level of oil production and fully develop reserves. Technologies such as drilling horizontal wells and hydraulic fracturing are undoubtedly technologies with a wide range of applicability at various sites and in different mining conditions. Only application of these technologies will allow increasing oil recovery factor in old fields and supporting the development of objects at a cost-effective level. According to the strategy of Oil and Gas Production Department, it is projected to drill 55-60 horizontal wells and carry out 20-30 fracturing processes in horizontal wells every year until 2025.



Наименование	План	Факт
Длина, м	122,8	127,6
Ширина, мм	3,8	4,5
Высота, м	2,8	2,8

Наименование	Суммарная добыча жидкости, м3	Суммарная добыча нефти, м3
1 интервал	2038	1011
2 интервал	5846	5056

Fig. 10. Example of hydraulic fracturing in a clay reservoir in a horizontal trunk

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IMPROVEMENT OF THE DEVELOPMENT EFFICIENCY OF RESERVES DIFFICULT TO RECOVER USING HORIZONTAL AND MULTIBRANCH WELLS ON THE EXAMPLE OF NEKRASOVSKY FIELD DEVELФOPED BY CARBON-OIL LLC

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Abstract. In connection with the growth of oil reserves difficult to recover in the structure of reserves, the task of efficient development is becoming more complicated. The development of carbonate reservoirs having a complex structure and containing heavy oil is caused by the low rates of extraction and values of oil recovery factors. At present, there are no low-cost technologies that ensure high efficiency of development of such fields. The pilot site of the Bashkirian stage drilled with wells of various structure was considered, including the first in the Republic of Tatarstan experience of drilling complexly designed wells with two horizontal boreholes in complex carbonate reservoirs containing heavy oil and selective operation of each borehole using double elevator unit of dual completion. The average characteristics of wells with various designs are compared, and measures for improving efficiency of further exploitation of these wells are given.

Keywords: oil reserves difficult to recover, carbonate reservoirs, horizontal wells, multistage wells

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In connection with the growth of oil reserves difficult to recover in the structure of reserves, the task of efficient development is becoming more complicated. The development of carbonate reservoirs having a complex structure and containing heavy oil is caused by the low rates of extraction and values of oil recovery factors. At present, there are no low-cost technologies that ensure high efficiency of development of such fields. The pilot site of the Bashkirian stage drilled with wells of various structure was considered, including the first in the Republic of Tatarstan experience of drilling complexly designed wells with two horizontal boreholes in complex carbonate reservoirs containing heavy oil and selective operation of each borehole using double elevator unit of dual completion. The average characteristics of wells with various designs are compared, and measures for improving efficiency of further exploitation of these wells are given.

In connection with the growth of oil reserves difficult to recover in the structure of reserves, the task of efficient development is becoming more complicated. The development of carbonate reservoirs having a complex structure and containing heavy oil is caused by the low rates of extraction and values of oil recovery factors. At present, there are no low-cost technologies that ensure high efficiency of development of such fields. In these conditions, one of the methods of increasing the efficiency of reservoir development is the use of horizontal and multibranch wells. The present paper considers a pilot site where Bashkirian stage of the Nekrasovsky field is being developed, drilled by wells of various designs. It has the first experience in the Republic of Tatarstan of drilling and developing wells of complex construction (with two horizontal boreholes) in complex carbonate reservoirs containing heavy oil and selective operation of each borehole using double elevator unit of dual completion.

Nekrasovsky field of heavy oil is confined to the inner side of the Aksubaevo-Melekess depression of the Republic of Tatarstan. Geologically it refers to the category of complex structures, with a high degree of heterogeneity in the section and along the strike. The main objects of development are carbonate reservoirs of the Bashkirian stage of the Middle Carboniferous, which are characterized by low reservoir properties, weak hydrodynamic connection with aquifer and inter-well zones.

In order to increase the efficiency of field development, a drilling program was developed and implemented by a system of horizontal and multibranch horizontal wells (Fig. 1).

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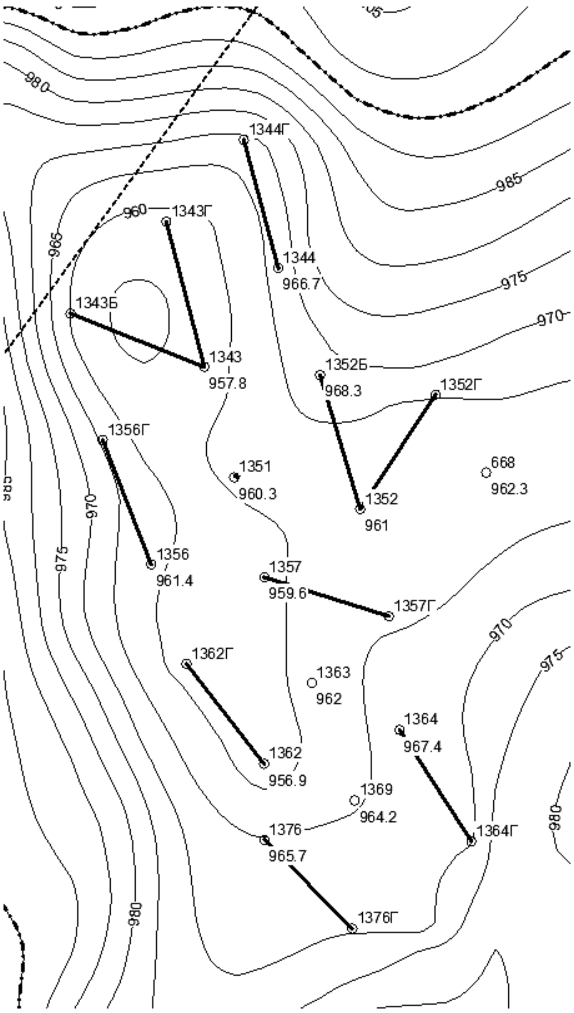

Fig. 1. Fragment from the map of the Bashkirian stage roof in the Menchinsky uplift of the Nekrasovsky field

System development of deposits with horizontal wells requires a certain location of the boreholes in the reservoir. Drilling wells requires drilling of an initial vertical section. Thus, in system development of deposits with horizontal wells, it becomes necessary to connect two independent segments of a straight line (the vertical part of the borehole and the horizontal borehole). In general, the problem is solved in three-dimensional space (Khabibullin, Galikeev, 1992). Among the possible solutions are drilling in two vertical planes (Galikeev, 2000), i.e. when developing deposits with horizontal well systems, the wells become three-dimensional, but most importantly - the opening of productive deposits is not point-like, but linear. The hydrodynamics of the system well – reservoir is drastically changed.

The development of well construction technology and field development should be expected in the distribution of drilling multilateral and multibranch wells (Fig. 2). Conditionally multibranch wells can be attributed to two-dimensional wells in productive sediments (within a single bed), and multilateral wells - to three-dimensional ones (with the location of boreholes in different beds).

Currently, there is a complexity classification of completing and fastening the joints of multilateral wells, which is called TAML (Technology Advancement for Multi-Laterals). The operation method of individual boreholes, and the depletion degree of individual zones of the reservoir are of great interest.

In 2014-2015 at the Nekrasovsky field LLC Carbon Oil drilled 13 wells with horizontal trunks, including

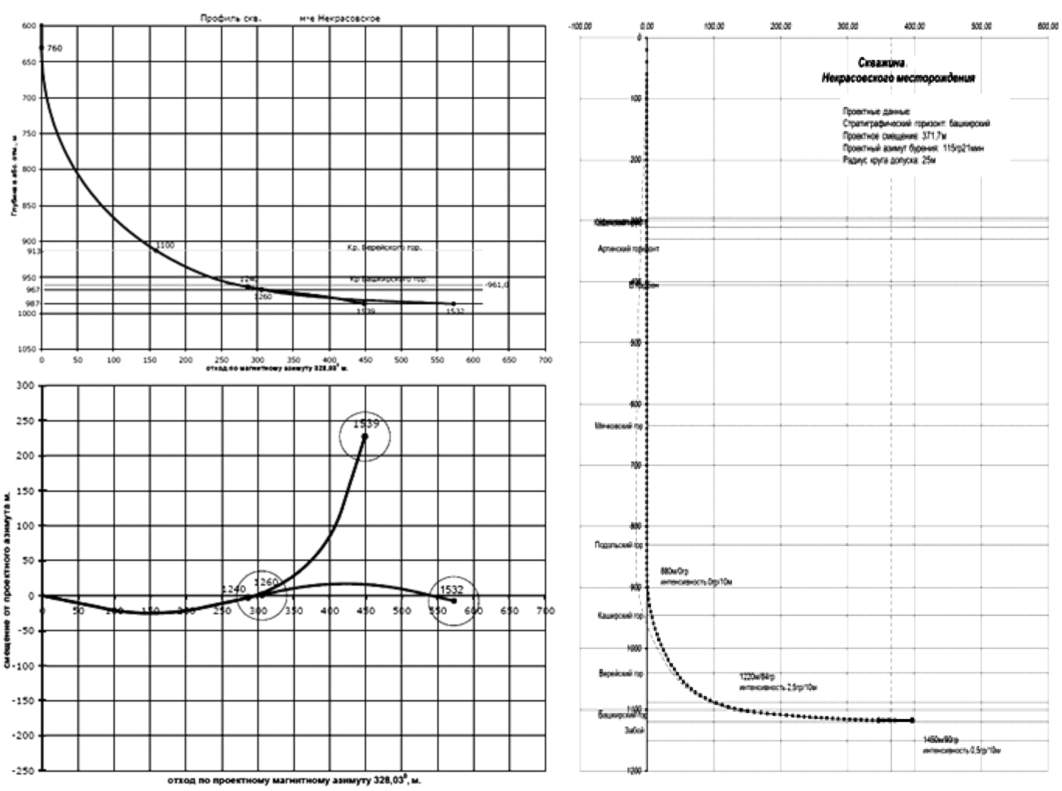

Fig. 2. Wells that were drilled and put into operation at the Menchinsky uplift of the Nekrasovsky field (multibranch horizontal wells, horizontal wells, controlled directional wells)

two with two boreholes, each of which is operated by a separate elevator.

Controlled directional and horizontal wells were drilled with bits of diameter 155.6 mm, 114 mm production columns were run in hole. Multibranch horizontal wells were drilled with bits of diameter 215.9 mm, combined columns 146/168 mm were run in hole, one borehole is cased and not cemented, and the second borehole is open.

It should be noted that only domestic equipment has been used in the construction, development and operation of wells, including deflected wedges (Galikeev, 2000). The development and further operation of each borehole were selective from each other.

For the first time in the two-borehole horizontal well, the equipment of double-elevator construction for dual completion with the separation of boreholes and separate operation of each was introduced (Fig. 3). The problem of separating the two horizontal boreholes by packer consisted in a secure fit of the packer in the interval with an angle of more than 83 degrees. Several options were considered: layout with thrust, rotary axial packers. Calculations of loads on the "head" of the packer gave the result of insufficient weight for securely fit of the packer in the horizontal part of borehole due to weight loss when the tubing string was laid. The issue was solved together with the specialists of the Packer Research & Production Company by fitting a packer with the help of a hydraulic jack that creates an additional 13 tons of weight on packer. After fitting, the working tool was separated by means of a fitting tool from the remaining part of the long elevator column and was raised. Then the pipe pump with the shank and counter part of the tool with the centralizers was run in hole, the remaining part of the column was docked with the packer, the tightness of fitting and docking was checked by swabbing from under the packer on the tubing and tracking the level in the annulus. To operate the open borehole, the tubing pump was run to the tubing.

The advantage of these wells is in increasing the degree of the deposit coverage at a smaller amount of drilling (multibranch horizontal well covers an area of 3 controlled directional wells over the drainage area). Ultimately, it affects on the increase in recovery factor with a reduction in the cost for construction and operation, as well as reducing the impact on the environment. With the help of wells of this design, it is possible to drill a field with a smaller number of wells and ensure a more complete development of the deposit.

To compare the performance of wells of various designs, a 19-month mode of operation was considered. The comparative average parameters of the operation of controlled directional wells, horizontal wells and multibranch horizontal wells are presented in Table 1

The performance of wells in the dynamics is shown in the graphs – Fig. 4-7:

Accumulated oil production (Q_{accum}) in the controlled directional wells for 19 months is in average 1144 tons of

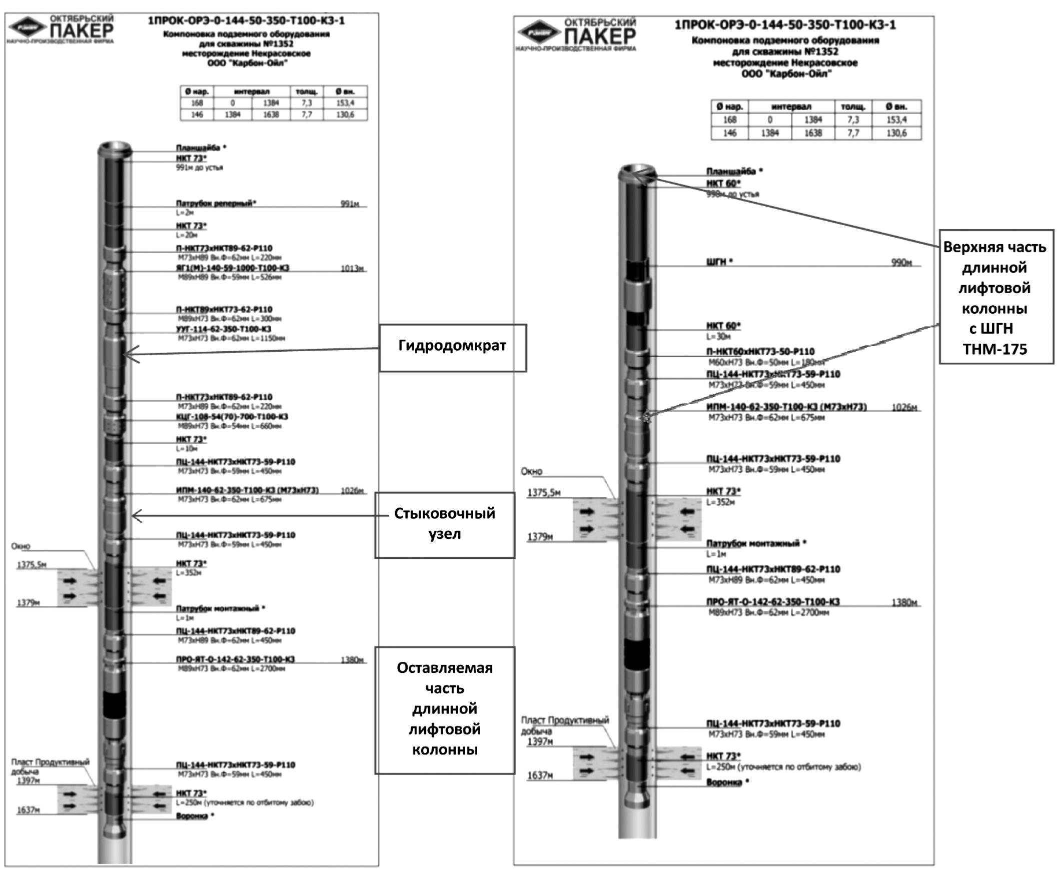

Fig. 3. Scheme for the introduction of double elevator immersed pumping equipment

oil per well; in horizontal wells Qaccum is in average 1.7 times higher and an average of 1906 tons of oil per well; in multibranch horizontal wells Qaccum is in average of 2.2 times higher than that of controlled directional wells and 1.5 times higher than that of horizontal wells and an average of 2,945 tons of oil per well.

The development of heavy oil deposit with horizontal wells makes it possible to shorten the development term of the field due to higher rates of extraction, to increase the rate of extraction from the initial recoverable reserves by 18.7%, from the current recoverable reserves by 20.2% and to improve the economic indicators of the project.

The calculation of technical and economic indicators of drilled wells showed as follows:

- the payback period of the controlled directional wells is 6.9 years, the index of profitability is 1.2;

- the cost of drilling horizontal wells is 24% higher in comparison with the controlled directional wells, payback period of horizontal wells is 4.4 years, the index of profitability is 1.34;

- the cost of drilling the multibranch horizontal wells is twice as high as that of controlled directional wells and 1.65 times that of horizontal wells, while the payback period is 5.7 years, the index of profitability 1.3.

If all types of wells are drilled with the standard bit diameters, the best results of payback and index of profitability are for multibranch horizontal wells.

Analyzing the work of the three patterns of the Menchinsky uplift of the Nekrasovsky field drilled with wells of various designs, it can be concluded that horizontal wells are more effective than controlled directional ones, the use of uncemented shanks in

Type of well/ No. well (Horizontal well), well design	Q_{liquid}, m^3/day		Q_{oil}, t/day		Bottom-hole pressure, atm.		Q_{accum} for 19 months tons of oil	Perforate/Filter part of Horizontal well, filter+trunk of Multibranch horizontal well, m	Botomm-hole treatment by acidic compositions, m^3/Ru
	initial	current	initial	current	initial	current			
Directional wells (average)	5,8	1,2	5,1	1,1	20	21	1144	6,4	3,1 / 65
Horizontal wells (average)	8,4	3,0	7,7	2,7	31	26	1906	231	15 / 60
Multibranch horizontal wells (average)	13,9	4,6	12,7	4,2	30	26	2945	244 / 312	15/50 13/45

Table 1. Average parameters of the operation of controlled directional wells, horizontal wells and multibranch horizontal wells

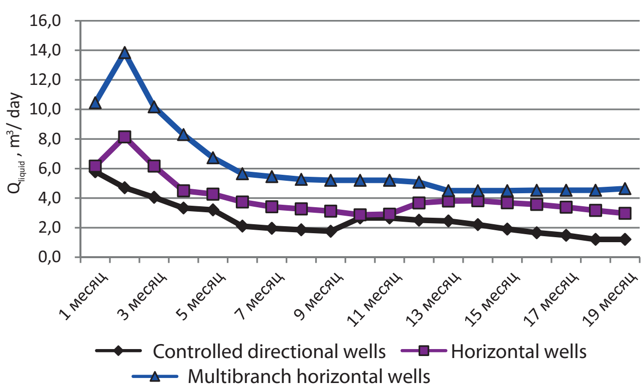

Fig. 4. Dynamics of liquid flow rate depending on well design (months)

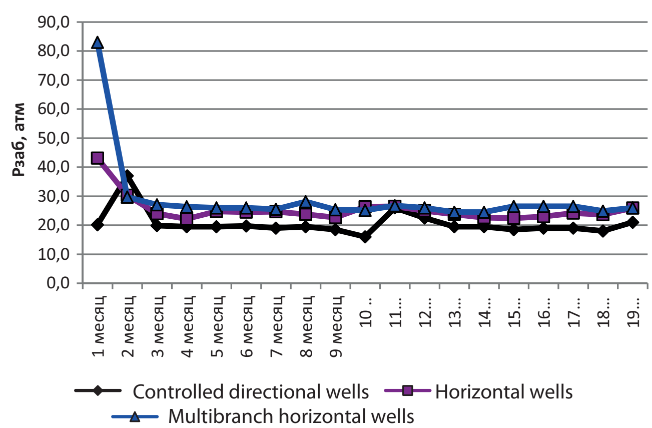

Fig. 6. Dynamics of bottomhole pressures depending on well design (months)

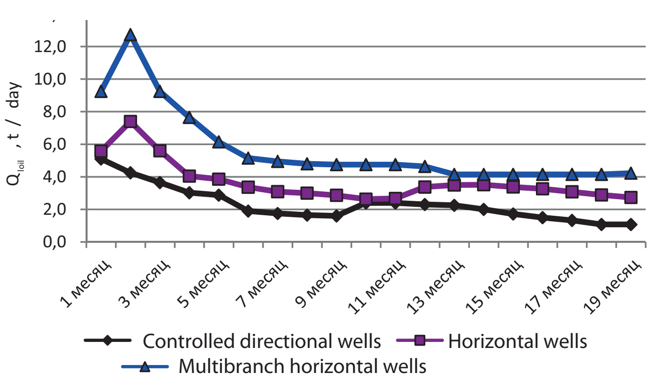

Fig. 5. Dynamics of oil flow rate depending on well design (months)

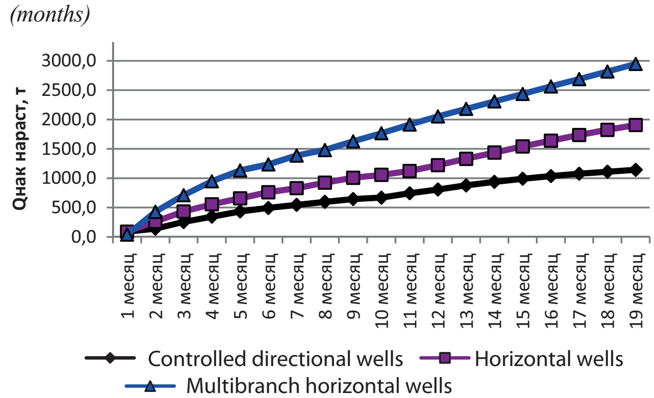

Fig. 7. Accumulated oil production depending on well design (months)

the horizontal well design does not always lead to an increase in initial and current oil production rates and to the growth of accumulated recovery in comparison with the cemented ones; and in some cases on the contrary, cemented endings of horizontal boreholes with conducted intermittent botomm-hole treatment showed great efficiency at production and technical and economic performance. To maintain well flow rates of all the structures considered it is necessary to create waterflooding centers and develop a system of reservoir pressure maintenance, as well as periodic intermittent treatment of wellbores with acidic compositions.

References

Galikeev I.A. Kustovanie gorizontal'nykh skvazhin [Horizontal well arrangement]. Tretii mezhd. seminar «Gorizontal'nye skvazhiny» [Proc. Third int. seminar «Horizontal wells»]. Moscow: Russian State University of Oil and Gas. 2000. Pp.28-29. (In Russ.)

Galikeev I.A., Averin M.G., Abdrakhmanov G.S., Zainullin A.G., Bayanov V.M., Glukhov S.D. Device for multi-hole opening of reservoirs with one well. Patent RF 2197593. 2003. (In Russ.)

Khabibullin I.T., Galikeev I.A. Design of well profiles of spatial type. *Sb. nauchnykh trudov bashkirskogo gos. nauchno-issledovatel'skogo i proektnogo instituta neftyanoi promyshlennosti* [Collected papers of the Bashkir State Scientific Research and Design Institute of the Oil Industry]. Ufa. 1992. No. 86. Pp. 75-81. (In Russ.)

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Review article

THE ROLE OF HORIZONTAL WELLS WHEN DEVELOPING LOW-PERMEABLE, HETEROGENEOUS RESERVOIRS

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Abstract. The widespread use of horizontal drilling in recent years has shown that horizontal wells can be successfully used both at the initial and late stages of development. This is due to the fact that horizontal wells, in contrast to vertical wells, contact a larger area of the productive formation, while the surface of drainage of the oil-saturated layer, productivity of the wells due to the formation of cracks, and also the influence on thin layers increases. One of the methods of impact on the reservoir is the steam-thermal method. The main advantage of the use of the heat wave method in horizontal wells is a significant increase in the well production rate, a decrease in the water cut of the reservoir, a decrease in the oil viscosity, an increase in the injectivity of the injection well, and an increase in the inflow in producing wells.

As a result of the total effect, a significant increase in production is obtained throughout the entire deposit. Enhanced oil recovery from the injection of steam is achieved by reducing the viscosity of oil, covering the reservoir with steam, distilling oil and extracting with a solvent. All this increases the displacement coefficient. One of the most effective ways to increase oil recovery at a late stage of field operation is sidetracking in emergency, highly watered and low-productive wells. This leads to the development of residual reserves in weakly drained zones of reservoirs with a substantial increase in well productivity in low-permeable reservoirs. This approach assumes that the initial drilling of wells is a 'pilot' stage, which precedes the development of oil reserves in the late stages of deposit development.

In the fields of Western Siberia, multiple hydraulic fracturing of the reservoir has been improved due to a special stinger in the liner hanger of multi-packer installation, which excludes the influence of high pressures on the production column under the multiple hydraulic fracturing. Employees of BelNIPIneft RUPPO Belorusneft have developed equipment and technologies for creating a network of deep permeable radial filtration channels under the SKIF trademark, which is based not just on multiple hydraulic fracturing of a formation, but on hydraulic fracturing in each of the interlayers creating a network of deeply penetrating radial channels. The calculations show that the technology of deeply penetrating radial channels significantly increases the production rates in comparison with the multiple hydraulic fracturing technology. In China and other countries, deep-seated, low-permeability carbonate reservoirs are operated with the use of an acid fracturing in open horizontal trunks with two technological innovations at the final stage of drilling: reorientation of the fracture and retraction of the fluid.

Keywords: horizontal wells, multiple hydraulic fracturing, controlled directional wells, lateral trunks, steam-thermal action, filtering channels network, new equipment for hydraulic fracturing, acid fracturing of low-permeable carbonate layers.

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The widespread use of horizontal drilling in recent years has shown that horizontal wells can be successfully used both at the initial and late stages of development (Muslimov, Suleimanov, Fazlyev et al., 1998). This is due to the fact that horizontal wells, in contrast to vertical wells, are in contact with a larger area of the productive formation, that is, the drainage surface of the oil-saturated layer increases, well productivity is increased due to the formation of cracks, and the influence on thin layers increases. In other words, the profitability of developing low-permeability and depleted layers, as well as deposits with high-viscosity oil and natural bitumen is increasing.

One of the most effective methods of impact on the reservoir in horizontal wells is the steam-thermal effect.

• The point of the complex effect by thermal and wave fields is that the coolant is fed into the reservoir through a pressure oscillator installed in a horizontal well. In the emitter, 4-10 % of the potential and kinetic energy is converted into the energy of acoustic oscillations. As a coolant, both compressible liquid (steam gas, air, etc.) and incompressible (water, aqueous solutions, etc.) are used. When the wave field is formed, not the rock of the formation (the formation skeleton) but the liquid in pores, capillaries and cracks of the rock come into the vibrational motion. The horizontal well in the productive layer is a linear source of thermal and wave energy. The impact of wave energy is most effective when the waves propagate perpendicular to the roof or the bottom of the productive formation. Repeatedly reflected from the roof and the bottom, these waves are damped without leaving the reservoir limited by the length of the well (Gataullin, Marfin, Kokhanova, 2007).

The main factor in the development of deposits of any oil, especially heavy, is the heating of the reservoir and fluids contained in it. The conventional way of steam heating impact is to supply a certain volume of coolant through the injection wells to create a thermal rim and then move it along the reservoir to the producing wells with the help of cold water. Thus, the thermal rim, increasing the temperature of the reservoir, lowers the oil viscosity, density and interfacial ratios, and the vapor pressure increases, which increases oil recovery.

The viscosity of oil sharply decreases with increasing temperature in the range from 20 to 80 °C. Since oil production is inversely proportional to viscosity, well productivity is increased by 10-30 times or more, especially in the initial period. When a certain temperature is reached, the viscosity decreases. High-viscosity oils with high density cool faster (Baibakov, Garushev, 1988).

Usually hot water or superheated steam is used as the coolant. However, superheated steam is the most effective agent. The volume of injected steam can be 25-40 times greater than the volume of hot water, which allows almost 90% of oil from the porous medium to be displaced with steam (Gataullin, Marfin, Kokhanova, 2007). The injection of hot water is used in cases where steam injection is unacceptable (in deep wells, with swelling clays, etc.).

When the oil is displaced by steam, three displacement zones are formed (Fig. 1):

- Zone of oil displacement by steam;
- Hot condensate zone where oil is displaced by water under non-isothermal conditions;
- Zone where oil is displaced by water of the reservoir temperature.

The selected zones interact with each other.

The main advantages of using heat wave action on productive layers in horizontal wells are: multiple increase in oil recovery, reduced water cut of the reservoir, reduction in oil viscosity, increase in the injectivity of the injection well and inflow to production wells. As a result of the total effect across all wells, we have a significant effect in production throughout the deposit. The increase in oil recovery from the injection of steam is achieved by reducing the oil viscosity, which contributes to the reservoir sweep due to the increase in the volume of oil, fermenting it with steam and solvent extraction, which increases the displacement coefficient (Gataullin, Marfin, Kokhanova, 2007).

One of the most effective ways to increase oil recovery at a late stage of field development is sidetracking in emergency, highly watered and low-productive wells. This leads to the development of residual reserves from weakly drained zones with a significant increase in well productivity in low-permeability reservoirs. This approach assumes that the initial drilling of wells is a kind of "pilot" stage, which precedes the development of oil reserves in the late stages of reservoir development (Nuryayev, Medvedev, Sulima et al., 2007). So, in OJSC Surgutneftegas 7 types of lateral trunks are used (directional single-barreled, horizontal single-barreled, horizontal multi-barreled, etc.) that allow:

- Gradual full transition to lateral trunks during depression in the reservoir in low-permeability formations;
- Development of efficient technologies for the dual completion of multilateral wells with the ability to control operating modes for each trunk and other measures by which it is possible to significantly increase oil production in all types of deposits at various stages of their development (Nuryayev, Medvedev, Sulima, et al., 2007).

The experience of Oil and Gas Production Department Aznakaevskneft, which unites 6 areas of the Romashkino field (Taipova, 2016), is interesting. The development of oil reserves from low-permeable clay-stratified reservoirs by conventional methods is ineffective. The extraction of oil from such layers requires new technologies. In 30% of the newly constructed controlled directional wells for the last 6 years, collapsed overflows have been identified. To restore these wells, significant investments are needed. In this connection, a solution was proposed for the construction of wells with an address horizontal ending. The first well with 10 branched trunks was built in 1953 at the Kartashovsky field in Bashkortostan. The distance between the bottomholes was 322 m, and the longest horizontal trunk was 168 m. The production rate of this horizontal well was 120 tons/day versus 7 tons/day in vertical wells.

Subsequently, everything was focused on methods and technologies for increasing productivity: flooding, chemical stimulation on the reservoir, development of only highly productive deposits. Only in 2012, Oil and Gas Production Department Aznakaevskneft began drilling a directed horizontal well No. 194521. As a result of drilling, a significant zonal inhomogeneity of the reservoir was revealed: porosity varied from 9 to 23%, permeability from 15 to 650 mD, oil saturation from 52 to 80%. The average production rate for the well was 20.5 tons per day, which is 5 times greater than the production rate of a neighboring vertical well. The projected payback period of the controlled directional well is 2.5 times less than in the next vertical well. Thanks to the technology of horizontal

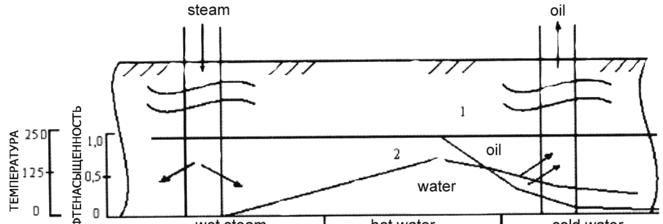


Fig. 1. Continuous steam injection scheme (Gataullin, Marfin, Kokhanova, 2007)

drilling, it became possible to increase oil reserves in the inter-well space of vertical wells. The results of drilling horizontal wells in Aznakaevo and Zelenogorsk areas are shown in Fig. 2. Horizontal drilling makes it possible to increase the efficiency of producing upper horizons, operated by the return stock of vertical wells. The experience of studying horizontal wells in Oil and Gas Production Department Aznakaevskneft showed that it is impossible to expect sustainable development without the use of horizontal drilling technologies (Taipova, 2016).

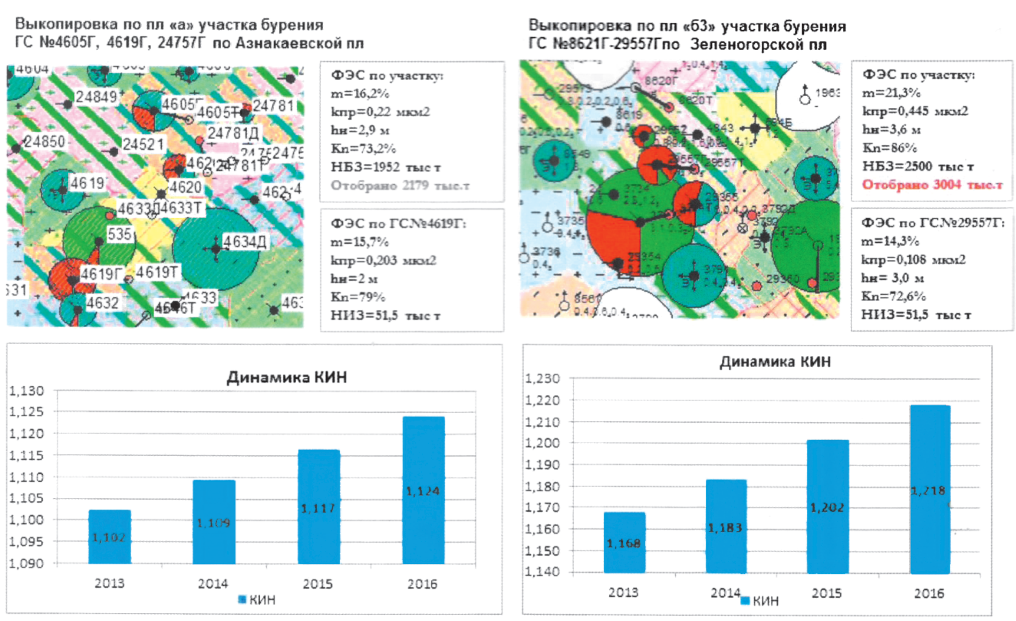
Employees of BelNIPIneft RUPPO Belorusneft developed equipment and technologies for creating a network of deep permeable radial filtration channels under the SKIF trademark (Demyanenko, Serebrennikov, Povzhik et al., 2017). Investigations have shown that in the construction of horizontal wells in hard-to-recover, highly heterogeneous, highly dissected low-permeability formations, it is more effective to complete not with multiple hydraulic fracturing of the reservoir, but to perform hydraulic fracturing in each of the interlayers, that is, penetrating radial filtration channels. If there is a significant heterogeneity of the reservoir (permeability 0.001-0.0001 μm^2), up to 5-stage fracturing is performed within a single zone of the horizontal trunk, that is, a reservoir fluid collection system consisting of 5 channels (cracks), which are directed in opposite directions from the trunk. This experiment was carried out in wells 204 and 310 of the Rechitsky field (Fig. 3).

In the well 204 Rechitsky reservoirs are not identified at all in logging data. In these wells, 5-stage fracturing was performed within a 500-800 m horizontal trunk, creating 5 channels (cracks) of reservoir fluid oriented in the opposite direction from the well trunk. The calculations show that the creation of the technology of penetrating radial filtration channels significantly increases the production rates in comparison with the multiple hydraulic fracturing technology (Demyanenko, Serebrennikov, Povzhik et al., 2017).

Multiple hydraulic fracturing at the late stage of development to involve hard-to-recover reserves of the Achimovskian deposits from the Vyngayakhinsky and Yety-Purovsky fields was carried out by Muravlenkovskneft branch by drilling a horizontal end of the trunk followed by a multiple hydraulic fracturing of the reservoir. The technology of conducting the multiple hydraulic fracturing provides for the descent into the well of a special shank that uncouples the horizontal well trunk into separate sections in which hydrofracturing takes place alternately (Shirokov, Azamatov, Artamonov, 2013). The technology of multiple hydraulic fracturing using uncoupling swelling packers and special circulation couplings is widespread in the territory of Western Siberia. For the first time such options of multiple hydraulic fracturing was carried out in the Muravlenkovsneft branch on a well that was tested on the BP16 reservoir of the Vyngayakhinsky field (Fig. 4).

Features of downhole equipment for multiple hydraulic fracturing is that a special stinger device is installed on the tubing string, which is hermetically fixed in the liner hanger of the multi-packer arrangement and, thus, excludes the effect of high pressure on the main production column (Fig. 5c).

Technologically, the multiple hydraulic fracturing differs from the standard hydraulic fracturing by the necessity of discarding balls during the performance of the stimulation operation. The moment the ball is



год	2013	2014	2015	2016
Qн, год	9795	13301	14221	14832

год	2013	2014	2015	2016
Qн, год	33348	39147	45902	40900

Fig. 2. Dynamics of oil recovery factor for horizontal wells with "off-balance" production of reserves (Taipova, 2016)

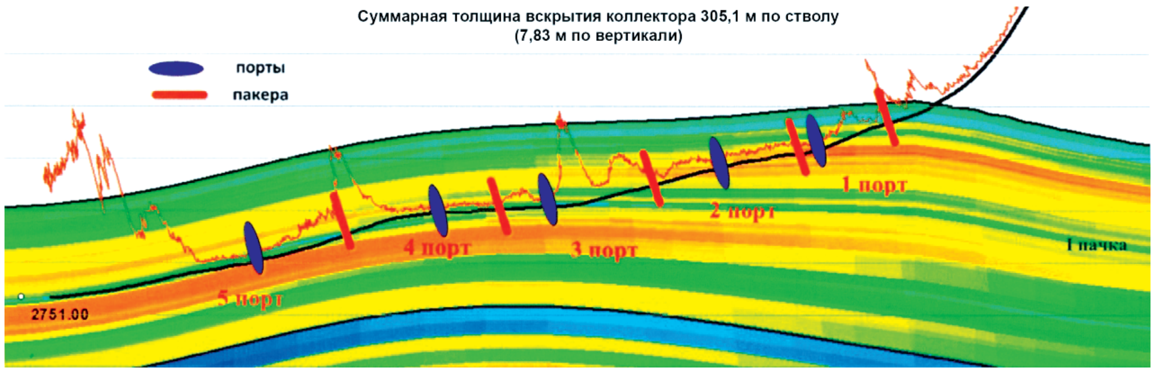


Fig. 3. Geological section within the horizontal section of the trunk of well 310 Rechitsky (Demyanenko, Serebrennikov, Povzhik et al., 2017)

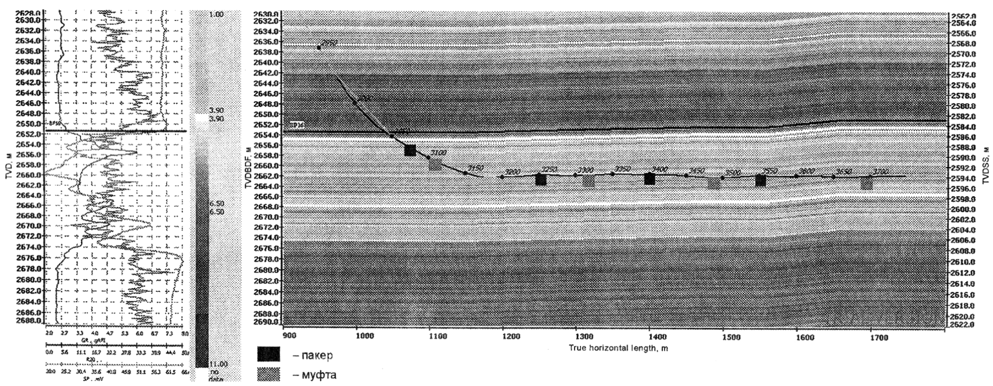


Fig. 4. Actual profile of the horizontal well trunk of the Vyngayakhinsky field (reservoir BP16) for a four-stage multiple hydraulic fracturing (Shirokov, Azamatov, Artamonova, 2013)

launched is fixed with metallic noise at the wellhead. The ball should be run in a stitched-in-place system to reduce the amplitude of the oscillation during injection and only after this completes the stage of the sale. For the next stage of the multiple hydraulic fracturing, it is possible to immediately start the injection test through the open circulating coupling (Shirokov, Azamatov, Artamonova, 2013).

Unlike standard fracturing operations, the implementation of the multiple hydraulic fracturing does not involve the use of proppant with a special coating that is sintered by the temperature of the reservoir and prevents the proppant from drifting into the well trunk after the end of the operation. The result of a comparative analysis of the production data showed that the efficiency of the multiple hydraulic fracturing conducted on a horizontal well is 2.5 times higher than the efficiency on an controlled directional well with a standard fracturing operation (Fig. 6).

The experience of developing complex carbonate reservoirs in China is very interesting (Table 1), where two new methods of wells completion have been

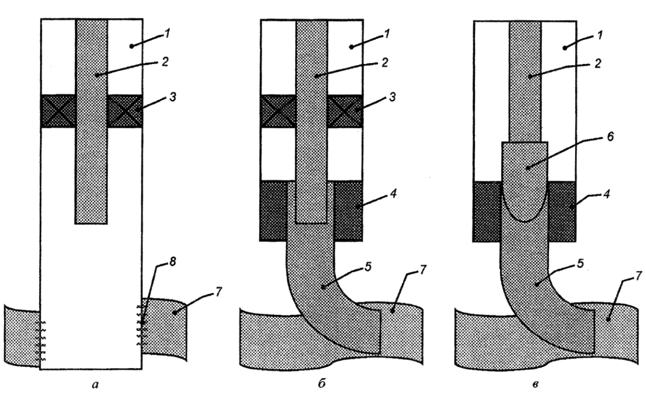


Fig. 5. Scheme of descent of underground equipment for standard hydraulic fracturing on a controlled directional well (a), standard hydraulic fracturing on a horizontal well (b) and multiple hydraulic fracturing on a horizontal well (c). 1 – the main production column; 2 – tubing string; 3 – hydraulic fracturing packer; 4 – liner hanger; 5 – shank; 6 – stinger; 7 – reservoir; 8 – interval of perforation (Shirokov, Azamatov, Artamonova, 2013)

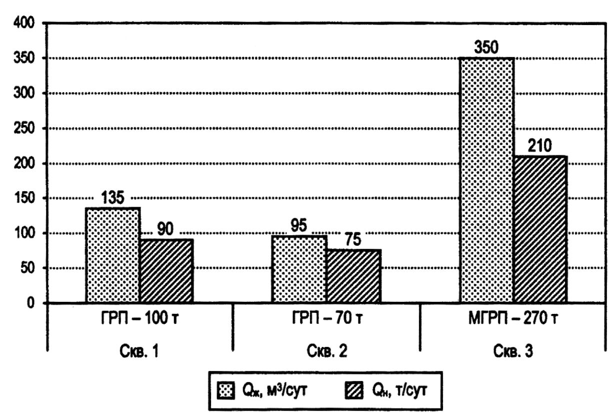


Fig. 6. Comparative results of standard hydraulic fracturing and multiple hydraulic fracturing for liquid and oil flow rates: Well 1 – controlled directional well with a standard fracturing of 100t proppant; Well 2 – controlled directional well with a standard fracturing of 70t proppant; Well 3 – horizontal well with a multiple fracturing performed with a total volume of 270 t proppant (Shirokov, Azamatov, Artamonova, 2013)

	Tarim basin	Sichuan basin			Ordos basin
Gas field	Tazhong	Yuanba	Puguang	Moxi-Anyue	Daniudi
Productive formation	Ordovician	Permian	Triassic	Cambrian	Ordovician
Depth, m	5100–6600	6710–7500	4350–5200	4600–4800	3000–3600
Thickness, m	120–270	10–75	102–411	80–120	90–120
Pressure, Mpa	65,68–68,1	66,33–69,23	55–57	78	31,68
Temperature, ^{0}C	150–160	145–159	120–134	144,8	90–120
Porosity, %	0,001–0,8	0,62–24,65	0,94–25,22	2,0–8,0	0,58–14
Permeability, mD	0,001–19,67	0,002–2385,5	0,002–3354	0,01–10	0,011–5,89
Formation fluid	Oil, gas, water, H_2S, CO_2, N_2	Gas, water H_2S, CO_2	Gas, water H_2S, CO_2	Gas, water H_2S	Gas, water
Content of H_2S, %	6,2	3,71–6,61	15,16	2	–
Content of $C_0$2, %	4,65	3,33–15,51	8,64	0	–
Lithology	Psammitic limestone	Limestone Dolomitite	Dolomitite	Psammitic Dolomitite	Limestone

Table 1. Characteristics of China's carbonate reservoirs (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

successfully implemented, which solve acid fracturing problems in open horizontal trunks. Using these methods, production was increased in the Tarim, Sichuan, Ordos oil and gas basins (Fig. 7) (Guo Jian-Chun, Gou Bo, Yu Ting, 2015).

Reservoirs of these fields have:

- low porosity and ultra-low permeability;
- extremely heterogeneous due to random distribution of cracks, cavities and pores of dissolution;
- depth of occurrence of these rocks is 5000-7000 m;
- the reservoir temperature reaches 160 °C;
- Reservoir pressure up to 78 MPa.

To increase the flow rate of such wells, it is necessary to drill horizontal wells perpendicular to natural cracks in order to cover the maximum possible space with hydrocarbon accumulations (cavities, dissolution pores and cracks). In order to create a grid of communicating cracks connecting the accumulation sites and hydrocarbon filtration pathways, multiple acid fracturing is necessary. However, because of three reasons, the following is impossible:

1) Conventional acid fracturing is not effective in heterogeneous reservoirs with intermittent cracks and pores. The usual crack of acid fracturing controls only a few zones of hydrocarbon accumulations (Fig. 8a);

2) as a rule, gel-like acids are used in low-permeability carbonate reservoirs, but at high reservoir temperatures their viscosity drops to 10 MPa/sec. This factor contributes to a greater consumption of acid, reduces the length of the crack of acid etching, reduces the productivity of the well after treatment;

3) at high temperatures and pressures

Fig. 7. Recently discovered gas fields in China (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

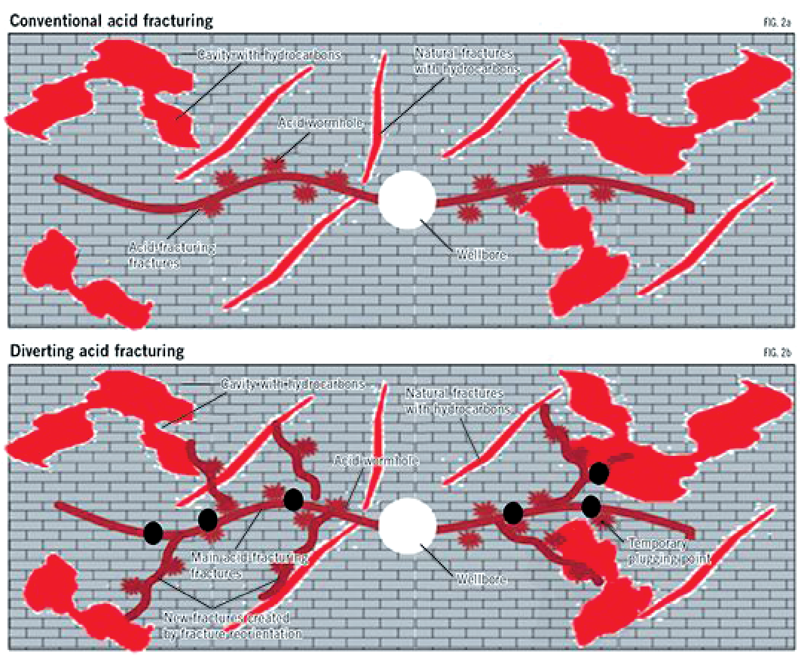


Fig. 8. Normal (a) and deflecting (b) acid fracturing (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

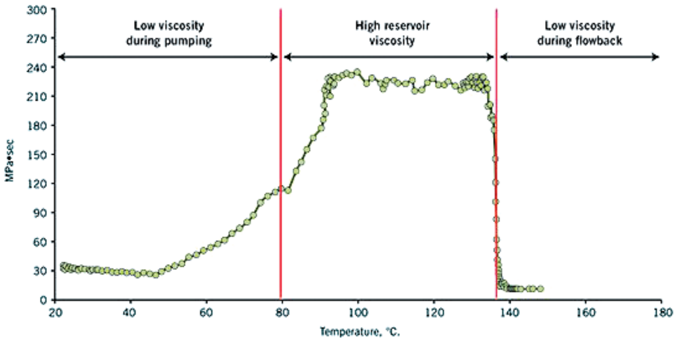


Fig. 9. Dependence of the acid viscosity on temperature (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

of China's carbonate deposits, acid treatment of fracs contributes to the release of a large amount of gases (hydrogen sulphide and carbon dioxide) that cause corrosion of equipment and other complications.

To overcome these difficulties, two new technologies were introduced, which are combined in a deflecting acid frac. Such an approach involves a reorientation of the fracture and a deviation of the fluid and allows more channels of hydrocarbon accumulations to be channeled than in the conventional way (Fig. 8b).

To reduce the rate of acid reaction with the rock and to reduce the amount of acid leakage, two types of TCA and SDA acids are used at once, which allow minimizing frictional drag and provide acid treatment and protection of the layer in deep-lying, high-temperature and complex carbonate reservoirs. The TCA acid has a low viscosity when pumped, which is favorable due to a higher feed rate and less friction loss. However, in the well, its viscosity rises to 220 MPa/sec, which leads to acid rejection and an increase in crack length. When working out, its viscosity drops, and it is freely carried out (Fig. 9).

The SDA acid contains viscoelastic surfactants when pumped as single molecules; it is easy to pump. After pumping in the reservoir, its viscosity increases to and above 350 MPa/s. This is due to a decrease in the acid concentration and an increase in the concentration of calcium and magnesium ions during the reaction of acid with the rocks of the reservoir. At the same time, a grid of viscoelastic surfactants is formed. After processing, the structure of the grid is destroyed by hydrocarbons, its viscosity decreases and it easily escapes from the well. For separate completion of complex horizontal wells in the acid fracturing of carbonate reservoirs, special downhole tools are used in China (Fig. 10).

The first option is the most popular. The completion layout consists of an installation packer, a lifting pipe, open hole packers, a sliding sleeve and a ball seat (Fig. 10a). This method provides up to 15 completion stages in long horizontal wells.

The second way of completing consists of an installation packer, an open packer lifting pipe, perforated tubes with filters and a ball seat (Fig. 10b).

These new technologies were applied in 677

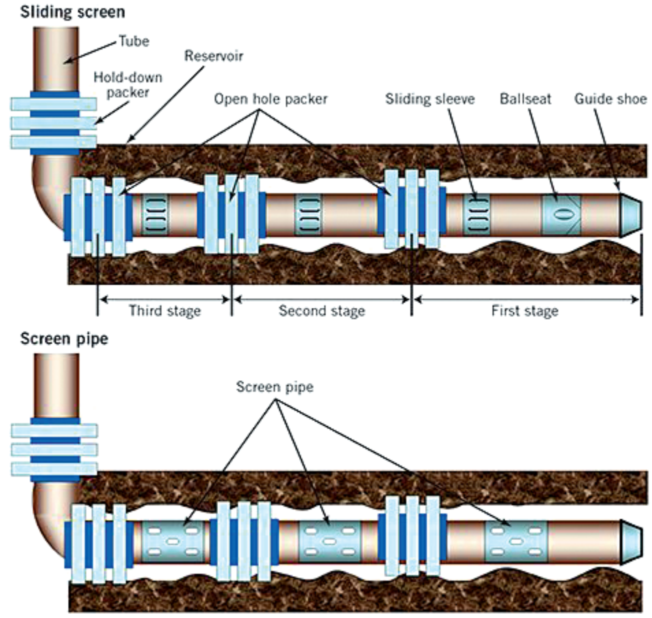


Fig. 10. Methods of separate completion of horizontal well in acid fracturing in an open trunk (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

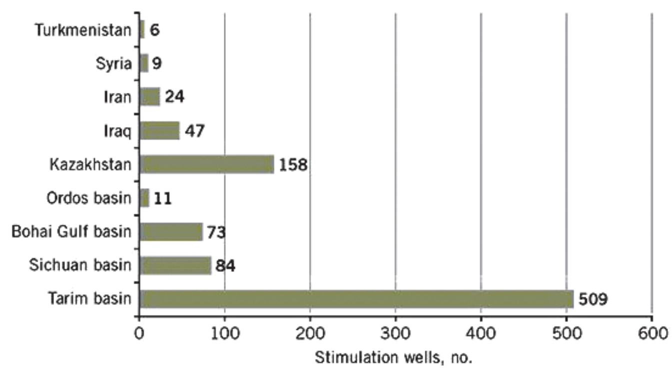


Fig. 11. The scope of new technologies for the completion of horizontal wells with acid fracturing (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

horizontal wells of China's carbonate reservoirs in the Tarim, Sichuan and Ordos oil and gas basins, as well as in the Bohai Sea, ensuring an increase in production. Similar successful results were also obtained in other countries (Fig. 11).

Thus, horizontal wells solve the following problems in low-permeability heterogeneous reservoirs:

- increase the productivity of wells by increasing the filtration area of low-permeability, heterogeneous layers of small thickness,

-continue the period of anhydrous operation,

- increase the efficiency of water injection into the reservoir,

- develop hard-to-reach areas of oil and gas deposits,

-increase the oil recovery of well by reducing the oil viscosity and increasing coefficient of displacement when exposed to steam,

- facilitate hydrocarbons recovery from deep-seated, low permeable carbonate reservoirs with acid fracturing, etc.

The equipment of horizontal wells is constantly being improved, which contributes to the reduction of accidents and more safe extraction of hydrocarbons from the subsoil.

References

Baibakov N.K., Garushev A.R. Thermal methods for the development of oil fields. Moscow: Nedra. 1988. (In Russ.)

Gataullin R.N., Marfin E.A., Kokhanova S.Ya. Thermal energy losses during integrated impact on the reservoir in horizontal wells. *Mat. Mezhd. nauchno-prakticheskoi konf. «Povyshenie nefteotdachi plastov na pozdnei stadii razrabotki neftyanykh mestorozhdenii i kompleksnoe osvoenie vysokovyazkikh neftei i prirodnykh bitumov»* [Proc. Int. Sci. and Pract. Conf. "Enhancement of oil recovery in the late stage of development of oil deposits and the complex development of high-viscosity oils and natural bitumen"]. Kazan. 2007. Pp. 162-166. (In Russ.)

Guo Jian-Chun, Gou Bo, Yu Ting. Novel completions increase horizontal well production. *OIL&Gas JOURNAL*. 2015. April, 6. http://www.ogj.com/articles/print/volume-113/issue-4/drilling-production/novel-completions-increase-horizontal-well-production.html

Demyanenko N.A., Serebrennikov A.V., Povzhik P.P. et al. The efficiency of completion of horizontal wells in highly nonuniform low-permeability reservoirs with multi stage hydraulic fracturing and ways of increase in efficiency of works. *Nedropol'zovanie XX1 vek* [Subsoil use]. № 1, February 2017, Pp.76-85. (In Russ.)

Muslimov R.Kh., Suleimanov E.I., Fazlyev R.T. et al. Design and application of horizontal technology in the fields of Tatarstan. Development of oil fields by horizontal wells. Materialy seminara-diskussii [Proc. Seminar-Discussion]. Almetyevsk. 1996. Kazan: Novoe znanie Publ. 1998. Pp. 3-18. (In Russ.)

Nuryaev A.S., Medvedev N.Ya., Sulima S.A. et al. Side tracks – a highly effective method of additional development of residual oil reserves at the fields of OJSC "Surgutneftegas". *Mat. Mezhd. nauchno-prakticheskoi konf. «Povyshenie nefteotdachi plastov na pozdnei stadii razrabotki neftyanykh mestorozhdenii i kompleksnoe osvoenie vysokovyazkikh neftei i prirodnykh bitumov»* [Proc. Int. Sci. and Pract. Conf. "Enhancement of oil recovery in the late stage of development of oil deposits and the complex development of high-viscosity oils and natural bitumen"]. Kazan. 2007. Pp.472-476. (In Russ.)

Shirokov A.N., Azamatov M.A., Artamonov A.A. The main features of multistage fracturing in horizontal wells. *Geologiya,geofizika i razrabotka neftyanykh i gazovykh mestorozhdenii = Geology, Geophysics and Development of Oil and Gas Fields.* 2013. No. 5. Pp.46-51. (In Russ.)

Taipova V.I. The use of horizontal technologies for extracting hard-to-recover reserves. *Mat. Mezhd. nauchno-prakticheskoi konf. «Innovatsii v razvedke i razrabotke neftyanykh i gazovykh mestorozhdenii»* [Proc. Int. Sci. and Pract. Conf. "Innovations in exploration and development of oil and gas fields"]. Kazan. 2016. Pp.66-73. (In Russ.)

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AML (ADVANCED MUD LOGGING): FIRST AMONG EQUALS

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Abstract. During the past ten years an enormous development in mud logging technology has been made. Traditional mud logging was only qualitative in nature, and mudlogs could not be used for the petrophysical well evaluations which form the basis for all subsequent activities on wells and fields. AML however can provide quantitative information, logs with a reliability, trueness and precision like LWD and WLL. Hence for well evaluation programmes there are now three different logging methods available, each with its own pros and cons on specific aspects: AML, LWD and WLL.

The largest improvements have been made in mud gas analysis and elemental analysis of cuttings. Mud gas analysis can yield hydrocarbon fluid composition for some components with a quality like PVT analysis, hence not only revolutionising the sampling programme so far done with only LWD/WLL, but also making it possible to geosteer on fluid properties.

Elemental analysis of cuttings, e.g. with XRF, with an ability well beyond the capabilities of the spectroscopy measurements possible earlier with LWD/WLL tools, is opening up improved ways to evaluate formations, especially of course where the traditional methods are falling short of requirements, such as in unconventional reservoirs.

An overview and specific examples of these AML logs is given, from which it may be concluded that AML now ought to be considered as "first among its equals".

Keywords: mud logging technology, AML, LWD, WLL, mud gas analysis, elemental analysis of cuttings
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Reasons to consider applying AML technologies

The information provided by conventional mudlogging, however valuable, was only qualitative, and simply did not provide most of the measurements which are necessary for a full petrophysical well evaluation. However, now that AML is getting mature, there are three groups of techniques which can be considered for routine well evaluation programmes: AML, LWD (Logging While Drilling) and WLL (WireLine Logging). Note that coring and production testing, however valuable, i.e. even, rightfully, considered as ground truth when applied, are not suitable for routine application for all wells and intervals, and that many measurements, traditionally requiring core plugs, and thus necessitating coring, can now be done with sufficient trueness and precision on cuttings and chunks, either already in AML operations on the well site, or in laboratories.

There are numerous applications of AML for drilling purposes, e.g. monitoring of operations, including quality control of mud chemicals, well safety, and improving drilling operations. This paper will focus mainly on the AML formation evaluation aspects. Figure 1, modified marginally from earlier publications, e.g. (Loermans, Kimour et al., 2012) gives a broad overview of various techniques and their application for conventional petrophysical interpretations. Further in this paper some of these measurements are further addressed and illustrated with examples.

The reasons to include AML in an evaluation programme can be grouped into three categories: (i) TINA (There Is No Alternative), i.e.: LWD and WLL simply cannot be run or cannot provide the necessary answers, (ii) VOI (Value Of Information) / second opinion, where AML would be one of at least two completely independent evaluation methods to reduce the uncertainty from having only one imperfect method, and (iii) Money, i.e., as the cheaper one of a few technically acceptable methods, or situations where a balancing of costs and operational risks, including well control and other safety issues is required.

TINA but AML

There are situations where only AML can provide information. When for an abandoned the cuttings are available, AML cuttings analysis may provide very useful information. For new wells with drilling conditions beyond the LWD & WLL tool limits of e.g. hole size, temperature and/or pressure. Also, however good the elemental analysis is which can be obtained from the available LWD/WLL spectroscopy tools, those measurements simply fall short of what can be obtained from e.g. XRF (x-ray fluorescence), as part of an AML system. Also, obviously, any new methods, such as TOC (Total Organic Carbon) derived from existing laboratory methods, can be carried into an AML development much faster and cheaper than into WLL and LWD.

VOI – second opinion

Our logs and our evaluation methods are not perfect, providing 100% certainty for a decision to be made

	gas chromatogr.	mass spectr.	POPI	fluid inclusions	isotope logging	LIBS	XRD	XRF	FTIR	spectral GR	"conv." core anal.	mini por, gr.dens	cutt. cap crves	x ray ct scanning	rock typing	IFP permcut	AGIP perm on cuttings	NMR on cuttings	sonic on cuttings	micro mud losses	image anal./PNM	nano indent.	drilling param.
net reservoir ind.	x				x					x					x	x	x	x	x	x			x
fluid contacts	X	X	x	x	x													x					
fluid type	X	X	x	X	x													x					
fluid composition					x																		
fluid properties	x	X	x	x	x													x					
mineralogy						x 4)	X	X	X	x				x	x				x				x
elemental comp.								X	X	x													
correlation steering					x	X		X	X	x													
bulk density											X	x		X					x				x
grain density						x					X	x			x								
porosity											X	x	x	X **)	x	x	x	x	x		x		x
electr. params ***)															X						x		
pore size distr																							
Swi													X		X			X			x		
cap curve													X		X			x			x		
saturation, Sh			x										x *)										
perm. - matrix													x		x	X	X	X		x	x		
perm. - fract./high k																				X			
rel.perms															x						x		
vp/vs																			X				
mechanical param.															X				x			X	x

*Fig. 1. Overview of AML measurements. *) if contact given and if virgin conditions still present. **) if matrix density known. ***) m, n, Qv. 4) LIBS has lost in potential/hope for uncalibated lithology*

on the information derived therefrom. Decision tree analysis, using Bayes' theorem then quickly shows that, in order to have any desired certainty, two independent methods are required[1]. Our log interpretations, however good, when using input from only one out of the three of AML, LWD and WLL, sometimes cannot be regarded other than being based on only one set of truly independently acquired information sets. While, of course, one of the main drivers within the areas of LWD and WLL technology development over the past decades has been to provide truly independent methods, e.g. formation pressure testing and sampling to confirm interpretations based on resistivity/density logs, we have to remain conscious of the potential limits of our data sources.

Even a perfect formation pressure test graph may be misleading

To corroborate further that even our most trusted tools are not 100 % reliable, consider figure 2, showing the first set of pressure points obtained in a normal formation pressure job in an appraisal well in a mature area. The

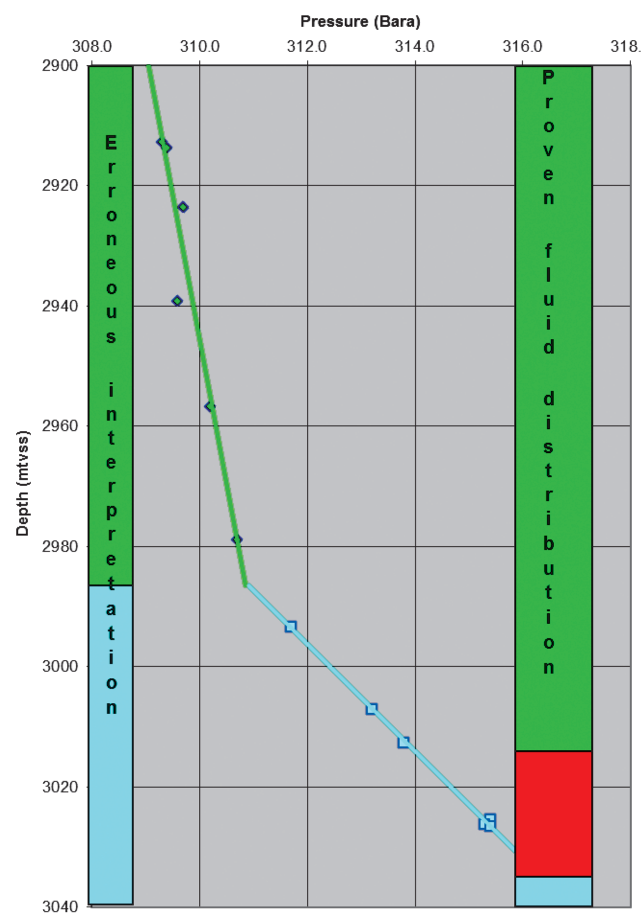

Fig. 2. Even formation pressure graphs may be misleading

[1]Also, consider the following almost classical situation. A young petrophysicist having evaluated an exploration well as water bearing, and thus advising against production testing, being overruled. Such decision tree analysis will quickly show that, given the stakes and, however clear the interpretation might be, nevertheless the small risk of that interpretation being a false negative, it is often not unwise to indeed overrule such interpretation.

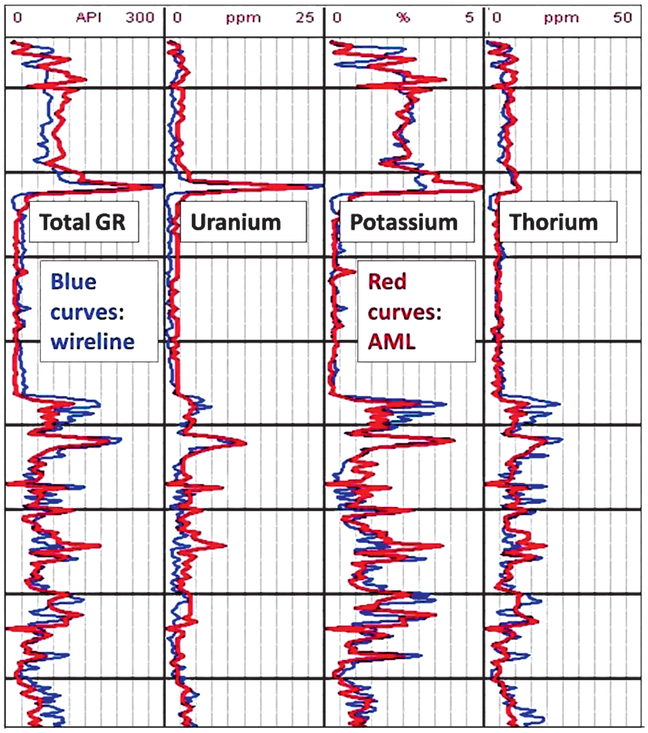

Fig. 3. Equivalence AML and WLL spectral GR curves

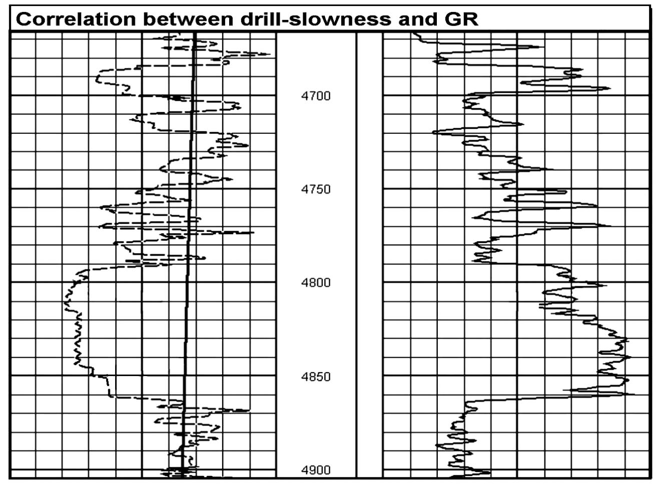

Fig. 4. ROP as possible low cost proxy for a GR. The two main curves shown in this plot are a GR and an ROP. However, scales are not shown on purpose, because each of these curves might be displayed in an unconventional manner, eg the GR might be shown in either track, with reversed scales, and not as a solid but dashed curve and resampled from its original. It is obvious that for all practical purposes, the ROP and GR curves are interchangeable. Hence, if cost saving is relevant, in cases like this one would could even save on the costs of running a GR… (The author welcomes any correspondence reasoning which curve is which.)

initial interpretation of the well site staff involved, based on the resistivity/density/neutron logs run before was for a GWC (Gas Water Contact) at the suggested FWL (Free Water Level) by the pressures, around 2984 m. All the pressure points had a good drawdown mobility, so could be considered reliable. Hence, this fluid column (green – gas, blue – water) as depicted on the left of that plot could well have been the final conclusion. However, after several more formation pressure runs (not presented in this plot), and fluid and side wall samples were taken, the interpretation as depicted on the right hand side, with some 150 ft of extra HC column, including an oil rim (red), was firmly established[2].

Cost savings

When there are two methods available providing technically sufficiently acceptable and equivalent information, i.e. including sufficient certainty that no "second opinion" is required, then obviously the alternative with the lowest costs, in terms of direct expenditure of acquiring the data costs and the, properly weighted, risks of mishaps associated with the alternatives, should be taken.

The spectral GR comparison in figure 3 illustrates that AML is now[3] in the position where LWD was in the 1990's: many measurements are available, but only from a few service companies and these logs are not generally recognised and accepted yet by all operators/oil companies for their qualities and business value.

Proxies for certain measurements are typically used when the desired measurement cannot be obtained, i.e. the proxy then is taken as best practically possible. However, when evaluation cost reduction is very critical, i.e. when the evaluation methods are extremely well established and when in a mass operation development drilling, even low cost proxies for simple logs, might be considered. Consider figure 4, from which it is obvious that an ROP, at almost truly zero incremental costs, might serve as a proxy for a GR, thus saving this little bit of additional costs from an MWD-GR.

Note that, apart from just a low cost proxy for some other logs, the ROP, could be an indicator for mechanical properties. That is, not so much raw ROP by itself, but transcended further than modified d-exponent to Mean Specific Energy (MSE), the specific energy needed to drill a piece of rock. Such MSE is an obvious potential proxy for some rock mechanical strength parameters, vital of course to decide on the fraccability of formations. And for unconventional (shale) developments fraccability more than anything else still remains the current well evaluation golden grail.

Depth matters

Depth is the most important logging parameter, and hence depth matters matter very much also for AML. Concerns still exist with many AML is falling short of requirements because of various depth related issues, the AML sampling depth and resolution in particular. However, as will become clear in the following, the AML depth problems are smaller than often perceived, not that much different from similar issues with LWD

[2] A quantitative explanation for this case is yet to be provided. The author thus welcomes any suggestion any reader might have.

[3] Many examples like this have been published for more than five years already; ao. the presentation of (Marsala et al., 2012)

and WLL curves, and that there even some points where AML actually can provide significant added value.

Depth matching various AML curves to one common standard AML-depth, and subsequently matching the AML curves to the LWD and/or WLL curves is not different from depth-matching various WLL or LWD curves to each other. In any mudlogging operation, the depths for the measured drilling parameters, are to be matched to those from the mud gas readings and cuttings coming to surface. While the exact mechanisms of such process are of course different the corresponding ones to match WLL and LWD curves, e.g. especially the lag time of cuttings needs to be carefully established, as numerous examples have shown, and indeed is routine, depth matching different curves is not a problem.

Mud mixing, especially when there are many large washouts, may affect the smooth transport of cuttings, and thus have a negative impact on the depth resolution which can be obtained from cuttings samples. But when the drilling hydraulics are good, which of course also is better for the drilling and hole cleaning process, it has been shown that sampling cuttings with a resolution of about 2 ft may very well be possible. Also the high resolution response often obtained from AML mud gas readings, including isotope measurements, confirm that mud mixing and depth resolution is not a fundamental problem barring AML applications.

Given that for several AML measurements only small amounts of cuttings are needed, hand picking of cuttings for special cases is very well possible. That means that, while even with coreplugs only average properties can be measured for e.g. a package of a few feet thick consisting of 5 mm sand/shale layers, AML can separately measure the properties of those thin sand and shale layers.

Establishing the absolute correct depth, i.e. the TAH (True Along Hole) depth, is an issue which the discipline as a whole is still trying to improve on. WLL and LWD absolute depths too often clearly are simply of too poor quality and on too many a conference, problems are reported and methods to improve are proposed. In this respect AML may even help matters, especially for drillers = LWD depths. Because of the nature of mudlogging, almost intrinsic in its operations, even more so than with LWD, is a monitoring and recording of those parameters which are necessary for a TAH depth determination, e.g. friction of the drillstring as it is moved along the well trajectory. Hence, given that AML does have the operating system and computing power on site to do so, we might see a development where TAH depth as established by AML services actually become the standard depth, in a way that (long ago now already) WLL provided the logging depth as unchallenged default, with superior quality over drillers depth.

Mud gas analysis

For the mud gas analysis, during the past decade an enormous leap has been made from only qualitative to very accurate and reliable measurements now with the best available AML systems. See figure 5, showing a perfect match between HC composition (C1-C5) obtained in real time with an AML system, and the results of PVT analysis on WLL formation fluid samples. With a mud gas system like this, the LWD or WLL formation fluid sampling programme can be optimised and adjusted as needed. Sometimes taking more samples and at other points than initially anticipated, sometimes making further LWD/WLL sampling superfluous. Altogether of course an enormous added value for well and reservoir evaluation.

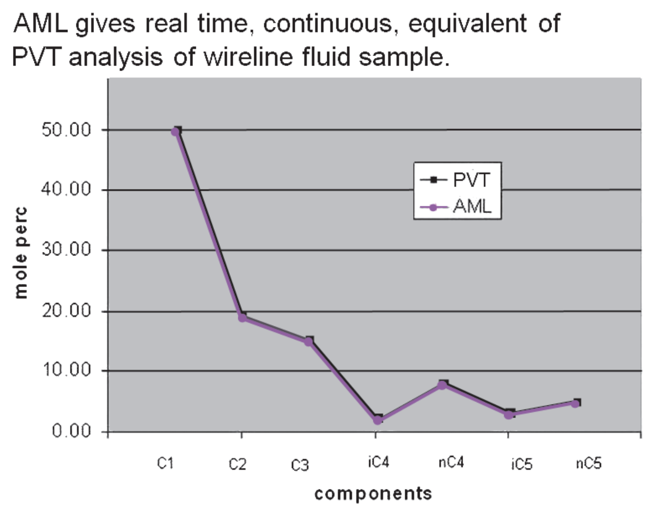

Fig. 5. Perfect match HC composition AML and PVT samples

Similarly excellent measurements of isotopes can now be made, see figure 6 for just two examples, also real time, making it also possible to do geosteering based on the encountered HC composition.

This leap forward in mud gas analysis, was possible only by concerted efforts on every part of the whole mud gas chain. Sampling, ie gas extraction from the return mud flow, traditionally certainly was the weakest link in that chain, and nowadays still might be. Many modern AML gas systems feature a high performance gas chromatograph and a mass spectrometer, located in the mud loggin unit, thus a mud gas line from the shale shakers, or flow line/bell nipple, where the gas extraction system is located. However, further development of the mud gas systems, see e.g. figure 7, eliminates not only the need for the, high capex, mass spectrometer, but achieves a size reduction and explosion proof encapsulation, eliminating the need for a gas line.

XRF and XRD analysis on cuttings

What is generally accepted as a revolution in the mud gas analysis capabilities, is on the cuttings measurements side possibly matched by XRF/XRD (x-ray fluorescence

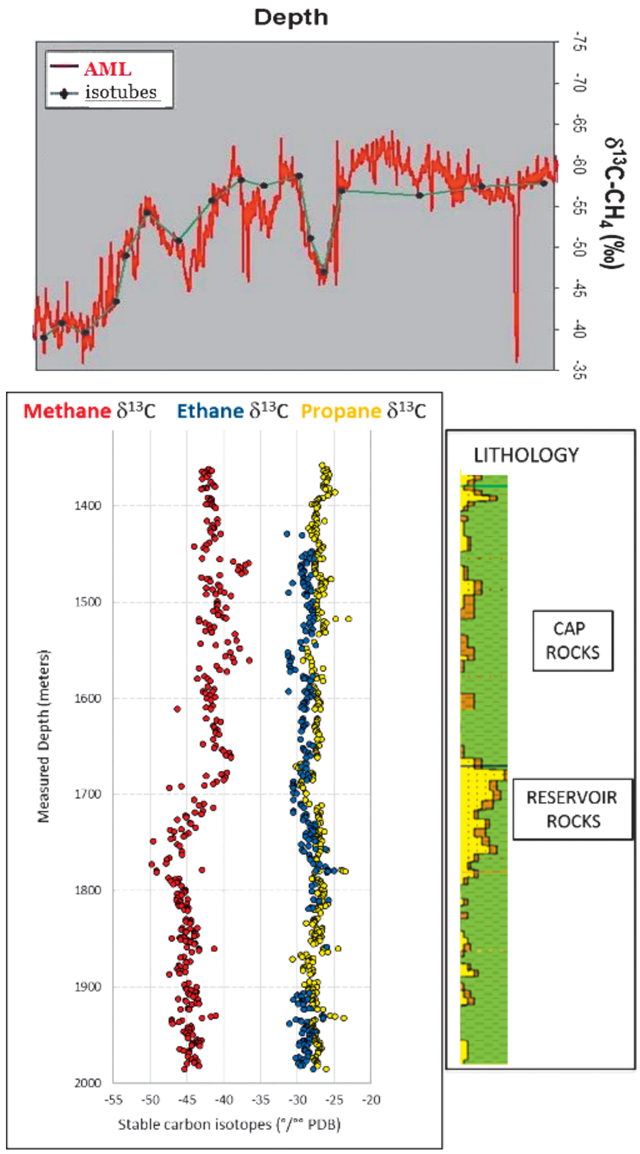

Fig. 6. Isotope logging

Fig. 7. Complete mud gas system. Note the extraction probe, and the complete system being a stand alone system, safe to be used directly near the shale shakers or flowline

and x-ray diffraction) analysis, now possible on site in AML units. XRF can give very accurate elemental composition for Na and higher atomic number elements, XRD provides mineral analysis. The enormous spectrum of elements provided by XRF in particular, has an enormous potential for evaluations in situations where conventional methods just do not suffice. See figure 8, where, to many people's surprise, Pb, Zn and Mn from the XRF appeared to correlate with the mud gas analysis.

Calculating spectral GR from the XRF analysis is now also so well established and proven that systems where the spectral GR is measured directly, are not needed, other than for possible lower operating costs reasons, including, an aspect not to be underestimated, the lack of need for relatively elaborate sample preparation including cleaning, pulverising and pelletising, still necessary for high quality XRF. Also, like for the direct spectral GR measurement on cuttings, for for some NMR and Pulsed Neutron Spectroscopy (PNS) measurements, little to virtually no sample preparation is needed. On the other hand, the sample volume required for XRF is so small that, as mentioned under 2 above, careful selection and hand picking of the cuttings being analysed is possible.

Other measurements … "looking better" maybe most important?

This paper does not, because it simply cannot, not do justice to all the other measurements now available. Therefore, as a last example, a reminder maybe that "looking better", might be said to be the main feature allowing progress in our discipline, so, "just looking better at cuttings".

The most rudimentary element of conventional mud logging was the lithological cuttings description. And on this front too, AML can do better. See figure 9, where, rather than just the conventional lithological description, a rock typing classification was done, as per standard rock classification schemes (Archie,

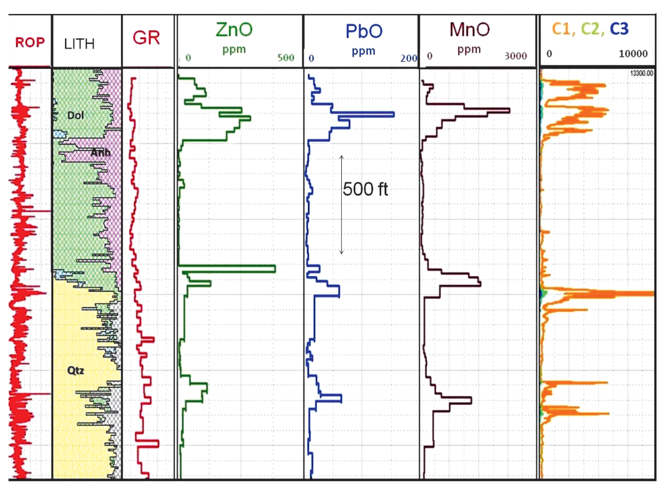

Fig. 8. Interesting correlation some trace elements from XRF with mudgas (from the (Marsala et al., 2012))

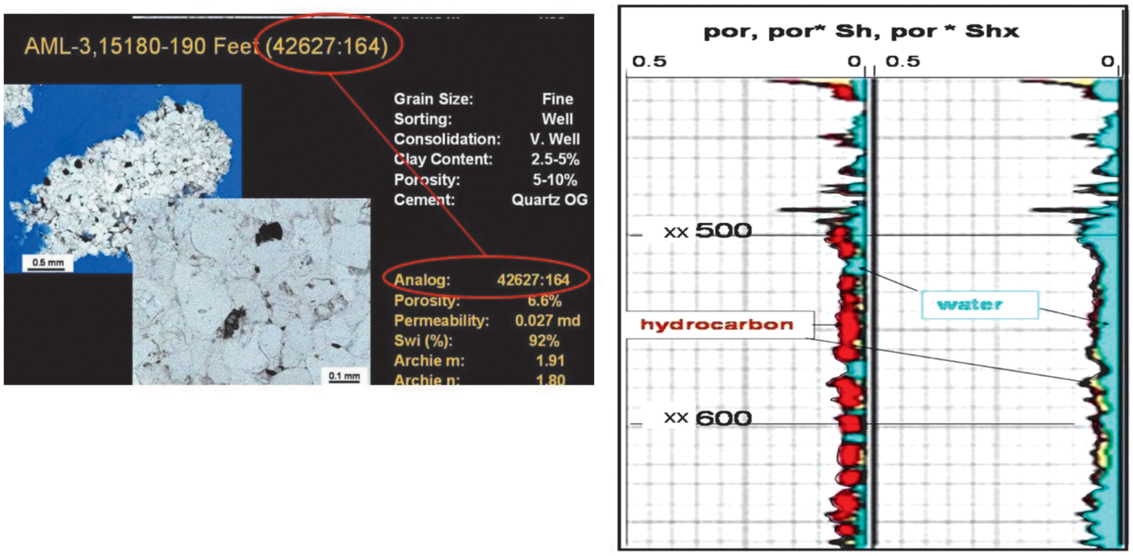

Fig. 9. "Looking better", may save expensive production tests. Using the electrical parameters from the rock catalogue for the corresponding rocks, as opposed to only regional knowledge in this area when the well was drilled, changes the evaluation from gas to water bearing.

world famous for his saturation equation, actually also did excellent rock classification work; the objective being to reduce the amount of necessary laboratory measurements). Next, with the properties then obtained from the rock catalogue, an evaluation was made. While that rock typing could have been done in real time, on site, unfortunately it wasn't. hence, for the petrophysical evaluation of that well, only general regional knowledge parameters could be used. As a result the well was interpreted as HC bearing, and thus production tested, sadly producing only water. As can been seen from the evaluation with the parameters derived from rock typing, had AML been around for this well, chances are the costs of the production test would have been saved.

Acknowledgements

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References

Loermans, T., Bradford, C., Marsala, A., Kimour, F., & Bondabou, K. Successful Pilot Testing Of Integrated Advanced Mud Logging Unit. *SPWLA 53rd Annual Logging Symposium*. Cartagena, Colombia. Paper VVV. 2012.

Marsala, A. F., Loermans, T., Shen, S., Scheibe, C., & Zereik, R. Real-time Mineralogy, Lithology, and Chemostratigraphy While Drilling using Portable Energy-Dispersive X-ray Fluorescence. *SPWLA Annual Conference*. Colorado Springs. Paper XXX. 2011. doi:10.2118/143468-MS

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Review article

HYDRAULIC FRACTURING AND MICROSEISMICITY: GLOBAL PERSPECTIVE IN OIL EXPLORATION

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Abstract. Induced microseismicity is a common phenomenon in oil and gas reservoirs due to changes in internal stress accompanied by hydraulic fracturing and oil-gas extraction. These microseismicity can be monitored to understand the direction and type of hydraulic fracturing and pre-existing faults by precise hypocenter location and focal mechanism studies. Normal as well as strike-slip faulting earthquakes occur due to opening up of new cracks/fractures, and thrust/reverse faulting earthquakes due to compaction or closing of existing fractures.

Further, frequency-magnitude relation (b-value) and fractal dimension (D-value) of the spatial and temporal clusterization of induced microseismicity may be much useful to characterize the fractures/existing faults and the stress regimes. Seismic tomography, on the other hand, can image the heterogeneous velocity structures/perturbations in the reservoir due to fractures and oil-gas-water contents. A few global case studies are illustrated to understand these processes and to draw attention towards importance of these studies in oil industries.

Keywords: Hydraulic Fracturing, Microseismicity, Oil Exploration
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1.Introduction

Hydraulic fracturing is a process in which liquids, gas or solids (proppants) are pumped or injected into a formation under high pressure to cause cracks in the formation for enhanced oil and gas production. This technique is routinely used to increase permeability in the reservoirs. During or soon after hydraulic fracturing by injection, there will be an increase fluid pressure along existing fault planes as well as along new fracture planes that cause induced microseismicity. The microseismicity from fluid injection at depth associated with hydraulic fracturing have been recorded with reported magnitudes in the range of -3.0 to < 3.0 (e.g. Verdon et al., 2010; Cipolla et al., 2012; Holland, 2013). Sometimes in a seismically active area such process may trigger larger or felt earthquakes ($M \geq 3.0$). Monitoring of microseismicity to understand the fracture growth and fault reactivation may be done using downhole geophones and or by massive surface arrays comprising hundreds of seismometers (e.g. Grechka, 2010; Gei et al., 2011). Clusters of microseismic events are recorded; the short bursts of events can be temporal as well as spatial. The opening of new fractures may generate normal and strike-slip faulting earthquakes and closing of old fractures may cause thrust/reverse faulting earthquakes. Frequency-magnitude relation *(b-value)* as well as fractal dimension (*D-value*) of induced microseismicity may also show variation with time and space, and shed light on seismic characteristics.

Evaluation of spatio-temporal dynamics of induced microseismicity helps to estimate physical characteristics of hydraulic fractures, like its length, propagation and contraction, its direction and penetration, permeability of the reservoir rock etc. (e.g. Shapiro and Dinske, 2007). The hydraulic fractures may grow from 3 m to 20 m, sometimes more, and could be conjugate to preexisting faults. Thus, understanding and monitoring of fluid-induced microseismicity helps to characterize oil and gas reservoirs and the growth of hydraulic fracturing and or reactivation of preexisting fault system.

Applications of microseismic monitoring in oil and gas industry have seen remarkable growth during the past decades (e.g. Maxwell, 2010). Oil and gas companies have made significant expenditures for microseismic monitoring, but face extraordinary technological challenges to fully utilize the results. The efforts are hampered by a number of factors, including an incomplete understanding of seismological processes that are associated with the induced microseismicity. This paper illustrates a few global case studies to understand some aspects of seismological processes of hydraulic fracturing microseismicity in oil and gas boreholes emphasizing its vital applications in oil industry.

2. Microseismicity Monitoring and Analysis

2.1 Monitoring microseismicity and hypocentre locations

The hydraulic fracturing (here after called *hydrofracturing*) microseismicity usually occurs as clusters, and varies with time and space. Monitoring or recording the hydrofracturing microseismicity by *borehole geophones* at depths, the usual practice, may produce good seismograms with higher signal to noise ratio (S/N), but azimuthal control for precise hypocentre locations of the events could be poor. Surface monitoring by hundreds or sometimes thousands of seismometers may produce much precise locations of the microseismic events. The surface seismometers, however, may be installed at a shallower (5~10 m) depth for recording at a higher S/N.

Sometimes even a 50-staion array on the surface in a smaller area can produce better results (e.g. Li et al., 2011, Tselentis et al., 2011). Long period waveforms of the microseismic events due to hydrofacturing give clear P and S arrivals. The long period character is due to the source effect, not the path effect (Bame and Fehler, 1986). The injection into a reservoir creates new fractures, as well as close, shear or open existing fractures. These various failure mechanisms lead to microseismic events which need to be understood in terms of reservoir productivity.

High precision hypocentre locations are extremely necessary to track the direction of fractures/fault structures or changes in the rock masses. Routine or initial locations may be obtained using most widely used Seisan program, which is basically based on multiple regression analysis using an assumed local homogeneous velocity model or an inverted 1D velocity model. However, due to heterogeneities in velocity structure in the reservoir area, the earthquake locations will not be much precise.

For much precise locations of the hypocentres, *hypocentre double difference* (HypoDD) *technique* is mostly used (e.g. Waldhauser and Ellsworth, 2000). A simple homogeneous 1D velocity model is justified in this analysis since in this technique relative relocations of the events are precisely computed. The relative relocations are insensitive to inaccuracies in the velocity model. These locations should be used to understand the active faults and hydrofractures in the oil fields.

In further advancement, the new hydrofracture zones and or the existing fault zones may be imaged by *double differential tomography* (TomoDD) method (Zhang and Thurber, 2003). This is basically a *simultaneous inversion* technique; it not only relocates the events with much higher precision developing inverted 3D velocity structure, but also produce the *tomograms or images* at any desired depth levels to visualise the perturbed or hydrofractured rock masses with heterogeneous velocities due to faults/fractures and fluid/gas content.

2.2 Fault plane solution

Fault plane solution or source mechanism is an important aspect to understand the nature of faulting that caused the earthquakes. The stress orientation plays the main role for different types of faulting, like normal faulting, strike slip faulting and thrust or reverse faulting.

There are two different methods to obtain fault plane solutions. The most classical method is the P-wave first-motion plot on equal area projection. With the digital seismograms, moment tensor solutions may also be obtained by waveform inversion, and the solutions may be compared with the respective first-motion solutions. The moment tensor analysis consists of generating synthetic seismograms and matching it with the observed seismic waveform including the P-wave first motion and its amplitude.

2.3 b-value and D-value estimation

Frequency of seismic events is considered to be a log-linear function of magnitude, corresponding to the power law distribution (Gutenberg and Richter, 1954), and it is given as: $\mathrm{Log}_{10}N = a - bM$, where N is the cumulative number of earthquakes having magnitude larger than M, **a** is a constant and **b** is the slope of the log-linear relation. In this analysis cumulative number of seismic events are plotted against magnitude; slope of the log-linear relation is known as *b-value,* which is normally 1.0 in a tectonically active region. This is an important seismological parameter to know stress condition of rock masses.

It has been reported that before a large event, the b-value decreases corresponding to sudden increase of stress in the rock masses. In case of cluster of events due to earthquake swarm, volcanic activity or induced microseismicity, the b-vale may be more (1.5-2.5) (Kayal, 2008).

Fractal dimensions (D), fractal properties of seismicity, a stochastic self-similar structure in time and space distribution of earthquakes, can be measured, which is introduced as a statistical tool to quantify dimensional distribution of seismicity, its randomness and clusterisation (e.g. Hirata, 1989). The fractal dimension of hypocentre distribution of seismicity may be estimated from the correlation integral given by Grassberger and Procaccia (1983): $C_r \sim r^D$, where (C_r) is the correlation function.

The correlation function measures the spacing (r) or clustering of a set of points, which in this case are earthquake hypocentres, and D is fractal dimension. By plotting C(r) against r on a double logarithmic

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coordinate, we can obtain the fractal dimension D from the slope of the curve.

Grob and Van der Baan (2011) illustrated that possible values of fractal dimension range between 0 and 3, which indicates the dimension of the embedding space. Interpretation of such limit values is that a set with D = 0 indicates a point i.e., all events clustered into one point; D = 1, a straight line i.e., events are homogeneously along a straight line, D = 2, a planer i.e., the events are homogeneously distributed over a two-dimensional embedding space, and D = 3, a sphere or cube, in a three dimensional space.

3. Case Studies

3.1 Oman Oil Filed

A surface-station network in the Oman oil field was established in 1999 by the Petroleum Development Oman (PDO), one of the pioneer oil industries to monitor hydrofacture microseismicity. In addition to surface-station network, the borehole geophones were also in operation for comparative study. During the period from 1999 to 2007, over 1500 induced microearthquakes were recorded and precisely located by Li et al. (2011) using the double difference seismic tomography (TomoDD); the epicenters and depth sections of the events are shown in Figure 1.

Most of the earthquakes occurred just above the oil layer, which is located at ~ 1.5 km below the surface. The oil and gas reservoir, a deep seated large anticline dome, ~ 15×20 km in size, is dominated by two fault systems with two preferred directions, southeast-northwest and northeast-southwest. The microseismicity trend shows that the northeast-southwest trending major fault system and the conjugate hydrofractures produce the microearthquakes, and these faults/fractures connects the oil horizons in the field (Fig. 1).

Fault plane solutions of some 40 selected events obtained by waveform inversion show normal, strike slip and reverse faulting (Li et al., 2011) (Fig. 1). Most of the events show normal faulting mechanism, some strike-slip and some reverse faulting. The normal or strike-slip faulting earthquakes indicate opening up of new fractures, and the thrust/reverse faulting earthquakes, on the other hand, indicate closing of old fracture zones. The epicentre trend and the determined fault planes indicate reactivation of the preexisting northeast-southwest fault system as well as the conjugate fractures caused the induced microseismicity.

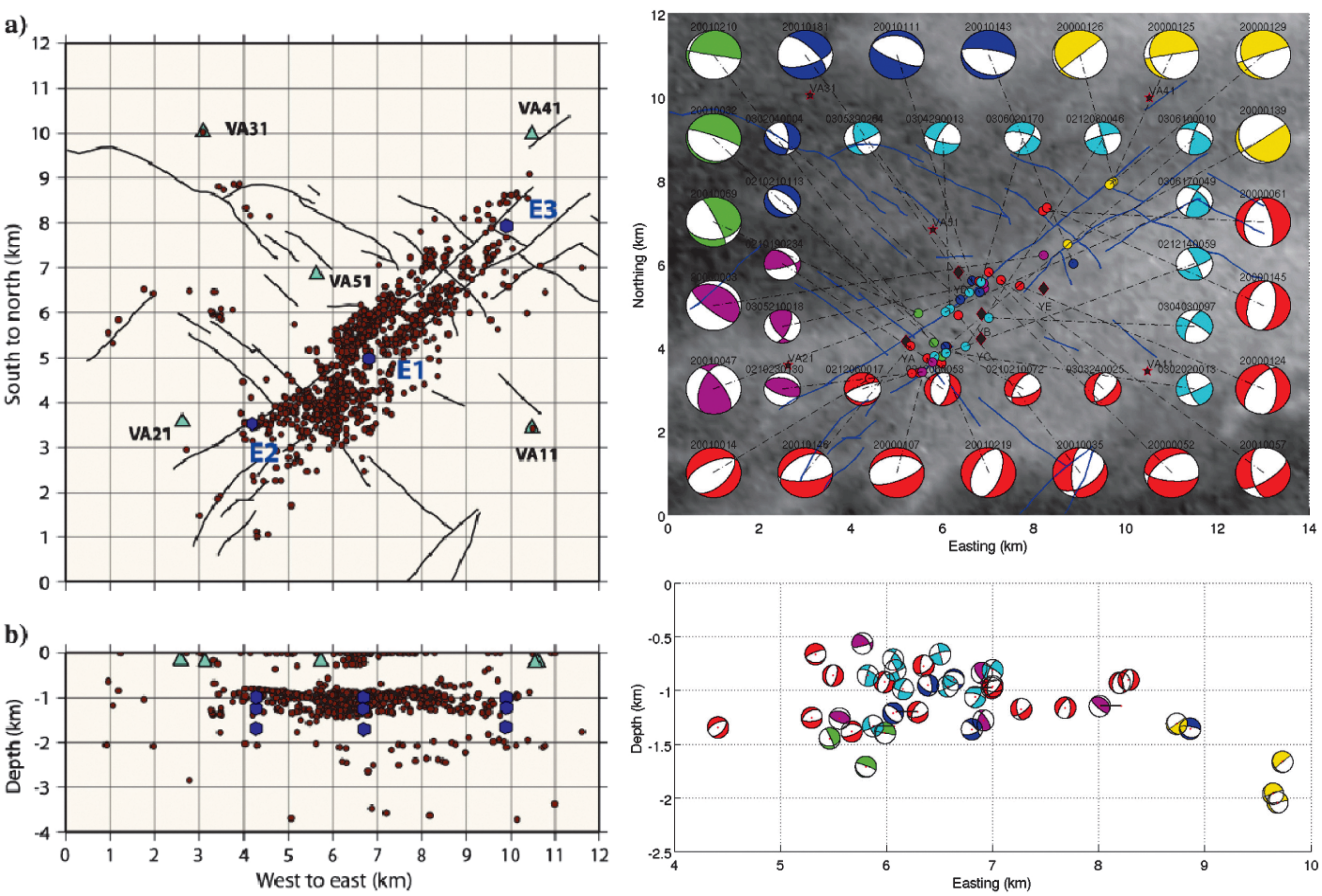


Fig. 1. (a) Left panel shows the precise epicentre map and the right panel shows 40 selected fault plane solutions; shade indicates the topography variation, and (b) left panel shows depth section of the microearthquakes and right panel the fault plane solutions at depths, the Oman oil field (after Li et al., 2011)

It was also found that the maximum horizontal stress derived from the source mechanisms trends in the northeast or north-northeast direction, which is consistent with the direction of the maximum horizontal stress obtained from the well breakout measurements and consistent with the known local tectonic stress (Li et al., 2011).

3.2 Kentucky Oil Field, USA

One of the early studies to map orientation of productive reservoir fractures was conducted in the Clinton County, Kentucky oil field using borehole sensors (Maxwell et al., 2010). In this field, oil is produced from low-porosity carbonate rocks at depths between 300 and 730 m. The existence of isolated fractures with high permeability and storage capacity was evident, but the fracture orientations were unknown and were assumed to be vertical.

The microseismicity monitoring was made near the high-volume production wells. The microearthquke locations and source mechanisms delineate a set of low-angle thrust faults that lie above and below the currently drained interval (Fig. 2). The identification and correlation of these faults with oil production indicated for the first time that these low-angle features should be considered important drilling targets in the exploration and development of the area.

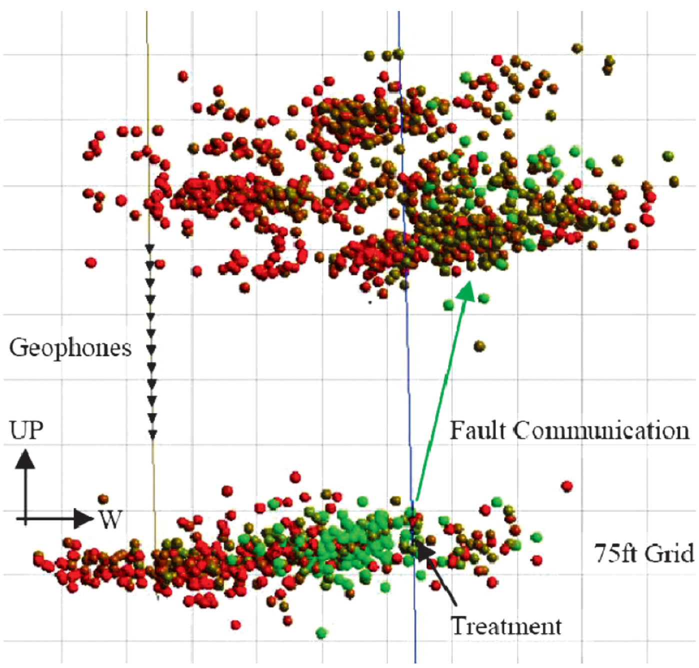
3.3 Alberta Oil Field, Canada

In this case study, we discuss b-value and D-value variation in microseismicity in an oil field in Alberta, Canada. The heavy-oil reservoir is drained using cyclic steam stimulation that produced some 2132 events in seven months, from September 2009 to March 2010. Prior to December 2009, only injection and then a combined injection and production strategy were adopted.

The frequency-magnitude distribution show that the b-value is 1.20 over the reliable magnitude-distribution part of the data set (Fig. 3a). The correlation integral plot estimates a D-value 2.36 over the linear part of the curve (Fig. 3b); this implies that the events are distributed rather spherically in space.

The Figure 3c represents temporal variations of the *b*-value from September 2009 to March 2010. The *b*-values are computed over 300 events with a moving window shift of 30 events. Three different stages are observed as highlighted by the ellipses. At the first stage during steam injection, fracturing with predominant tensional stress causes higher b-value, in the second stage injection and production cause lower b-value, and in the third stage when injection stopped, lowest b-value indicates fracture closing with predominant compression. Similarly, the Figure 3d represents three stages of D-value; the lowest D-values occur in the middle or second stage, indicating the possible presence of strike-slip faulting.

The measured temporal variations in *b-value and D-value show* a strong variation in local stress over a seven-month period; it ranges from extensional faulting (fractures opening), via a strike-slip regime, to finally compressive faulting (fractures closing).



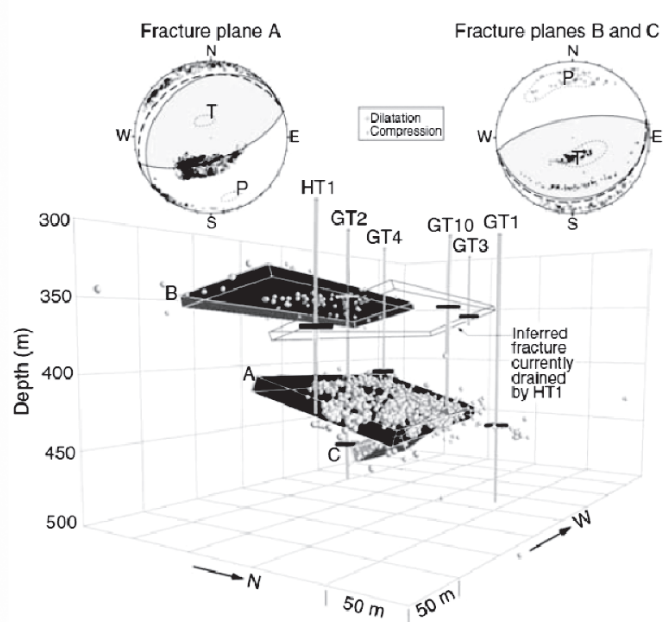


Fig. 2. (a) Depth section of microearthquakes recorded in two formations, the brittle failure occurs first in the right-most part of the bottom formation, and then suddenly jumps to the top sand formation, no activity in the middle shale layer. Green dots indicate microearthquakes when injection started, and red dots when along with injection, production made. (b) Fracture planes defined by 3D plot, the composite fault plane solutions indicate reverse / thrust faulting, Clinton County, Kentucky oil field (after Maxwell et al., 2010)

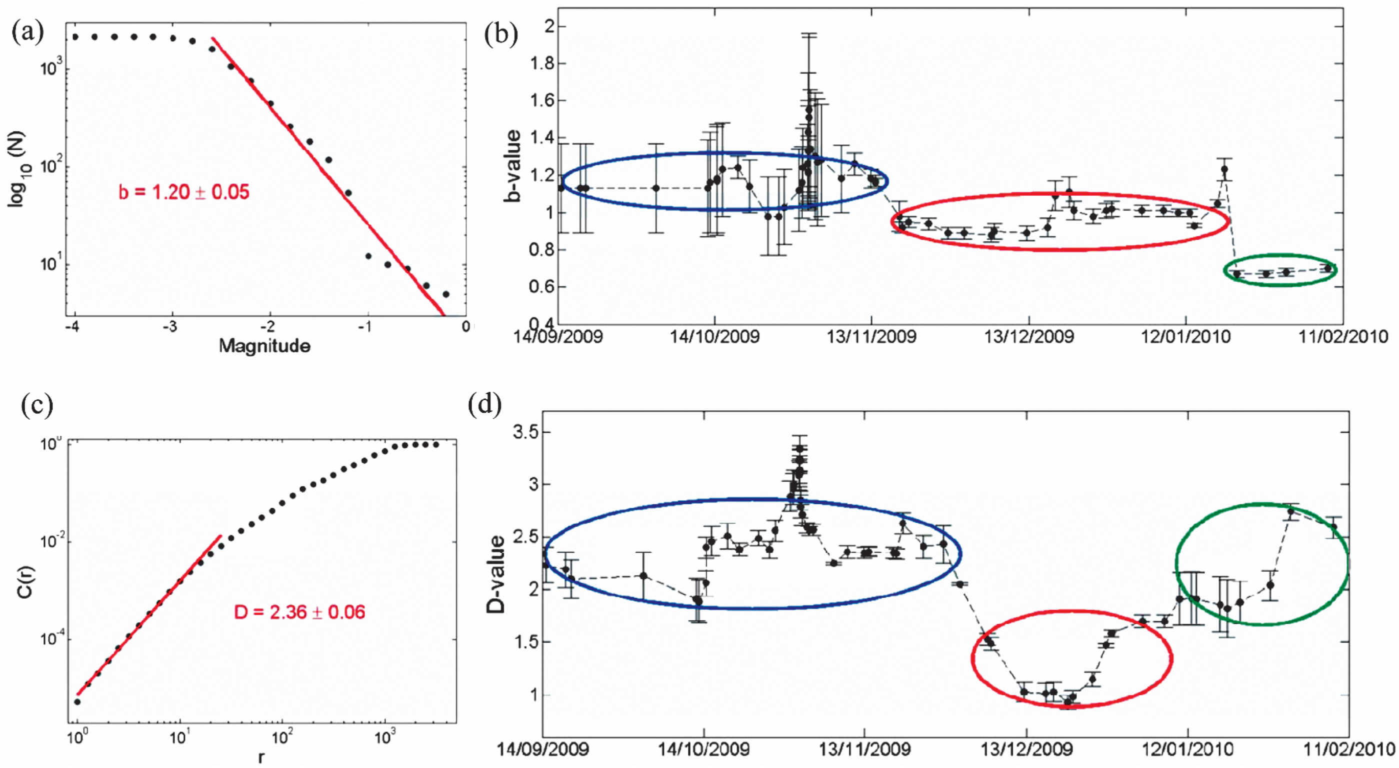


Fig. 3. (a) Frequency-magnitude relation with an average b-value 1.20, (b) temporal evolution of b-values, (c) correlation integral with an average D-value 2.36 and (d) temporal evolution of D-values; the ellipses emphasize the three different stages (see text); heavy-oil data set, Alberta (after Grob and Van der Baan, 2011)

The fractal dimension *D* indicates predominantly planar-to-spherical hypocenter distributions in the first and last stages, but changes to a more linear-to-planar spatial pattern in the middle stage of strike-slip regime.

Thus the microseismic event locations and their magnitudes contain a wealth of information to facilitate reservoir management.

3.4 Delvina hydrocarbon field, Southern Albania, Europe

Here, we discuss the important role of seismic tomography in oil exploration. The Delvina hydrocarbon field was designed with a network of 50 three-component borehole seismometers and 50 three-component surface seismometers. Magnitudes of the events ranged from 0 to 3 with most events occurring between M 1.0-2.0, and hypocentral depths between 0 and 20 km, with most located at depths 2-10 km (Fig. 4). Some 1860 microearthquakes were used in seismic tomography that imaged heterogeneous structures of the oil and gas reservoirs. Some 47,280 phase data, 24,438 P-arrivals and 22,842 S-arrivals, are used for the tomographic simultaneous inversion (Tselentis et al., 2011).

The results provided a wealth of information where conventional 2D seismic surveys did not work well. Using the tomography results two sub-regions of the investigated area are identified, one corresponding to an oil field and the other to a gas field. At the depth (~2 km) where the oil reservoir is encountered, the V_P/V_S values reach a maximum, and it is minimum in the gas field (Fig. 4).

4. Conclusions

This paper made an attempt to emphasize the importance of monitoring hydraulic fracturing microseismicity for better understanding of the fracture growth in oil and gas reservoirs in production. Hydraulic fracture, a rather complex structure, does not allow for modeling with required precision based on reservoir geology and fluid dynamics model.

Precise locations of microseismicity, fault plane solutions, temporal and spatial variations of b-values and D-values and differential seismic tomography can reveal wealth of information for reservoir development and management by mapping anomalous well drainage patterns, defining efficient drilling placement, correcting target depths ahead of the bit during exploratory drilling, correcting interpreted geologic horizon and so on. It is a modern technology in oil industry for efficient management and development.

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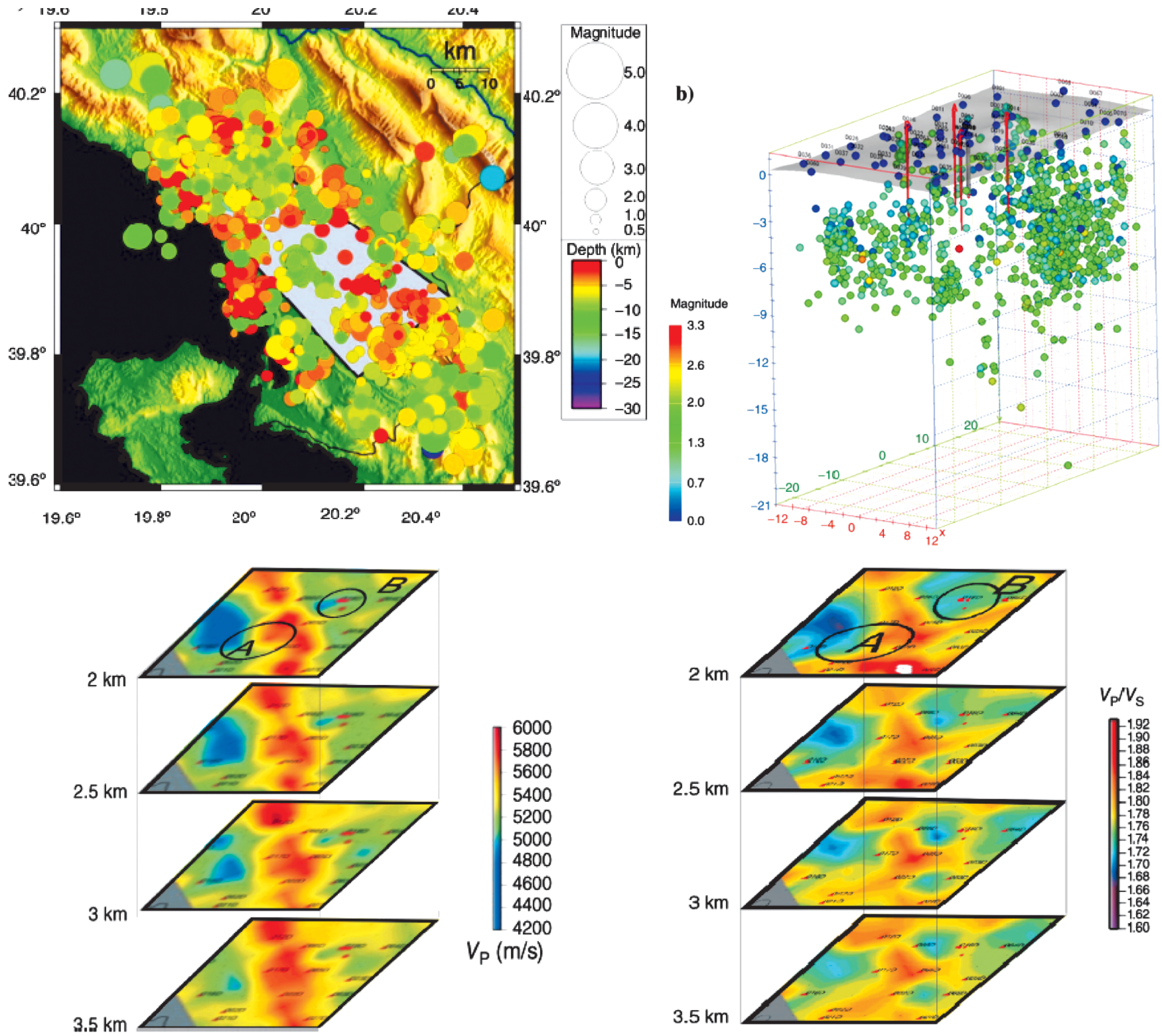

Fig. 4. (a) Microseismicity map, (b) 3D view of the hypocentres, and (c) Seismic Vp and (d) Vp/Vs depth slices differentiating the oil and gas bearing zones, Delvina oil field (after Tselentis et al., 2011)

the important International Scientific and Practical Conference «Horizontal wells and hydraulic fracturing to improve the efficiency of oil fields development» (September 6-7, 2017, Kazan, Russia) to deliver a lecture on such a fascinating topic. Thanks to all Russian friends who extended their kind help and support for giving me this opportunity to enrich myself and to interact with the august gathering in this Conference for future collaboration.

References

Bame, D. and Fehler, M. Conservations of long period earthquakes accompanying hydraulic facturing. *Geophys. Res. Lett*. 1986. 13. 149-152.

Cipolla, C., Maxwell, S., Mack, M. Engineering guide to the application of microseismic interpretations. SPE 152165. 2012.

Gei, D., Eisner, L., Suhadolc, P., Feasibility of estimating vertical transverse isotropy from microseismic data recorded by surface monitoring arrays. *Geophysics*. 2011. 76. WC117- WC126.

Grassberger, P. and Procaccia, I. Characterisation of strange attractors. *Phys. Rev. Lett*. 1983. 50. Pp. 346-349.

Grob, M. and Van der Bann, M. Inferring in-situ stress changes by statistical analysis of microseismic event characteristics. *The Leading Edge*. 2011. Pp. 1296-1301. doi: 142.244.191.132.

Gutenberg, B. and Richter, C. F. Seismicity of the Earth and Associated Phenomena. Princeton University Press, New Jersey. 1954. 310 p.

Hirata, T. A correlation between the b-value and the fractal dimension of earthquakes. *J. Geophys. Res*. 1989. 94. Pp. 7507-7514.

Holland, A. A. Earthquakes Triggered by Hydraulic Fracturing in South-Central Oklahoma. *Bull Seism Soc Am*. 2013. 103. doi: 10.1785/0120120109

Kayal, J. R., 2008. Microearthquake Seismology and Seismotectonics of South Asia. Springer, The Netherlands. 2008. 503 p.

Li, J., Kuleli, S. H., Zhang, H., and Toksöz, M N.Focal mechanism determination of induced microearthquakes in an oil field using full waveforms from shallow and deep seismic networks. Geophysics. 2011. 76(6). doi: 10.1190/GEO2011-0030.1

Maxwell, S. C., Rutledge, J., Jones, R. and Fehler, M. Petroleum reservoir characterization using downhole microseismic monitoring. *Geophysics*. 2010. 75 (5). doi: 10.1190/1.3477966

Maxwell, S. C., Cho, D., Pope, T., Jones, M., Cipolla, C., Mack M., Henery F., Leonard, J. Enhanced reservoir characterisation using hydraulic fracture microseismicity. SPE 140449. 2011.

Shapiro, S.A. and Dinske, C. Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing. *Geophysical Prospecting*. 2009. 57. Pp. 301-310.

Tselentis, G., Martakis, N., Paraskevopoulos, P., and Lois, A. High-resolution passive seismic tomography (PST) for 3D velocity, Poisson's ratio and P-wave quality QP in the Delvina hydrocarbon field, southern Albania, *Geophysics*. 2011. 76(6). doi: 10.1190/1.3560016

Verdon, J. P., J. Michael Kendall, M. and Maxwell, S. C. A comparison of passive seismic monitoring of fracture stimulation from water and CO_2 injection. *Geophysics*. 2010. 75. No. 3. MA1-MA7

Waldhauser, F. and Ellsworth, W.L. A double-difference earthquake algorithm: Method and application to the Northern Hayward Fault, California. *Bull. Seism. Soc. Am*. 2000. 90(6). Pp. 1353-1368.

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IDENTIFICATION OF HYDRAULIC FRACTURE ORIENTATION FROM GROUND SURFACE USING THE SEISMIC MOMENT TENSOR

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Abstract. Microseismic monitoring from ground surface is applied in the development of hard-to-recover reserves, especially in the process of hydraulic fracturing (HF). This paper compares several methods of HF microseismic monitoring from the surface, including diffraction stacking, time reverse modeling, and spectral methods. In (Aki and Richards, 1980) it is shown that signal enhancement from seismic events under correlated noises significantly improves when applying the maximum likelihood method. The maximum likelihood method allows to exclude influence of the correlated noise, and also to estimate the seismic moment tensor from ground surface.

Estimation of the seismic moment tensor allows to detect type and orientation of source. Usually, the following source types are identified: "Explosion Point" (EXP), "Tensile Crack" (TC), "Double-Couple" (DC) and "Compensated Linear Vector Dipole" (CLVD). The orientation of the hydraulic fracture can be estimated even when there is no obvious asymmetry of the spatial distribution of the cloud of events.

The features of full-wave location technology are presented. The paper also reviews an example of microseismic monitoring of hydraulic fracturing when there is no obvious asymmetry of microseismic activity cloud, but due to the estimation of the seismic moment tensor it becomes possible to identify with confidence the dominant direction of the fracture.

Keywords: Microseismic monitoring, seismic moment tensor inversion, fracturing, seismic event, maximum likelihood method

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Introduction

The task of locating deep microseismic events from the ground surface in the oil and gas industry has become particularly relevant recently when there is a depletion of conventional hydrocarbon reserves, and the development of reserves difficult to recover is usually carried out by hydraulic fracturing (Islamov, 2017). Knowledge of the real parameters of the fracture formed as a result of the hydraulic fracturing allows optimizing development of the field.

The most important parameter to be determined in the monitoring of hydraulic fracturing is the direction in which the fracture spreads. Knowledge of the fracture direction allows optimally orienting the horizontal trunk of the following wells, and also optimizing the locations of vertical wells to optimize the drainage area. The fracture direction is parallel to the direction of the main stress axis in the geological environment, which makes it possible to use this information for geomechanical simulation in order to optimize the construction of nearby wells.

Location technology

The direction of fracture propagation is usually determined by the orientation of the cloud of events accompanying the process of fracture formation. To localize microseismic events, various techniques for observing and processing microseismic information are used. The most well known is the technique of diffraction stacking, which is used to localize microseismic events for more than 50 years (Krey, 1952; Hagedoorn, 1954). The main principle of the diffraction stacking method is to calculate the time delays corresponding to the time of the signal travel from the analyzed points of the geological medium to the receiving points. After

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applying the calculated delays, the amplitudes of records are summed.

The method of computations in reverse time is also known (Gajewski and Tessmer, 2005); this method is based on the numerical simulation of the process of elastic waves propagation. The signals received during the monitoring are inversed on the time domain and used as sources at the location of sensors. For a time equal to the time of travel from the source to the observed group of receivers, the pulses are localized at the place of origin.

The spectral method (Kushnir, 2014) of the microseismic location and a number of other less well-known approaches are also known.

In (Aki and Richards, 1980) it is shown that the reliability of location of seismic events against the background of correlated noises increases significantly when using the maximum likelihood method. The authors use it to locate one center of an earthquake against the background of another. However, the presence of correlated noise is not typical for seismology, given the considerable spacing of seismological stations.

When microseismic events are located, on the contrary, correlated noises from operating equipment (hydraulic fracturing fleet, oil and gas infrastructure) make up the bulk of the noise. As shown in (Birialtsev, Demidov, Mokshin, 2017), the maximum likelihood method allows to exclude the correlated noise component, and also allows to determine not only the coordinates, but also the tensor of the seismic moment when localizing from the ground surface.

The definition of the seismic moment tensor makes it possible to calculate the direction of the fracture causing the microseism in a single event. Thus, it becomes possible to clarify the direction of fracturing at the site of the hydraulic fracturing, even if the cloud of microseismic events is not clearly expressed.

To apply the maximum likelihood method, we need to know the form of the useful signal. In the general case, a useful signal is the full-wave response of the medium to the impulse action. Calculating the shape of a useful signal in a geological medium is possible by using full-wave 3D numerical simulation (Birialtsev, Berezhnoj, Birialtseva, Hramchenkov, 2008). To calculate the seismic moment tensor, it is necessary to simulate 6 types of impulse actions of various types (Birialtsev, Demidov, Mokshin, 2017).

Full-wave 3D numerical modeling and event location using the maximum likelihood method require significant computational capacity, thus supercomputer calculations are used to obtain the results at an acceptable time (Galimov, Birialtsev, 2010).

The full-wave location technology is characterized by a number of features:

1. Registration during monitoring of hydraulic fracturing is performed from the ground surface by independent sets of broadband highly sensitive seismometers installed in the quietest areas of the territory (Ryzhov, Sharapov, Birialtsev, Feofilov et al., 2015);

2. Due to the use of full-wave 3D numerical simulation, the complete information about the signal at the sensor installation sites is used during localization by three components (full-wave response, including compression, shear, exchange, and re-reflected waves) from single impulse actions;

3. Event location is performed using the maximum likelihood method – theoretically the most noise-immunity method of signal isolation against the background of noise, which best localizes the event at a low signal-to-noise ratio.

4. The tensor of the seismic moment is calculated for each seismic event, which allows determining the type of event and the orientation of fracture that formed the event. The events that are not related to the fracture opening are rejected by type, and in the orientation of events it is possible to estimate the azimuth of the crack formation without accumulating a significant event cloud for the statistics.

At the same time, a technological leap forward in the development of supercomputer computing systems (Galimov, Birialtsev, 2010; Demidov, Ahnert, Rupp and Gottschling, 2013; Birialtsev et al., 2015; Anastasiya Belyaeva, Eugeniy Biryaltsev, Marat Galimov et al., 2017), allowed the use of resource-intensive location methods (Birialtsev, Demidov, Mokshin, 2017), using the most complete information about the seismic event.

The full-wave location has been used to solve problems in the oil and gas industry since 2011, several articles with the results of its application appeared (Biryaltsev et al., 2016; Ryzhov et al., 2015; Khisamov et al., 2015; Shabalin et al., 2013).

Location results

Deformation of porous liquid-saturated rocks is a complex process during which the mineral skeleton of the rock is simultaneously distorted (under the influence of changing effective stresses and reservoir pressure gradients) and fluid filtration in the pores (as a result of the action of reservoir pressure gradients and volumetric deformation of the skeleton) (Smetannikov, Kashnikov, Ashihmin, Shustov, 2015; Shapiro, 2015).

Consequently, the zones of increased microseismic activity detected during the monitoring of hydraulic fracturing can be associated with the processes occurring in the reservoir under the influence of hydraulic fracturing and which inextricably include the following:

1. Formation/closing of fractures;
2. Fracture opening during filling with proppant;
3. Deformation of the rock in areas with a precritical state due to the spreading of the pressure front along the natural channels of filtration;
4. Deformation of the rock in areas with a precritical state due to the spreading of the pressure front through the solid rock.

When the fracture is opened, the created pressure in the port area begins to be set along the entire fracture. After that, the whole plane of open fracture, and not just the port becomes the source of pressure. Further, new fracturing zones may be formed, while the previously opened fracture may be elongated, branched off and expanded.

During the expansion of the fracture, deformation of nearby rocks occurs, causing microseismic activity in the form of a cloud of events around the fracture. Also, the reason for the formation of a cloud of events, and not lineaments, is a limitation in the accuracy of the location.

The result of the location is a set of events with space coordinates and the seismic moment tensor. On the basis of seismic moment tensor the degree of belonging of the event to the base types of events is estimated. There are several basic types of events:

1. “Explosion Point” (EXP);
2. “Tensile Crack” (TC), “Double Couple” (DC);
3. “Compensated Linear Vector Dipole” (CLVD).

The orientation of the tensile crack is evaluated only for high-weight events “Tensile Crack” (TC).

For events such as “Explosion Point” (EXP), it is not appropriate to speak about azimuth, since all three of its eigenvectors are equivalent and the azimuth parameter is determined unstable in this case. For events of mixed type, for example, 45% TC and 40% EXP, the estimate of the azimuth of fracture is valid, but with less certainty than for a more pronounced tensile crack of 80% TC. For DC and CLVD events, the determination of the fracture orientation is not performed; on the contrary, such events are excluded from processing, as events not related to the volume change (opening/closing of the fracture).

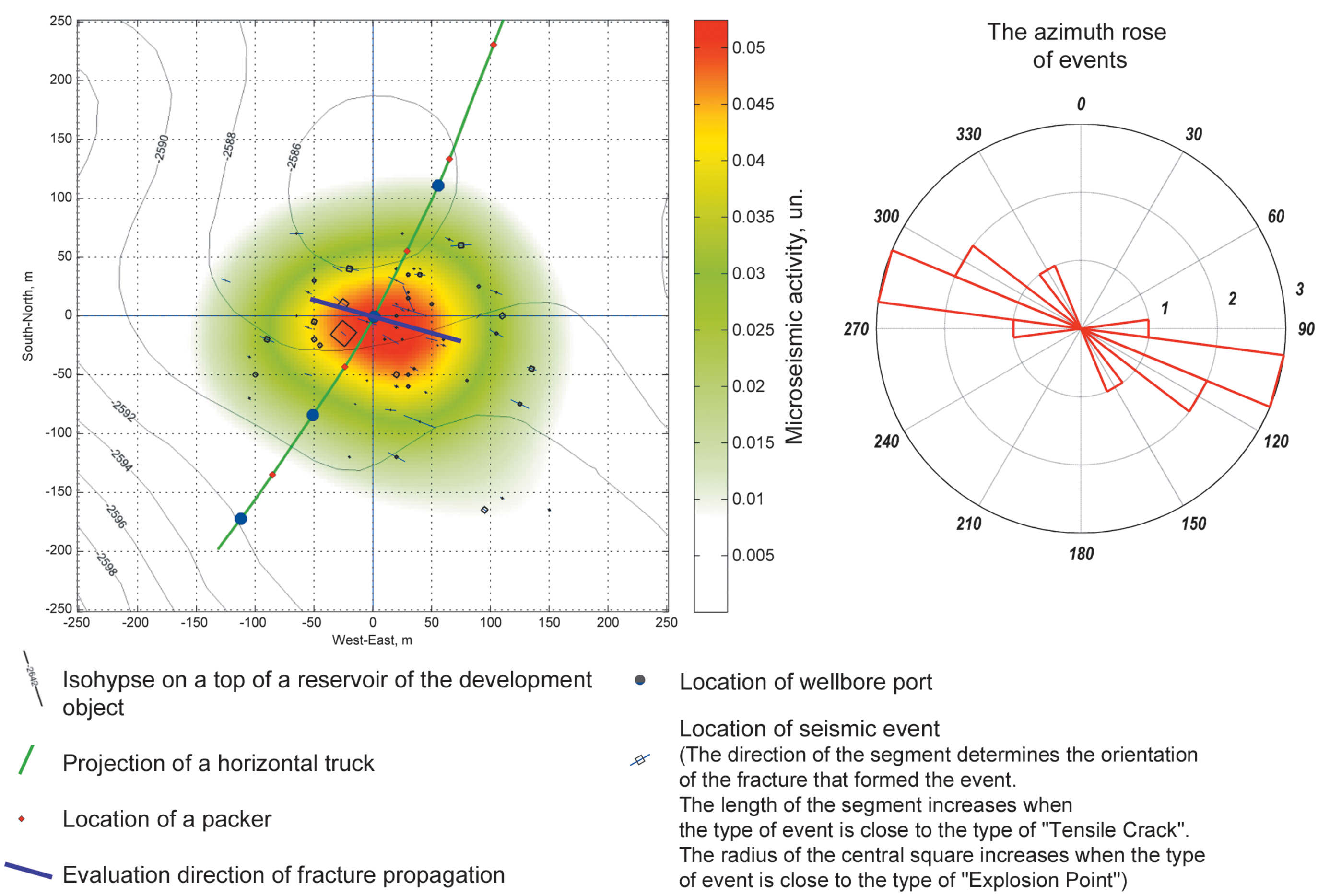

Fig. 1. An example of a result of hydraulic fracturing monitoring with the definition of the seismic moment tensor

Figure 1 presents the results of the events location from the surface by the technology of full-wave location for vertical depths of the order of 2.7 km. As a result of simulation, estimates of location accuracy for these conditions were obtained: the error of the location is not more than 35 m, the error in determining the azimuth of the crack is not more than 15 degrees.

On the resulting map, events in the port area are fairly wide spread, which does not allow us to confidently identify the direction of the fractures only at their location, but due to the azimuth rose of each event, through the seismic moment tensor, it became possible to estimate the direction of the fracture.

Conclusion

Thus, the technology of microseismic location from hydraulic fracturing using the maximum likelihood method makes it possible to determine the direction of hydraulic fractures even under conditions of low accuracy spatial location of microseismic events.

Low accuracy location of events can be caused by difficultly removable causes: high noise level of technogenic activity on the surface, low-frequency operating range (due to attenuation of the high-frequency component of the signal due to high depth), as well as the very complex nature of fracture propagation, like fracture fabric (Cipolla, Weng, Mack, Ganguly, Gu, Kresse, Cohen, 2011), which forms a network of parallel fractures.

The definition of the seismic moment tensor and the direction of fracture with its use is more stable to the listed factors, which justifies the use of a computationally more complex maximum likelihood method in a complex geological environment.

References

Aki, K. and Richards, P.G. Quantitative seismology. Freeman and Co. 1980.

Anastasiya Belyaeva, Eugeniy Biryaltsev, Marat Galimov, Denis Demidov, Aleksandr Elizarov, Ol'ga Zhibrik. Architecture of HPC clusters for Oil&Gas Industry. *Program systems: Theory and applications*. 2017. 8:1(32). Pp. 151-171. (In Russ.). http://psta.psiras.ru/read/psta2017_1_151-171.pdf

Biryaltsev E., Bogdanov P., Galimov M., Demidov D., Elizarov A. HPC Platform for Oil & Gas Industry. *Program systems: theory and applications*. 2016. 7:1(28). Pp. 15-27. (In Russ.). http://psta.psiras.ru/read/psta2016_1_15-27.pdf

Birialtsev E.V., Berezhnoj D.V., Birialtseva T.E., Hramchenkov M.G. The results of numerical simulation of the propagation of natural microseisms in the zones of occurrence of oil and gas deposits. *Conference EAGE, GEOMODEL*. Gelendzhik. 2008. (In Russ.)

Birialtsev E.V., Demidov D.E., Mokshin E.V. Determination of moment tensor and location of microseismic events under conditions of highly correlated noise based on the maximum likelihood method. *Geophysical Prospecting*. 2017. doi: 10.1111/1365-2478.12485

Biryaltsev E.V., Shabalin N.Y., Ryzhov V.A., Sharapov I.R. Application of Full Wave Location technology with determining seismic moment tensor of events for Hydraulic Fracture Monitoring and Natural Fractures. *Sixth EAGE Workshop on Passive Seismic: From Data to Decisions*. 2016.

Cipolla C., Weng X., Mack M., Ganguly U., Gu H., Kresse O., Cohen C. Integrating microseismic mapping and complex fracture modeling to characterize fracture complexity. *Society of Petroleum Engineers*. 2011. doi:10.2118/140185-MS.

Demidov D., Ahnert K., Rupp K. and Gottschling P. Programming CUDA and OpenCL: A case study using modern C++ libraries. *SIAM Journal on Scientific Computing*. 2013. 35(5). Pp. 453-472.

Hagedoorn J.G. A process of seismic reflection interpretation. *Geophysical Prospecting*. 1954. 2. Pp. 85-127.

Galimov M.R., Birialtsev E.V. Some technological aspects of applying high-performance computing on graphics processors in application software systems. *Vychislitelnye metody i programmirovanie = Numerical methods and programming*. 2010. V. 11. Pp. 77-93. (In Russ.)

Gajewski, D. and Tessmer, E. Reverse modelling for seismic event characterization. *Geophys. J. Int*. 2005. 163(1). Pp. 276-284.

Islamov D.Je. Improvement of methods for designing fracturing operations to improve well productivity. *Diss. dokt. tech. nauk*. [Dr. engineer. sci. diss.]. Tyumen. 2015. 124 p. (In Russ.)

Khisamov R.S., A.S. Ahmetshina, V.A. Taipova, M.M. Salihov, I.R. Sharapov Passive surface microseismic monitoring of hydraulic fracturing in injection wells of Tatneft PJSC. *Neftyanoe hozyaystvo = Oil Industry*. 2015. 7. Pp. 34-38. (In Russ.)

Kushnir A., Varypaev A., Dricker I., Rozhkov M. and Rozhkov N. Passive surface microseismic monitoring as a statistical problem: location of weak microseismic signals in the presence of strongly correlated noise. *Geophys. J. Int*. 2014. 198 (2). Pp. 1186-1198.

Krey T. The significance of diffraction in the investigation of faults. *Geophysics*. 1952. 17. Pp. 843-858.

Ryzhov V.A., Sharapov I.R., Birialtsev E.V., Feofilov S.A., Ryzhov D.A., Kamilov M.R., Stepanov A.I. Experience Applying the Full-Wave Location Method for Microseismic HF Monitoring in Horizontal Well in Western Siberia. *EAGE – Horizontal Wells. Problems and Prospects*. 2015. (In Russ.)

Smetannikov O.Ju., Kashnikov Ju.A., Ashihmin S.G., Shustov D.V. Numerical model of crack growth in hydraulic re-fracturing. *Vychislitel'naja mehanika sploshnyh sred = Computational Continuum Mechanics*. 2015. V. 8. No. 2. Pp. 208-218. (In Russ.)

Shapiro S.A. Fluid-Induced Seismicity. Cambridge University Press. 2015. 289 p.

Shabalin N.Ja., Birialtsev E.V., Ryzhov V.A., Mokshin E.V., Feofilov S.A., Sharapov I.R., Ryzhov D.A. Opportunity to study the upper part of section based on full-wave numerical simulation. *Exposition Oil & Gas*. 2013. No. 6. Pp. 40-43. (In Russ.)

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MULTISENSOR RESEARCH TECHNOLOGIES OF OIL HORIZONTAL WELLS ON FIELDS OF THE REPUBLIC OF TATARSTAN

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Abstract. In the Republic of Tatarstan the development widely involves hard-to-recover reserves of hydrocarbons, confined to low-permeable, heterogeneous and dissected reservoirs. Improvement of recovery efficiency of such reserves largely depends on the operational control system based on information about the filtration and thermal properties of the oil reservoir. Issues, related to the interpretation of geological field information, lead to incorrect mathematical problems in terms of Hadamard. The numerical solution of such problems requires the development of special methods. A mathematical model of thermohydrodynamic processes occurring in the 'horizontal well' system is constructed in the paper.

Based on this model and regularization methods of A.N. Tikhonov, a computational algorithm is proposed for interpreting the results of thermohydrodynamic studies of horizontal wells and layers. Curves of the temperature changes are taken as the initial information, taken simultaneously by several deep instruments installed at different parts of the horizontal part of the wellbore. This approach makes it possible to evaluate the filtration parameters of an inhomogeneous reservoir and to construct an inflow profile along the trunk of a horizontal well.

Key words: horizontal well, pressure, temperature, permeability, multi-sensor technologies, inverse task
DOI: https://doi.org/10.18599/grs.19.3.14

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Conducting and processing the results of thermohydrodynamic studies in the development of fields with hard-to-recover hydrocarbon reserves, as a rule, involve significant difficulties. These include: the mechanization of the producing wells stock, that makes it difficult to deliver deep measuring instruments to the bottom of wells; low rates, leading to low information content of debitometric studies; thermodynamic processes accompanied by small temperature changes; a long duration of hydrodynamic studies hindering the use of classical methods of interpreting pressure recovery curves.

Measurements of temperature and pressure in the trunk of a horizontal well based on multi-sensor technology (Farkhullin et al., 2003; Khairullin et al., 2006) provide quite complete information on the thermohydrodynamic processes occurring in the reservoir and the trunk. The change in temperature in the trunk of a horizontal well is an integral indicator of heat and mass transfer processes occurring both in the well itself and in the reservoir.

We will assume that the trunk of the horizontal well is parallel to the roof and the base of the reservoir; fluid movement in the trunk is one-dimensional. The process of pressure distribution in the trunk is quasi-stationary; the inflow of fluid to the trunk at the start of the well is radial. Under these assumptions, the laws of conservation of mass, momentum, and energy, it follows that (Vasilyev, Voevodin, 1968; Charnyi, 1975):

$$\frac{\partial v}{\partial x} = -\frac{2w}{r_c},\ w = -\frac{k}{\mu}\frac{\partial p_2}{\partial r}\bigg|_{r=r_c},\ 0<x\le L, \quad (1)$$

$$-\frac{\partial p_1}{\partial x} = \rho\frac{\partial (v^2)}{\partial x} + \frac{\psi}{4r_c}\rho v|v|,\ 0<x\le L, \quad (2)$$

$$\frac{\partial T_1}{\partial t} + v\left(\frac{\partial T_1}{\partial x} + \varepsilon\frac{\partial p_1}{\partial x}\right) = \frac{2(\alpha_m - w\rho C_p)}{\rho C_p r_c}\left(T_2\big|_{r=r_c} - T_1\right),$$

$$0<x\le L,\ 0<t\le t_{\exp}, \quad (3)$$

$$\beta^*\frac{\partial p_2}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k}{\mu}r\frac{\partial p_2}{\partial r}\right),$$

$$0<x\le L,\ r_c<r<R_k,\ 0<t\le t_{\exp}, \quad (4)$$

$$C_\pi\frac{\partial T_2}{\partial t} = \rho C_p\frac{k}{\mu}\frac{\partial p_2}{\partial r}\left(\frac{\partial T_2}{\partial r} + \varepsilon\frac{\partial p_2}{\partial r}\right),$$

$$0<x\le L,\ r_c\le r<R_k,\ 0<t\le t_{\exp}, \quad (5)$$

with initial

$$p_2(x,r,0)=p_0(x,r),\ T_2(x,r,0)=T_0(x,r),\ 0\le x\le L,\ r_c\le r<R_k, \quad (6)$$

and boundary conditions

$$\int_S \frac{k}{\mu}\frac{\partial p_2}{\partial r}dS = q,\ 0<t\le t_{\exp}, \quad (7)$$

$$p(x, R_k, t)=p_k,\ T_2(x, R_k, t)=T_k. \quad (8)$$

Here, $p_1=p_1(x)$, $T_1=T_1(x, t)$ is the pressure and

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temperature in the trunk of a horizontal well, $p_2=p_2(x, r, t)$, $T_2=T_2(x, r, t)$ is the pressure and temperature in the reservoir, p_k – reservoir pressure, T_k – reservoir temperature, q – horizontal well production rate, S – trunk surface of a horizontal well, r_c – trunk radius, R_k – external boundary radius, β^* – reservoir elasticity, $v(x)$ – fluid velocity in the trunk of a horizontal well, ρ – fluid density, ε – Joule-Thomson coefficient, ψ – coefficient of hydraulic resistance, α_m – coefficient of heat transfer of horizontal well trunk, C_p – the specific heat of fluid, w – filtration rate, L – the length of the horizontal well trunk, t_{exp} – operating time of the well.

The method of solving the boundary task (1)-(8) is based on the conjugation of the external (reservoir) and internal (trunk of a horizontal well) tasks. The system (1)-(8) is solved numerically by the method of finite differences. The filtration area is covered by a non-uniform grid, which thickens to the well. The resulting non-linear system of difference equations is solved iteratively.

The model task with data corresponding to the real deposits of the Republic of Tatarstan explores the thermohydrodynamic processes occurring in the "reservoir – horizontal well" system.

A simulated oil reservoir is considered, which is developed by a horizontal well. The horizontal well is put into operation with a constant recovery of liquid from the reservoir. Initial data:

$C_n = 1.48\ 10^6\ J/(m^3K)$,
$C_p = 1929\ J/(kg\ K)$,
$T_k = 300\ K$,
$p_k = 15\ MPa$,
$\beta^* = 10^{-4}\ MPa^{-1}$,
$\mu = 25\ mPa\ s$,
$\rho = 800\ kg/m^3$,
$\varepsilon = 0.4\ K/MPa$,
$L = 100\ m$,
$r_c = 0.1\ m$,
$R_k = 5\ m$,
$q = 30\ m^3/day$.

It is assumed that the permeability of the reservoir is a piecewise constant function. In each zone of the reservoir homogeneity, a deep instrument is located (Fig. 1). The following variants of zones of the reservoir heterogeneity are considered:

$k_1>k_2$, $k_1 = 0.05\ \mu m^2$, $k_2 = 0.01\ \mu m^2$,
$k_1<k_2$, $k_1 = 0.01\ \mu m^2$, $k_2 = 0.05\ \mu m^2$.

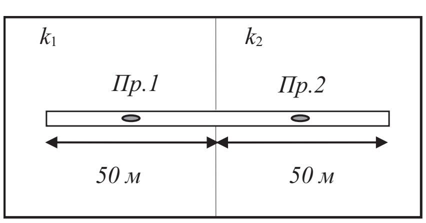

Fig. 1. Arrangements of instruments in a heterogeneous reservoir

In the trunk of a horizontal well, liquid comes from zones of heterogeneity of the oil reservoir with different temperatures due to the Joule-Thomson effect (Fig. 1). The change in temperature in the trunk of a horizontal well is due to the calorimetric effect.

The results of numerical calculations showed that for a homogeneous oil reservoir, the temperature along the trunk is constant and increases with time. The fluid velocity along the horizontal well trunk changes linearly. Figures 2-3 show the calculation results of the change in temperature and flow velocity for variants 1,2 at time = 120 h. The temperature (Fig. 2), the flow velocity (Figure 3) in the trunk of a horizontal well changes non-linearly. The intensity of the fluid inflow to the trunk of a horizontal well (Figu. 4-5) has a discontinuity at the point corresponding to the boundary of the reservoir homogeneity zones in terms of permeability. The distribution of temperature, flow velocity along the horizontal well trunk and the intensity of the fluid inflow to the horizontal well trunk depend on the permeability values and the size of the uniformity zones.

A distinctive feature of the inverse tasks of oil and gas hydromechanics, associated with the study of mathematical models of real filtration processes in oil reservoirs, is that the nature of additional information is determined by the capabilities of the field experiment. On the basis of the proposed mathematical model

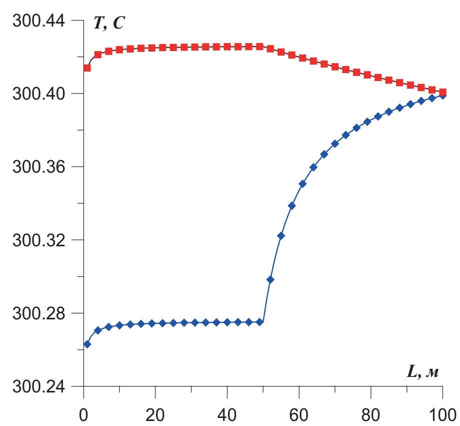

Fig. 2. Temperature distribution along the trunk of a horizontal well. ■ – *Var.1* $k_1>k_2$, ♦ – *Var. 2* $k_1<k_2$.

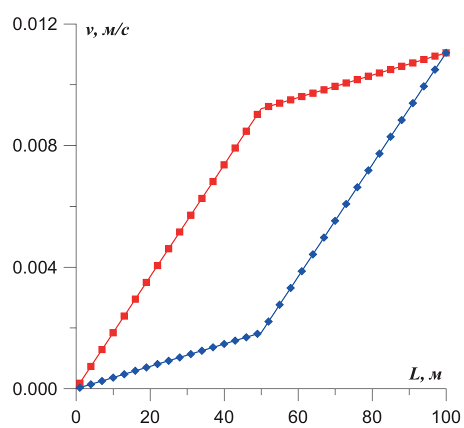

Fig. 3. Distribution of velocity along the trunk of a horizontal well. ■ – *Var.1* $k_1>k_2$, ♦ – *Var. 2* $k_1<k_2$

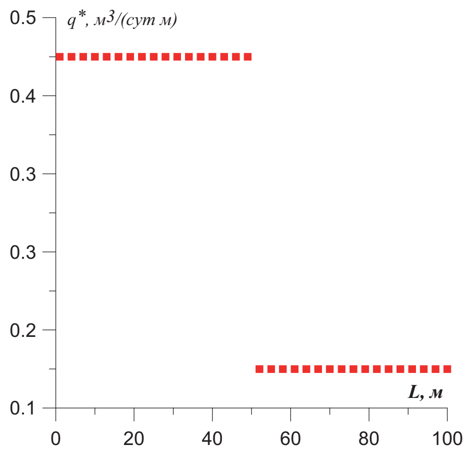

Fig. 4. Temperature distribution along the trunk of a horizontal well. ■ *– Var.1 $k_1>k_2$*

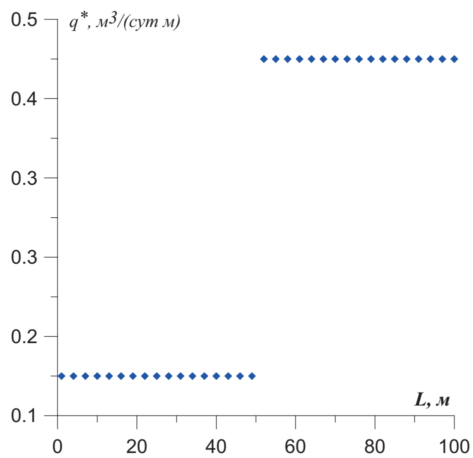

Fig. 5. Temperature distribution along the trunk of a horizontal well. ♦ *– Var. 2 $k_1<k_2$*

and regularization methods of A.N. Tikhonov, a computational algorithm is proposed for interpreting the results of thermohydrodynamic studies of horizontal wells. The results of measurements of the temperature change during the start-up period of the well at different sections of the horizontal well trunk are used as initial information. The locations of the deep measuring equipment are determined on the basis of geophysical studies of the well. In works (Farkhullin et al., 2003; Khairullin et al., 2006), a technology for performing thermohydrodynamic studies of a horizontal well with the help of several deep autonomous instruments is described.

Let us assume that in the locations of deep measuring instruments in the trunk of a horizontal well with coordinates x_i, $i=\overline{1,N}$, the curves of temperature changes are taken:

$$T_{1,i}(t) \equiv T_1(x_i, t)=\varphi_i(t),\ i=\overline{1,N},\ 0<t\le t_{exp}. \tag{9}$$

The inverse coefficient task is formulated as follows: determine the permeability coefficient $k=k(x,r)$, when the thermohydrodynamic processes in the oil reservoir and the horizontal well trunk are described by equations (1)-(8). As the initial information, the measured values of temperature by deep autonomous devices are used.

An estimate of the permeability coefficient is sought in the class of piecewise constant functions $k(x,r) = k_n$, $(x,r)\in V_n$, $\bigcup_{n=1}^{N} V_n = V$, where V_n, $n=\overline{1,N}$ – homogeneity areas (Fig. 1).

An approximate solution of the inverse coefficient task (1)-(9) is sought from minimizing the root-mean-square deviation between the observed and calculated quantities:

$$F(\alpha)=\sum_{n=1}^{N}\int_0^{t_{exp}}\left[T_{1,n}(t)-\phi_n(t)\right]^2 dt \tag{10}$$

Where $\varphi_n(t)$ – the observed values of the temperature, $T_{1,n}(t)$ – the calculated temperature values obtained from the numerical solution of equations (1)-(8), $\alpha=(k_1, k_2, \ldots, k_N)$ – the parameter sought, $0 < m_n \le k_n \le M_n$ (m_n, $M_n = const$).

Research of the horizontal well No 18326 (Nazimov, 2007). The well is located in the deposit No. 665 of the Romashkino field of the Republic of Tatarstan. The well has a 313 m open horizontal section in the Dankovo-Lebedyanskian horizon in the interval from 1475 to 1788 m. In 2004, deep thermohydrodynamic studies based on multi-sensor technologies were carried out in the well. Figure 6 shows the locations of the instruments. After the end of the underground repair, the well was put into operation with a flow rate of 7.8 m^3/day.

The proposed computational algorithm is used to

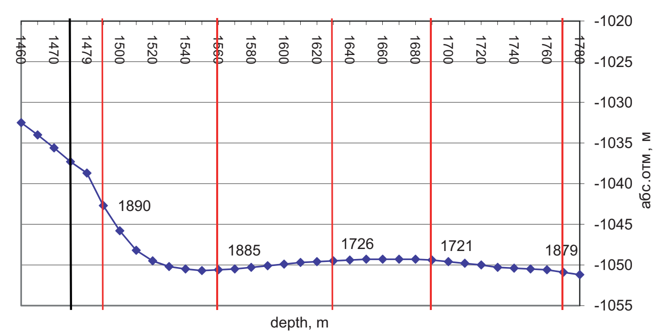

Fig. 6. Trajectory scheme of the trunk of the horizontal well No 18326 and the location of the instruments

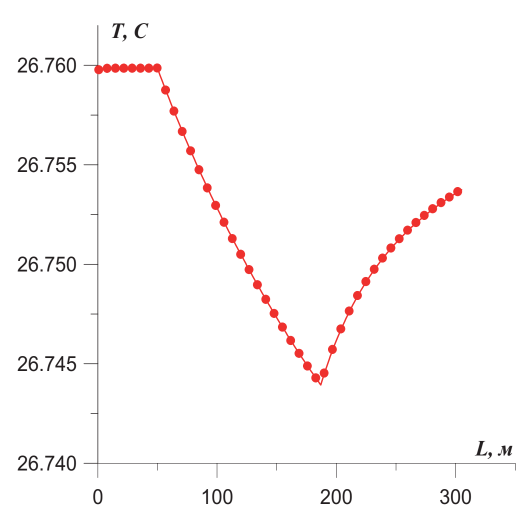

Fig. 7. Temperature distribution along the well trunk

interpret the temperature variation curves taken with the depth instruments No. 1879, 1721, 1726 and 1885. For this purpose, the reservoir was divided into four zones of homogeneity, in which the devices No. 1879, 1721, 1726 and 1885 were located.

Figures 7-8 show the calculation results of the distribution of temperature and fluid flow velocity in the trunk of a horizontal well. The distribution of fluid flow along the trunk of a horizontal well is shown in Figure 9. Figures 10, 11, 12 and the table show the interpretation results of the curves of temperature variation with respect to instruments No. 1879, 1721 and 1885. Figures 10, 11, 12 present the calculated and observed curves of temperature changes. The table provides estimates of permeability in the instrument areas.

From the results obtained, it follows that the locations of instruments No. 1721, 1726 have a low permeability – in these sections the inflow to the trunk of a horizontal well is the smallest (Fig. 9). Geophysical studies have shown that in the location of 1680-1721 m (instrument No. 1721), the well trunk passes through a low permeable inclusion, and in the location of 1620-1670 m (instrument No. 1726) – through a weakly

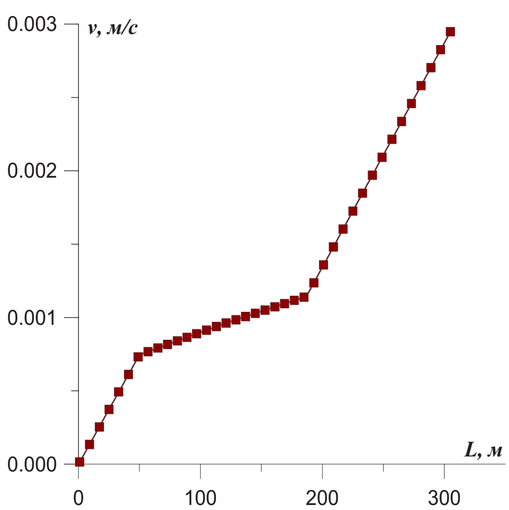

Fig. 8. Velocity distribution along the well trunk

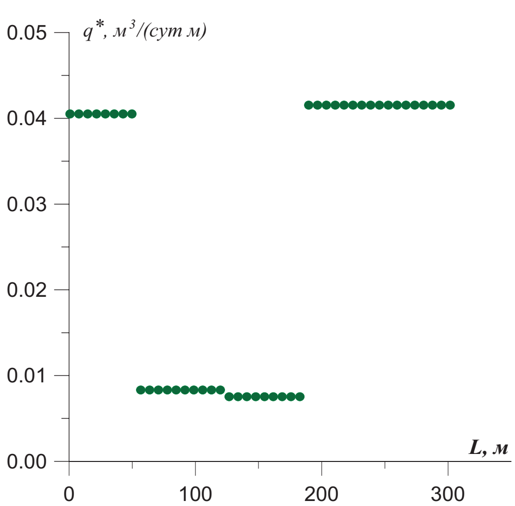

Fig. 9. Inflow distribution along the well trunk

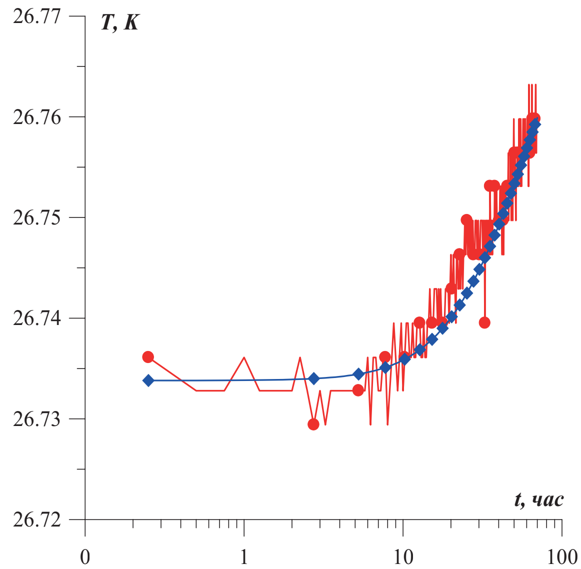

Fig. 10. Instrument No. 1879. Temperature change curve ● – observed, ♦ – calculated

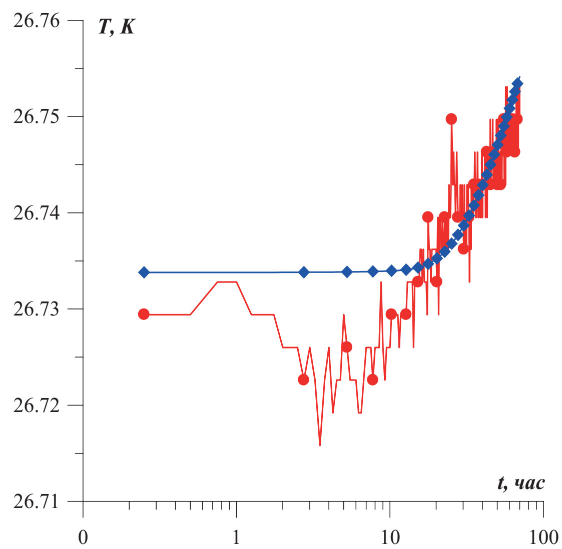

Fig. 11. Instrument No. 1721. Temperature change curve ● – observed, ♦ – calculated

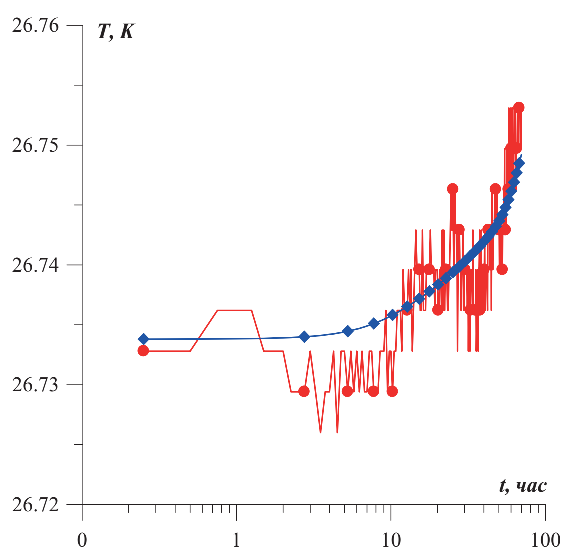

Fig. 12. Instrument No. 1885. Temperature change curve ● – observed, ♦ – calculated

	Zone device No. 1879	Zone device No. 1721	Zone device No. 1726	Zone device No. 1885
Interpretation of curves of temperature variation				
k/μ (μ m^2/mPa·s)	1.04 10^{-3}	2.13 10^{-4}	1.93 10^{-4}	1.07 10^{-3}
Interpretation of curves of pressure variation				
k/μ (μ m^2/ mPa·s)	3,42·10^{-3}	4,46·10^{-3}	3,63·10^{-3}	6,34·10^{-3}

Table. Horizontal well No. 18326. Estimates of the filtration parameters

non-highly-saturated inclusion. The results of the studies carried out by JSC Permneftegeofizika in mid-2006 with the LATERAL-2005 technological complex showed that in the areas where these instruments are located, a low inflow to the horizontal well trunk is observed.

Estimates of conductivity in the locations of instruments Nos. 1885 and 1879, obtained from the curves of temperature and pressure change are in good agreement. In interpreting the results of hydrodynamic studies, the skin effect was not taken into account, and therefore there is a discrepancy between the conductivity estimates in the locations of instruments No. 1721, 1726.

References

Charny I.A. Unsteady flow of a real kuids in pipes. Moscow: Nedra. 1975. 296 p. (In Russ.)

Farkhullin R.G., Nikashev O.A., Khairullin, M.Kh. Muslimov R. Kh., Khisamov R. S., Polushin, V. I. Method of hydrodynamic investigations of horizontal wells. Patent RF 2243372. 2003. (In Russ.)

Khairullin M.Kh., Khisamov R.S., Shamsiev M.N., Farkhullin R.G. Interpretation of the results of well hydrodynamic research by regularization methods. Moscow-Izhevsk: SRC "Regular and chaotic dynamics"; Institute of Computer Science. 2006. 172 p. (In Russ.)

Nazimov N.A. Features of flow of fluids in horizontal wellsusing deep investigations. *Avtoref. Diss. kand. tech. nauk* [Abstract Cand. engineer. sci. diss.]. Bugulma. 2007. 162 p. (In Russ.)

Vasiliev O.F., Voevodin A.F. On the gas-thermodynamic calculation of flows in simple and complex pipelines (statement of the problem). Izv. Sib. Otd. AN USSR. 1968. V. 3. No. 13. Pp. 53. (In Russ.)

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THE QUESTION OF ENVIRONMENTAL CONSEQUENCES AT HORIZONTAL DRILLING OF SHALE FORMATIONS IN CONNECTION WITH THEIR ENRICHMENT WITH MICROELEMENTS

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Abstract. Priority directions of horizontal drilling in shale formations in the USA (Bakken, Barnett, Monterey, etc.) are considered. Growth and further development of this type of drilling in the territory of shale plays of the USA and other countries, as well as productive horizons of the Western Siberia, was noted. With a fairly detailed coverage in the domestic and foreign literature of all the pros and cons of shale horizontal drilling projects, and in particular the negative environmental consequences of hydraulic fracturing, the problem associated with the high content of metals and nonmetals in shales and oils is practically not considered. A significant number of them belong to the category of potentially toxic microelements, dangerous for the habitat. The article presents the average trace elements content in the combustible and black shale from various basins of the world, the concentrations of a number of elements markedly exceeding in shale the clark content of clay rocks. High concentrations of a number of elements in the Kenderlik shale of the Republic of Kazakhstan, domanic deposits of the Volga-Ural oil and gas basin are shown, as well as some features of the distribution of radioactive elements and mercury in oils and shales. The release of toxic elements significantly increases with the thermal impact on the formation and some processes of hydrocarbon processing. In the case of hydraulic fracturing, it is possible that toxic elements from both shales and from the naphthides contained in them could be discharged to the environment. In the course of horizontal drilling, as with any other processes of impact on the reservoir, additional studies should be conducted to assess the microelements composition of the shale formations and the hydrocarbons contained therein for monitoring environmental processes.

Keywords: horizontal drilling, ecology, shale formations, microelements, potentially toxic elements, radioactive elements, mercury
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Introduction

With the conquest of the market by shale oil and shale gas, the method of horizontal drilling is widely used in oil and gas basins around the world. Importance and high economic effect, all the pros and cons of this type of drilling are reflected in the extensive domestic and foreign literature (Dmitrievsky, Vysotsky, 2010; Ivanov, 2014; Yarakhanova, 2014; Averyanova, 2015; Yurova, 2016; Johnson et al., 2016; Nemec, 2016 and others).

Opening the scientific and practical conference in 2015 "Black Shale" in Yakutsk in the Institute of Oil and Gas Problems of the Siberian Branch of the Russian Academy of Sciences, corresponding member of the RAS A.F. Safronov noted that in Russia, as conventional oil reserves are being depleted, it will be necessary to involve shale oil extraction of more actively even in the medium term.

Moreover, the oil recovery from clay plays can be more profitable than, for example, the production of hydrocarbons on the shelf of the Arctic seas. A.F. Safronov drew attention to the fact that in the early 70s of the last century Academician Nikolai Chersky, who headed the Yakutsk Scientific Center for more than 20 years, proposed using hydraulic fracturing to extract natural gas from the low permeable rocks of the Permian age of the Khapchagai megaswell.

The EAGE conference "Horizontal Wells 2017. Problems and Prospects", held in Kazan on May 15-19, 2017, highlighted the large role played by horizontal wells in improving the efficiency of oil and gas fields development in Russia and abroad. The chairman of the organizing committee, Vladimir Vorobyov, the head of the geology and development department of Gazpromneft-Angara LLC, repeatedly emphasized that in modern market conditions, when the cost of oil has significantly decreased, horizontal drilling allows minimizing the risks of lack of inflow, increasing the level of reservoir opening and well flow rates, improve the profitability of projects. It was also noted that

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Tatarstan and Bashkiria show a rational approach to the development of hydrocarbon fields, while projects with horizontal wells are widely implemented, the share of which in the Volga-Ural oil and gas basin is very high.

The 14th International Exhibition of Oil and Gas Equipment and Technologies "OIL&GAS"/MIOGE 2017 was held in the central exhibition complex "Expocenter" in Moscow on June 27-30, 2017. The exhibition advertised equipment for horizontal drilling. Unfortunately, foreign companies in this exhibition were few. We can note the American company Scientific Drilling International from Texas (Houston), Cognitive Technologies (UK) Limited (London), APA-KANDT GmbH Germany, Hamburg and some others, offering a wide range of technical tools for horizontal drilling.

Horizontal drilling of shale formations in the USA and productive deposits of Western Siberia

The development of oil shale deposits, primarily in the United States, has completely refocused the international oil market in recent years. Having made the shale revolution in the beginning of 2010, American producers have become one of the key suppliers of raw materials in the world, having increased production by 10% to 9.3 million barrels per day since mid-2016, which is close to the levels of Saudi Arabia and Russia (http://rusjev.net/2017/05/30/sanktsii-zadushili-slantsevuyu-neft-v-rf/). Great success was achieved with the use of horizontal and/ or cluster drilling.

The beginning of industrial gas production from oil shale dates back to the 80s of the last century. Shallow vertical wells (150-750 m) were drilled in the northeast of Texas and, using hydraulic stimulation, they began to extract gas from the Barnett Formation shale plays. The well production rates were about 3 thousand m3 per day, and the reserves for the well were estimated at an average of 7 million m^3. Gradually, the extraction technology was improved, and by the year 2000 it had already reached 13 billion m^3. In 2002, a new technological stage began – drilling horizontal wells with multistage hydraulic fracturing and proppant injection. Production began to grow, and in 2005 amounted to 23 billion m^3 (Dmitrievsky, Vysotsky, 2010). Shale formations are located mainly in the sedimentary basins as a platform (Perm, Michigan, Illinois, etc.), and intra-fold (Green River, Winta, Paradox, etc.) types.

Below are a few examples and statements of the leaders of major US corporations (Johnson, 2016; Nemec, 2016, etc.).

WPX Energy from Oklahoma is drilling in various American basins: the Bakken (North Dakota) and the Barnett (clayey coal shales) Formations of the Perm Basin (western Texas and eastern New Mexico). The head of the company Rick Moncrief, who is the pioneer of horizontal drilling in Bakken (it was on his initiative in 1987 that the first horizontal well was laid here), compares the two shale formations. He believes that there are high prospects both in Bakken and in the Perm basin, despite the fact that in 2016 Bakken's production rate fell.

While economically the Perm basin now looks more attractive, Rick Moncrief evaluates the positive outlook of his company in both basins, where the average cost per well has been reduced to $ 5-5.5 million in mid-2016. "I would like to have more plots in Bakken," said Rick Moncrief. He breaks the Permian basin from east to west into three plots: Midland, East Central and Delaware. Today WPX Energy is the 'new player' of the Perm basin due to the acquisition in 2015 of license areas (94,000 acres) in the area of Delawar. WPX Energy also has plots in the Williston Basin (North Dakota) and the San Juan Basin (New Mexico). In the first quarter of 2016, WPX Energy set a new peak in oil production with an average of 41,500 barrels per day and plans to invest 350-450 million dollars in 2016, more than half of these funds are destined for the Perm section of Delaware. Many executives of large corporations note that technology improvements of horizontal drilling leads to a reduction in costs, pushing the slogan – "less money, but more oil."

Improving hydraulic fracturing technology with multiple inlets (perforations) reduces costs and increases productivity, says Jim Volker, executive director of Whiting Petroleum Corporation, based in Denver. The 10,000-foot (3048 meters) lateral branches, 6 million pounds (2,700 tons) of sand, 200,000 barrels of water allow Whiting Petroleum to reach a capacity of 900,000 barrels per well. According to Gerbert Schoonman, vice president of Hess Corporation, his company managed to reduce the time of drilling the well from 45 to 16 days, thereby reducing costs for each from 34 million to 5.1 million dollars.

Don Hrap, president of Conoco Phillips (the part that operates in 48 continental US states), emphasizes that, because of the new technology, US oil reserves have increased by 90% over the past 6 years, and natural gas reserves by 125% over the past 20 years. "At the moment, North America has enough natural gas for the next 100 years," said Don Hrap.

The use of the latest technologies is of great importance: fiber optics and fiber coils are used to diagnose the performance of each perforation. Temperature, acoustics and some other parameters are evaluated for their reuse. A new fiber-optic monitoring system, jointly developed by Shell and Baker Hughes global oil exploration and production department, allows monitoring the distribution of stresses and strains in wells using anti-sand filters. This system can record even minor changes in casing and well bracing in real time (http://worldcrisis.ru/crisis/1518031; http://neftianka.ru/zima-trevogi-nashej/).

The new multi-trunk well construction technology was successfully used in 2017 at the Novoportovsky oil and gas condensate field, one of the largest hydrocarbon fields in the Yamal-Nenets Autonomous District. This allowed Gazpromneft-Yamal to increase the oil recovery of the reservoir and significantly improve the development efficiency of the field. The multi-trunk well has a vertical trunk, called the main one, from which a number of sidetracks are drilled. The intersection of the main trunk with a branch must be above the productive layer. Thanks to this technology, it is possible to open new productive horizons, continuing drilling of existing wells. The used drilling technology involves securing in each horizontal wellbore a metal pipe, the so-called shank, to prevent the rock from shedding and the loss of the drilled stem during its operation. The length of each trunk of the first 2-well borehole constructed at the Novoportovsky field is 1000 m. The initial production rate of the well is recorded at a level of more than 400 tons/day of oil.

Currently, five such wells have been constructed and are functioning at the Novoportovsky field, and each new well is drilled much faster than the previous one, which significantly reduces its cost. As a result, the specialists managed to reach a record speed of drilling multi-trunk wells for the company – 5.87 days/1000 m, which is comparable to the best results for drilling single-trunk horizontal wells. The recoverable reserves amount to more than 250 million tons of oil and gas condensate, more than 320 billion cubic meters of gas. Operational drilling began at the end of June 2014. The new grade of oil, known as Novy Port, is classified as average density by its properties. It should be noted that Gazprom Neft is actively developing modern technologies that are being introduced into exploration, production and processing (http://neftegaz.ru/news/view/158224-Proryv.-Gazpromneft-Yamal-postroila-na-Novoportovskom-mestorozhdenii-2-stvolnye-gorizontalnye-skvazhiny).

Ecological problems

The negative impact of this technology is well known and many times noted by many practitioners and scientists, which causes enormous harm to the environment. So T.I. Dvenadtsatova (2015) states that in recent times the controversy over the environmental consequences of the shale gas recovery and its role in the future of world energy has not only not abated, but inflames with renewed vigor (Fig. 1). The author cites the following risks that arise when drilling horizontal wells and using hydraulic fracturing:

1) Growth of seismic activity due to changes in the structure of subsoil;

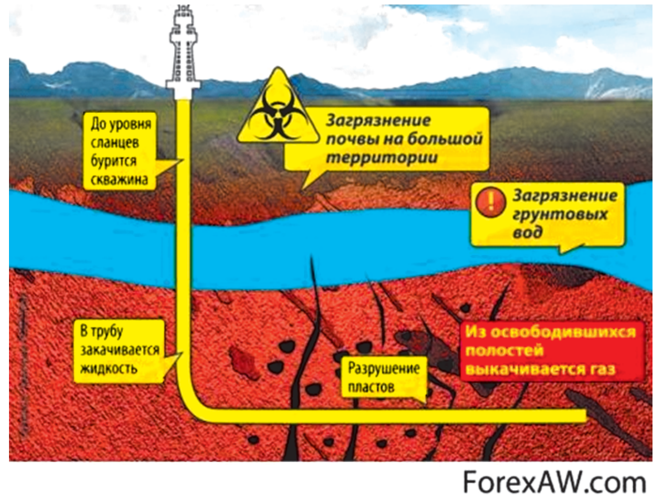

*Fig. 1. Scheme of horizontal drilling and deplorable consequences of the shale revolution (*http://economic-definition.com/Energy/Slancevaya_neft__Shale_oil__eto.html*).*

2) Pollution of groundwater, which is directly related to the subsequent contamination of drinking water in areas close to production («The Process of Shale Gas Development», http://shalegas-europe.eu/shale-gas-explained/the-process-of-shale-gas-development/, https://www.worldwatch.org/files/pdf/Hydraulic%20Fracturing%20Paper.pdf);

3) Contamination of surface water and soil (http://www.eriras.ru/files/Sorokin_Goryachev_OEPEE_slanec.pdf);

4) Methane emission («Texas Republicans work to squash local fracking ban», Laura Clawson, Daily Kos, 2014, https://www.dailykos.com/stories/2014/11/17/1345523/-Texas-Republicans-work-to-squash-local-fracking-ban#).

Drilling of vertical oil and gas wells with various directions, including controlled directional and horizontal, is carried out by Batys-Munai in the city of Aktobe, Republic of Kazakhstan. Studies of scientists of Kazakhstan (Ozdoev, Tsireltson, 2014, etc.) noted large environmental risks associated with the implementation of hydraulic fracturing, which resulted in the following problems:

1) The technology requires huge water reserves; from 5,000 to 20,000 tons of water, sand and chemicals for one fracturing, and such fracturing is performed in dozens in one year on a single well;

2) Large amounts of spent chemical contaminated water accumulate near the deposits, which inevitably falls into the soil, destroying its fertility and polluting groundwater;

3) The extraction of shale gas leads to a significant contamination of groundwater with toluene, benzene, dimethylbenzene, ethylbenzene, arsenic and other dangerous substances (in particular, in September 2014 unsafe amount of arsenic was discovered in the water well of Barnett shale, one of the largest gas storage facilities in Texas, (http://www.publicintegrity.org/2014/12/11/16477/sick-barnett-shale);

4) 80-300 tons of chemicals for up to 500 items are used for one operation;

5) The probability of contamination with radioactive substances that will be released to the surface as a result of shale gas recovery (http://neft-gas.kz/d/877050/d/slantsevyygaz-plyusyiminusy.pdf).

Microelement composition of shale formations

With a fairly detailed coverage of all the advantages and disadvantages of horizontal drilling of shale plays, and in particular the negative environmental consequences of hydraulic fracturing, the problem of the microelement composition of both shales and shale oil is practically not addressed. However, when developing and extracting oil and gas resources of shale formations, it is necessary to take into account the large contents of metals and nonmetals concentrating in them. Investigations of the environmental consequences of oil fields development of with an increased content of toxic elements were carried out by Yakutseni (2005). His review monograph "The prevalence of hydrocarbons enriched with heavy element-impurities. Assessment of environmental risks" is devoted to the geological and geochemical regularities of formation and distribution in the subsoil of hydrocarbon raw materials enriched with heavy impurity elements and its biological (toxic) activity.

The book contains a database on the content of microelements in oil of the oil and gas basins of the world and Russia. The great importance of the monograph lies in the fact that it "puts on the shield" environmental problems, environmental risks, urging humanity to take a more serious and scientific approach to these issues. It details the impact on humans of those harmful compounds that are formed during the disposal of oil production waste. The author analyzes toxic risks and suggests the basics of a strategy for preventive protection of the environment from negative effects when developing hydrocarbons enriched with potentially toxic elements. In the subsequent work (Yakutseni, 2010), deep zonation in the accumulation of microelements in oils was analyzed and attention was drawn to sufficiently high concentrations of toxic and volatile elements Cd, Hg, As , Tn, Se, Mo, etc. in oils from deep horizons (more than 4.5 km) with a low content of asphalt-tar components. Oil of this composition can also occur at shallow depths and, as a rule, are associated with rifts and young deflections. It is likely that they can also enrich the extracted shale hydrocarbons.

The estimation of associated heavy oil components in Russia, as well as the current problem of highly vanadium-rich oils are presented in the works (Sukhanov et al., 2012). The estimation of the vanadium resource base in the largest accumulations of metalliferous oils and natural bitumen abroad and in Russia is given, as well as the volume of losses *V* in the development of metalliferous oil raw materials. The existing foreign and domestic technologies for extraction of *V* and other valuable metals from oils, natural bitumen and products of their processing are analyzed. The authors urge manufacturers to think about those irrecoverable losses of valuable metals, which are due to the lack of cost-effective technology for their production.

In general, as S.P. Yakutseni (2005) believes, a paradoxical situation has developed. Against the background of relatively high study of the properties and consequences of hydrocarbon impact on the environment, many toxo-dangerous microelements present in the hydrocarbon raw materials remained practically without research. But about 15-20% of raw materials produced by HC already contain in their composition toxic microelements in quantities exceeding their safe level, and the volumes of its production increase with the years. Hg, Cd, As, etc. are the most migratory-mobile and volatile of them. Among the strongly chemically bound in complex organometallic compounds in hydrocarbons are V, Ni, Co, Cr, Cu, Zn and other biologically inert in natural oil and bitumens, but actively dangerous in the microdispersed state after anthropogenic impact on raw materials, especially at high-temperature (>450^{o}C). Actinides, regardless of the bond strength with the molecular structures of hydrocarbons, enter the class of actively dangerous in any state. Therefore, the content of such highly toxic and volatile elements as Cd, Hg, As, Se, Mo, etc. should be assessed at the preliminary stages of the development of any hydrocarbon deposits, including shale deposits.

Thermal effect on the reservoir, increase in pressure, injection of chemical reagents during hydraulic fracturing with a large number of perforations over a long horizontal section can lead to the release of organoelement compounds, possibly volatile metals and their release into the environment. Thus, it is known that thermochemical methods, for example, in-situ combustion in the development of reserves of vanadienous naphthides are not acceptable in view of the significant losses of metals in the reservoir, and also because of the possible entry of V and Ni into the overlying aquifers used for water supply of the population. Similar is already recorded on the section of in-situ combustion of the Karazhanbas field: according to T.V. Khismetova (1992), analysis of reservoir water samples from the wells of this section showed the presence in them of vanadium and other microelements.

Let us consider and estimate in greater detail the content of microelements in black and combustible shales.

Shales are rocks of mixed lithologic composition, consist of aleuritic and pelitic fractions, have schistose content and high content of OM. The permeability of shales, as a rule, is below 1 mD, the minimum is 0.01-0.001 mD.

Combustible shale is a sedimentary rock, clayey, calcareous, siliceous, thin-layered, with weathering leafy or massive; color is brownish-gray, brownish-yellow. Organic matter is aquatic, the stage of transformation does not exceed the initial mesokatagenetic, it is not soluble in low-boiling organic solvents, but generates a significant amount of liquid organic products during thermal destruction. Combustible shales are known in the Phanerozoic rocks of many countries of the world. Black shales are fine-grained sedimentary rocks of black or brown color, sapropel type of a higher transformation stage. The content of OM in them is lower than in oil shales and is from 8 to 20%. The amount of clay fraction, as a rule, does not exceed 30% of the volume fraction (Claire et al., 1988; Level, Sumberg, 1992; Spirt, Punanova, 2009).

When the OM content is below 8%, the black shales are converted to ordinary clay or clay-carbonate rocks. The black shales are also called domanicites, which, according to the ideas of geochemists, are typical oil source beds. The oil-producing transformation occurs at higher reservoir temperatures, which ensure the generation of sufficiently large quantities of gaseous and liquid hydrocarbons. These deposits are the main oil generators in many oil and gas basins of the world (West Siberian, Mexican, Timan-Pechora, etc.). Combustible shales at the present stage of their development are poorly transformed analogues of future oil deposits. Thus, shales are interesting as possible source oil beds, and additional information related to the great interest of the modern world in the study of shale gas and shale oil for further development is important in scientific and practical terms (Shpirt, Punanova, 2017).

Many researchers note that black shale formations are characterized by extremely low rates of sedimentation (i.e., conditions of severe undercompensation) and fossilization of OM by organomontmorillonite compounds in relatively deep seas or inland basins. In the section they form low-thickness (the first tens of m) and homogeneous packs, distributed in large areas with OM up to 20%. The most favorable conditions for the formation of shale deposits are associated (Safronov, 2015) with zones of transition from continent to ocean. Within this zone, during its evolution, the rift regime changed by the regime of the continental margin. Here the accumulation of huge masses of phyto- and zooplankton with elements of benthos occurred. The upwelling zones (the rise of deep cold waters to the surface) are the most productive; there is a unique enrichment of OM sediments (300 g C_{org}/m^2 per year), for example, over the continental shelf of the western coast of the American and African continents. This process involved the introduction of nutrient-rich solutions into the sedimentation basin, which resulted in an outbreak of plankton and other bios development. Goldberg et al. (1990) believe that the sharp enrichment of domanicites is due to a prolonged contact of sediments with seawater – sources of these elements, intensive diagenesis, including sulphide formation, high sorption and preserving ability of organomontmorillonite compounds. In diagenesis in humic acids in addition to organic compounds, heavy metals U, V, Cu, Ni, etc. were apparently concentrated (Tissot, Welte, 1981).

The possibility of mass transfer of ore and organic material by pore waters, pressed from clay rocks with a high OM content under conditions of geodynamic loads, is confirmed by experimental studies on the compaction of oil shales (kukersites) and the separation of pore waters significantly enriched by microelements (Abramova, Abukova, 2015) (Fig. 2).

The calculated concentration coefficients (for the whole mass of Qi and for the mineral matter, the ash Q_i^A), representing the ratio of the element content in shales to its clark (K) in clays (Vinogradov, 1956), allow us to evaluate the processes of their concentration in shales. Table 1 shows typomorphic elements (according to Ketris, Yudovich, 2009, these are the elements for which Qi > K) in the shales of different regions (according to analytical data (Kler et al, 1988, etc.).

The highest levels of microelements are established for oil shales in the Central Asia. In the Baysunsky field (Paleogene), the contents of a large number of elements: Yb, Co, Be, Ni, V, Ag, Mo, Re (calculated on dry matter of shale) exceed their clarks, with Qi values reaching very high values: for Re – 500, For Mo – 692, for Ag – 143. The total amount of microelements reaches 5-7 kg/t. For Suzak shale (Tajikistan, Ordovician) Qi values are a bit lower, but also very high. In these shales, the contents of Zn, V, Ni, Ag and Mo are also significantly higher than clarks. The maximum values of Qi are characteristic for Ag – 71 and Mo – 461. The shales in Ukraine and Belarus

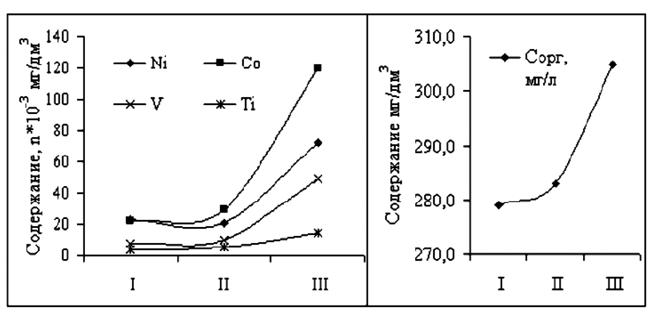

Fig. 2. The content of ore elements and organic substances in pore waters separated from oil shale (Abramova, Abukova, 2015). I – smooth increase in pressure from 0 to 20 MPa at a temperature of 25 °C; II – increase of pressure up to 40 MPa and temperature up to 40 °C with alternating loads; III – increase of pressure up to 60 MPa and temperature up to 80 °C with the influence of vibroacoustic oscillations from 5 to 60 kHz.

Field, region, age	Typomorphic ME	
	on a dry basis $Q_i > 1,4$	on a mineral substance $Q_i^A > 2,0$
The Baltic basin (kukersite), Ordovician	Sc, Ag, Mo, Hg, Re	*Sc*, **Ag**, **Mo**, Hg, Re
Volga-Pechora Province, Jura	Zn, Pb, Hg, Mo, Ag, Sc, Re	Mn, Ge, Zn, *Pb*, Hg, **Mo, Ag**, *Sc*, Re
Minelite shales of the Carpathians, Paleogene	V, Zn, Pb, Cu, Mo, Ag	Zn, *Pb*, Cu, **Mo, Ag**
Boltysh deposit (Ukraine), Paleogene	Zr, Sn, Pb, Sc	Ge, Zr, Sn, *Pb*, *Sc*
Novodmitrovskoe deposit (Ukraine), Paleogene	–	–
Turovskoye deposit (Byelorussia), Devonian	Ag, Mo, Pb, W	**Ag, Mo,** *Pb*, W
Baysun deposit (Uzbekistan), Paleogene	Pb, Ga, Ge, Cr, Yb, Co, Be, Ni, V, Ag, Re, Mo	*Pb*, Ga, Ge, Cr, Yb, Co, Be, Ni, V, **Ag,** Re, **Mo**
The Suzak horizon (Tajikistan), the Paleogene	Cr, Co, Ga, Pb, Cu, Ge, Zn, V, Ni, Ag, Mo	Cr, Co, Ga, *Pb*, Cu, Ge, Zn, V, Ni, **Ag, Mo**
Kenderlik field (Kazakhstan), carboniferous	Mn, Mo, Hg, Ag, Sc	Sn, Mn, **Mo,** Hg, **Ag,** *Sc*

Table 1. Classification of typomorphic microelements in shales of different regions (Shpirt, Punanova, 2012). In bold type, typomorphic elements are identified in terms of the mineral substance of the shales for practically all basins: Mo, Ag; in italics – many: Sc, Pb. The microelements are shown in ascending order of Qi and Q_i^A.

contain fewer typomorphic elements per dry matter, and shales of the Novodmitrovsky field generally do not have such elements. When recalculating to ash (mineral matter), a greater amount of microelements falls into the rank of typomorphic ones, since the Q_i^A values become significantly higher. For example, the Q_i^A for Mo in the Boysun field is 1225, for Ag – 253, for Re – 885; and in the shale from the Suzakskian horizon, the Q_i^A values for Mo are equal 816, and for Ag 126. The Re contents are also very high (in ash and dry weight) in the kukersite of the Baltic and the combustible Jurassic shales of the Volga-Pechora province, reaching values of 885 and 500 (Q_i^A) respectively (Shpirt, Punanova, 2012).

The study by Yu.N. Zanin et al. (2015) of clay-siliceous differences from the Upper Jurassic-Lower Cretaceous deposits of the Bazhenov Formation of the West Siberian oil and gas basin showed in them increased concentrations (in g/t): Au (0.035-0.02), Pt (0.013-0.005), Ni (336.7, which is 5.3 times higher than the values for ordinary clay rocks), Mo (264.5, 9 times), Co (30.3, 2.6 times), U (66.5), Th (5.0), K (0.81). The investigated deposits of shales are characterized by the highest content of organic carbon and pyrite, as indicators of the reduction regime, with a reduced content of clay material; they are also metalliferous.

At the present time, geochemical studies are conducted on high-carbon rocks of the Kuonamian combustible shale formation of the clay-carbonate and siliceous-carbonate-clayey composition, developed on the Siberian platform in the Cambrian part of the sedimentary cover. It has been established that oil shales are characterized by a high content of microelements: Mo, U, Cu, V, Ni, Co, Cr, Sr, Ba, etc., and can be considered as complex energy and mineral raw materials (Zueva et al., 2015). The authors cite high figures for the content of V. The geochemical background of the rocks of this sequence in V is estimated at 220 g/t. In high-carbon rocks of the Boroulakian horizon, the V content is 2277 g/t. The average concentrations of V, Ni, and Mo reach respectively 1500, 230 and 100 g/t, increasing in the Boraulakian 'metalliferous' horizon by about one and a half times. In the marginal part of the depression (Jelinda River), the mean concentrations of these same metals are equal to 811, 123 and 96 g/t.

We cite the microelement concentrations calculated in the ash of the naphthydes generated by the domanicites and in the shale domanic strata of the East European platform, which are an industrial object of the integrated development of hydrocarbons and metals. The kerogenous fractions of the clayey shale formations of the Ural-Volga region bear a high load in terms of ore content (Fig. 3).

We carried out a comparative analysis of the distribution of average microelement contents in the shales of the Kenderlyksky field from the Republic of Kazakhstan with the composition of microelements in the shale deposits of the former USSR (according to the analytical data of V.R. Kler et al., 1988) and clark contents of elements in clay rocks (Fig. 4).

The analysis showed that the Kenderlik shales contain a large complex of elements in increased concentrations. Compared with the average composition of the oil shale from the former USSR, Kazakhstan's Kenderlik shales are enriched with microelements. Thus, the sum of all identified elements was 2110 g/t, Σ (Mo, Pb, Zn) is equal to 120 g/t, Σ (V, Ni, Cr) reaches 190 g/t. In the shales of the former USSR, these figures are much lower and, accordingly, are (g/t): 1063; 90 and 170. The

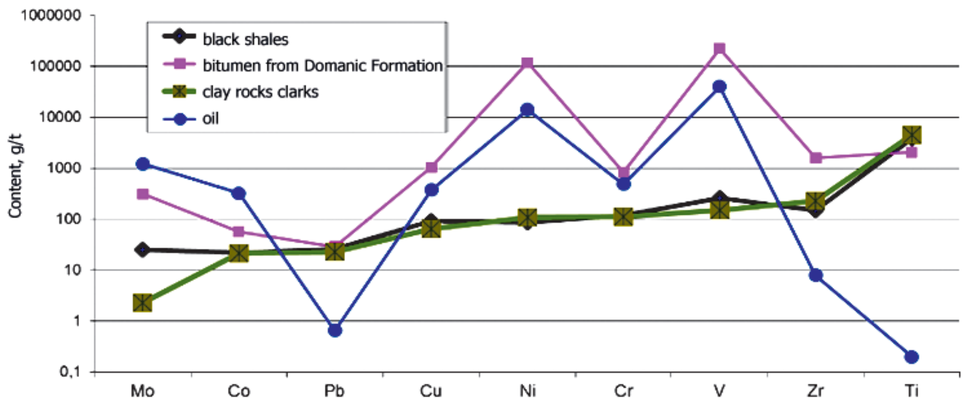

Fig. 3. Comparison of the microelements distribution in ash of bitumen and oil from Domanic Formation of the Volga-Ural (according to the analytical materials (Spravochnik po geokhimii nefti i gaza [Guide on the geochemistry of oil and gas], 1998) with black shales of the world (Shpirt, Punanova, 2012) and clay rocks clarks (Vinogradov, 1956) (ranked by clark content of elements in clay rocks)

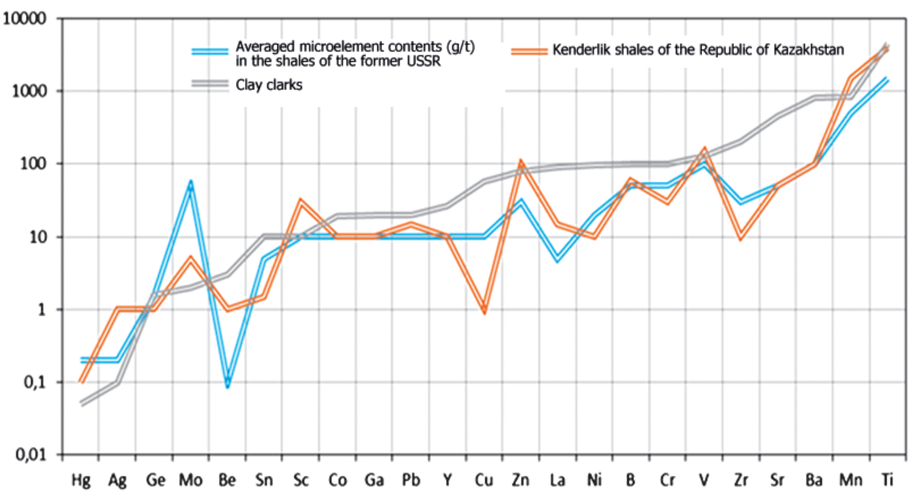

Fig. 4. Comparison of averaged microelement contents (g/t) in the shales of the former USSR, Kenderlik shales of the Republic of Kazakhstan and clay clarks (Vinogradov, 1956), the curves are ranked by clarks

concentrations of Ag, Be, Sc, Pb, Zn, La, Mn and Ti in the Kenderlik shales are much higher than in the shales of the former USSR. In the shales of this field, the content of Ba, Zn and V is ≥ 100 g/t, the concentration of Ti reaches 4000 g/t, and Mn – 4500 g/t. And in comparison with clayey rocks (clark contents), such elements as Ag, Hg, Mo, Sc, Mn, Zn, V, Ti are contained in the Kenderlik shales at higher concentrations. In the oil shale of the Bayhozhinsky field, high contents of Re – rare earth metal, widely used in catalysts and refractory alloys, are also noted.

Comparison of the microelement contents in shales of various age shows that a clear connection with the age of the shale bearing formations can not be detected. This is due to the influence of other factors, namely, the facies type of sediments and the geostructural position of the slate-bearing basin. The maximum content of ME in combustible shales is often confined to platform formations (bituminous domanic rocks of the Russian Platform, the Bazhenov Formation of Western Siberia), but some shale formations of geosynclinal regions can also be enriched by microelements (Baysun field of Uzbekistan, Suzak shales of Tajikistan). Such a confinement of increased concentrations of microelements in caustobioliths is due to the fact that in these basins or their parts favorable opportunities were created both for the syngenetic (with the maximum occurence of transport, resource, barrier, environmental and other functions of living and organic matter), and for epigenetic, (temperature, hydrothermal, geodynamic) accumulation of microelements in the studied caustobioliths (Patterson et al, 1987; Mossman et al, 2005; Shpirt, Punanova, 2012).

Enrichment of black and combustible shales by microelements (for some elements the content is higher than 100 g/t) is confirmed by detailed averaged data for 36 microelements (Fig. 5, Table 2).

In recent years, special attention has been paid to assessing the amount of environmentally hazardous pollution of the environment with mercury and its compounds, resulting from the extraction of shales, coals, oils and their processing. Mercury compounds are one the most environmentally hazardous among other potentially toxic microelements, and mercury releases to the environment largely depend on its content in the feedstock. Compared to other caustobioliths, oil ash is

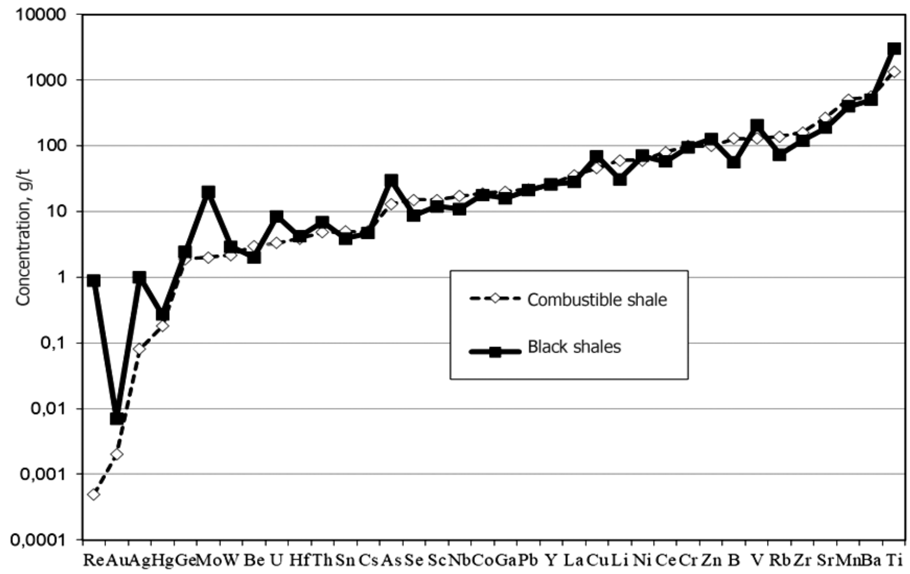

Fig. 5. Comparison of microelements in black and combustible shales (ranked by microelement content in combustible shales)

	Concentration of microelements in shales (by ten days), g/t						
	< 0, 01	0,01–0,1	0,1–1,0	1,0–10	10–100	100–1000	> 1000
Black shale	Au		Hg, Re, Ag	Ge, W, Be, U, Hf, Th, Sn, Cs, Se	Sc, Nb, Co, Ga, Pb, Y, Mo, As, La, Li, Cu, Ce, B, Rb, Ni, Cr	Zr, Sr, Zn, V, Mn, Ba	Ti
Combustible shale	Re, Au	Ag	Hg	Ge, Mo, W, Be, U, Hf, Th, Sn, Cs	As, Se, Sc, Nb, Co, Ga, Pb, Y, La, Cu, Li, Ni, Ce, Cr, Zn	B, V, Rb, Zr, Sr, Mn, Ba	Ti

Table 2. Distribution of averaged data by the microelement content in shales

the richest in microelements (Wilhelmetal, 2007). It is important to emphasize that mercury is practically the only element typomorphic in all types of caustobioliths, that is, the mercury content, both on dry matter and ash of caustobioliths, is much higher than clark. The revealed circumstance shows the wide prevalence of mercury in nature and the importance of estimating its quantities.

The largest number of studies on the assessment of mercury behavior in the combustion of solid and liquid fuels was carried out in the United States under the program for protecting the environment from the hazardous effects of mercury compounds (Kelly et al., 2003), etc. Mercury emissions into the atmosphere during oil combustion can be 1.0 x10^{-3} g/t. The revealed circumstance shows the wide prevalence of mercury in nature and the importance of estimating its quantities. Estimates of the average mercury content (mercury clark) in the oil fields of the Earth, given in the literature, fluctuate over a wide range (from> 0.001 to 2 g/t). Such a large range of calculated average mercury concentrations in oil is due to the different sensitivity and accuracy of the analytical methods used to quantify mercury and other factors (Shpirt, Punanova, 2011). There may have been mistakes in determining the mercury content due to possible losses during transportation through pipelines due to the partial volatilization of metallic mercury or the transition to the walls of pipelines when interacting

	Coal	Black shale *	Combustible shale	Sedimentary rocks	Earth crust**
U	1,9/0,6	9,9/3,1	3,2/1,0	3,0–3,4	2,5–3,0
Th	3,3/0,4	7,8/0,9	12/1,4	7,7–9,9	8–13
Ra	–	–	–	–	10^{-6}

*Table 3. Natural radionuclides content in caustobioliths and sedimentary rocks, g/t. Note. In the numerator – content, g / t, in the denominator – the ratio of the contents in caustobioliths and sedimentary rocks. * Ketris, Yudovich, 2009; ** Vinogradov, 1956*

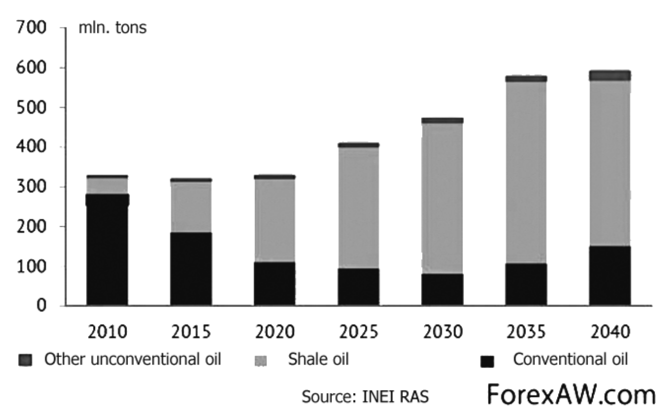

Fig. 6. Forecast of oil production of shale fields according to the Institute for Energy Studies of the Russian Academy of Sciences http://economic-definition.com/Energy/Slancevaya_neft__Shale_oil__eto.html

with metallic iron. The carried out researches allow to draw a conclusion that mercury is present in oils in the form of highly volatile fine droplets of metallic mercury, as the main form of its volatile compounds, mercury dialkyls, as well as nonvolatile sulphides and chemical compounds in asphaltenes, which can be its main component in some oils. Native mercury, its amalgams and the altmarkite mineral (Hg, Pb) (Wilhelm, 2001) are also found in oil. Even according to the lowest estimate of the average mercury content in oil when calculated for a mineral substance, it is many times higher than in sedimentary rocks and the Earth's crust (Shpirt, Punanova, 2015).

The natural radioactivity of caustobioliths is due to the content of so-called natural radionuclides in them: uranium, thorium, ^{40}K isotope and products of radioactive decay of Th, U, primarily radium and gaseous radon. Of all the natural radionuclides in combustible and black shale, the largest information is available for U, which appreciably accumulates in these shales and is undoubtedly a typomorphic (characteristic) element for them (Shpirt, Punanova, 2015).

Its average content in black shale is 8-13 g/t, and anomalously high values are considered to be more than 25 g/t. In this case, the "young" black shale (Phanerozoic) is characterized by a higher concentration of U compared with the Precambrian. In oil shales, the content of Th and U is 12 and 3.2 g/t, respectively (Table 3). The contents of U in oils usually vary for different fields or their sections in the range from $4 \cdot 10^{-4}$ to $5 \cdot 10^{-3}$ g/t, and their magnitude is probably influenced by geological processes of their formation, associated with oxidation, loss of light fractions, etc. A distinct tendency is identified of the U content increase with an increase in the density of oil and the amount of tar and asphaltenes in it. Consequently, in terms of the entire mass of caustobiolite, the content of natural radionuclides, in particular uranium is significantly lower in oil than in solid combustible fossils. However, when calculating the mineral matter of oils, which is proportional to their ash content, these figures are slightly different from each other. For example, with an ash content of 0.1%, the maximum uranium concentrations in the ash of oils can reach 5 g/t. When processing cautobioliths, products with increased radioactivity may be obtained in comparison with the initial ones (Ketris, Yudovich, 2009).

Conclusion

Thus, the development of shale formations by the method of horizontal drilling with the use of hydraulic fracturing in order to improve economic indicators remains a priority worldwide. It should be noted that according to the Institute for Energy Studies of the Russian Academy of Sciences, shale oil reserves are 4 times greater than the reserves of oil fields, since shales contain up to 70-80% of organic matter (Fig. 6) (http://economic-definition.com/Energy/Slancevaya_neft__Shale_oil__eto.html).

However, with all the above mentioned advantages, we should not underestimate the negative environmental consequences of hydraulic fracturing in connection with high contents of V, Ni, Mo, Sc, Ti, Zn, Ag, U, Re, Hg, U, As and other microelements in shale and oil. On the one hand, it is worthwhile for industrialists and scientists to think about those irrecoverable losses of valuable industrially significant metals that are due to the lack of cost-effective technologies for their recovery from naphthydes, and on the other hand, potentially toxic elements from shale and hydrocarbons contained in them could enter the downhole equipment and the environment during the hydraulic fracturing. In this regard, in order to take into account the ecological situation in shale plays introduced into the development and to make decisions on an integrated technology for the processing of shale with the recovery of gas, oil and metals, additional studies are needed to assess the microelement composition of both shale deposits and naphthys contained in them.

References

Abramova O.P., Abukova L.A. Clay sediments of sedimentary basins are generators of naphthydo- and ore-forming fluids. *Black shales: geology, lithology, geochemistry, significance for the oil and gas complex, prospects for using as an alternative hydrocarbon raw material: Proc. All-Russian Sci. and Pract. Conf*. Ed. A.F. Safronov. Yakutsk: Akhsaan. 2015. Pp. 9-11. (In Russ.)

Aver'yanova O.Yu. Oil and gas systems of shale maternal formations. *Avtor. diss. kand. geol.-min. nauk* [Abstract Cand. geol. and min. sci. diss.]. St. Petersburg. 2015. 25 p. (In Russ.)

Dvenadtsatova T.I. The ecological back of the shale revolution: risks, bans and prospects. *Neft', Gaz i Pravo*. 2015. No. 6. Pp. 36-46. (In Russ.)

Dmitrievskii A.N., Vysotskii V.I. Shale gas: a new vector in the development of worldwide market of hydrocarbon raw materials]. *Gazovaya promyshlennost' = Gas industry*. 2010. No. 8. Pp. 44-47. (In Russ.)

Gol'dberg I.S., Mitskevich A.A., Lebedeva G.V. Hydrocarbon-metalliferous world regions, its formation and localization. Problems of resource assessment and integrated development of natural bitumen, high-viscosity oils and related metals. Leningrad: VNIGRI. 1990. Pp. 49-60. (In Russ.)

Ivanov N.A. Shale America: US energy policy and the development of non-traditional oil and gas resources. Moscow: Magistr. 2014. 304 p. (In Russ.)

Johnson R.C., Birdwell J.E., Mercier T.J., Brownfield M.E. Geology of Tight Oil and Potential Tight Oil Reservoirs in the Lower Part of the Green River Formation, Uinta, Piceance, and Greater Green River Basins, Utah, Colorado, and Wyoming. Scientific Investigations Report 2016. Geological Survey, Reston, Virginia. U.S. 2016. 75 p.

Kler V.R., Nenakhova F.Ya., Saprykin F.Ya. et al. Metallogeny and geochemistry of coal-bearing and shale-bearing strata of the USSR. Regularities of concentration of elements and methods of their study. Moscow: Nauka Publ. 1988. 256 p. (In Russ.)

Kelly W.R., Long S.E., Mann J.L. Determination of mercury in SRM crude oils and refined products by isotope dilution cold vapor ICP-MS using closed-system combustion. *Anal. Bioanal. Chem*. 2003. No. 376. Pp. 753-758.

Ketris M.P., YudovichYa.E. Estimations of Clarkes for carbonaceous biolithes: World averages for trace element contents in black shales and coals. *Int. J. Coal. Geol.* 2009. V. 78. No. 2. Pp. 135-148.

Mossman D.J., Gauthier-Lafaye F., Jackson S. Black shales, organic matter, ore genesis and hydrocarbon generation in the Paleoproterozoic Franceville Series, Gabon. *Precambrian Research*. 2005. Vol.137. Issues 3-4. Pp. 253-272.

Nemec R. Thriving in a Major U.S. Shale Play the Bakken Unpacked. *Pipeline and Gas Journal*. November, 2016. Pp. 56-60.

Ozdoev S.M., Tsirel'tson B.S. Oil shale of Kazakhstan. *Neft' i gaz = Oil and gas*. 2014. No. 1. Pp. 25. (In Russ.)

Patterson J.H., Dale L.S., Fardy I.J. et al. Characterisation of trace elements in Rundle and Condor oil shales. *Fuel*. 1987. No. 3. Pp. 319-322.

Safronov A.F. Upwelling as a one of the factors for the formation of oil shale strata. *Black shales: geology, lithology, geochemistry, significance for the oil and gas complex, prospects for using as an alternative hydrocarbon raw material: Proc. All-Russian Sci. and Pract. Conf*. Ed. A.F. Safronov. Yakutsk: Akhsaan. 2015. Pp. 63-68. (In Russ.)

Spravochnik po geokhimii nefti i gaza [Guide on the geochemistry of oil and gas]. Ed. S.G. Nerucheva. St.Petersburg: Nedra Publ. 1998. 576 p. (In Russ.)

Sukhanov A.A., Yakutseni V.P., Petrova Yu.E. Metalliferous potential of oils – assessment of development prospects and possible ways of implementation. *Neftegazovaya Geologiya. Teoriya I Praktika*. 2012. Vol. 7. No. 4. http://www.ngtp.ru/rub/9/56_2012.pdf (In Russ.)

Shpirt M. Ya., Punanova S.A. Accumulation of Mercury in Petroleum, Coal, and Their Conversion Products. *Solid Fuel Chemistry*. 2011. No. 5. Pp. 330-336.

Shpirt M.Ya., Punanova S.A. Radioactive Elements of Solid Fossil Fuels. Buck of Abstracts. *27-th International Meeting on Organic Geochemistry (IMOG 2015)*. Prague (Praha), Czech Republic. 2015. P. 504.

Shpirt M.Ya., Punanova S.A. Microelements of caustobioliths and shales: problems of their genesis and industrial use. *Geokhimiya = Geochemistry.* 2009. No. 2. Pp. 216-224. (In Russ.)

Shpirt M.Ya., Punanova S.A. Mikroelementy kaustobiolitov. Problemy genezisa i promyshlennogo ispol'zovaniya [Microelements of caustobioliths. Problems of genesis and industrial use]. Saarbrucken. Germany: Lambert Academic Publishing. 2012. 367 p. (In Russ.)

Shpirt M.Ya., Punanova S.A., Mukhametshin R.Z., Nukenov D. Shale strata and oil as a source of hydrocarbons and metals. *Mezhd. nauchno-prakt. konf. «Osobennosti razvedki i razrabotki mestorozhdenii netraditsionnykh uglevodorodov»* [Conf. "Features of exploration and development of deposits of non-traditional hydrocarbons"]. Kazan. 2015. Pp. 80-82. (In Russ.)

Shpirt M.Ya., Punanova S.A. Mercury in caustobioliths: accumulation, burial and geoecology. *Mat. Mezhd. konf. «Resursovosproizvodyashchie, malootkhodnye i prirodookhrannye tekhnologii osvoeniya nedr»* [Proc. Int. Conf. "Resource-reproducing, low-waste and nature protection technologies for subsoil development"]. 2015. Kyrgyzstan, Bishkek. Pp. 158-159. (In Russ.)

Shpirt M.Ya., Punanova S.A. Oils and combustible shales as a raw for potentially trace elements producing. *Neftyanoe khozyaistvo = Oil industry*. 2017. No. 4. Pp. 58-62. (In Russ.)

Tisso B., Vel'te D. Formation and distribution of oil. Moscow: Mir Publ. 1981. 501 p. (In Russ.)

Urov K., Sumberg A. Characteristics of oil shale and shale-like rocks of known deposits and occurrence. Tallinn: Valgus. 1992. 63 p. (In Russ.)

Vinogradov A.P. Regularities of distribution of chemical elements in the Earth's crust. *Geokhimiya = Geochemistry*. 1956. No. 1. Pp. 6-52. (In Russ.)

Wilhelm S.M. Estimate of Mercury Emissions to the Atmosphere from Petroleum. *Environmental Science and Technology*. 2001. 35 (24). Pp. 4704-4710.

Wilhelm S.M., Liang L., Cussen D., Kirchgessner D.A. Mercury in crude oil processed in the United States (2004). *Environmental Science and Technology.* 2007. V. 41. No. 13. Pp. 4509-4514. Yurova M.P. The Prospects and Opportunities to Use Coal Bed Methane as Unconventional Energy Source. *Georesursy = Georesources*. 2016. V. 18. No. 4. Part 2. Pp. 319-324. DOI: 10.18599/grs.18.4.10

Yakutseni S.P. The abunance of hydrocarbons enriched with heavy element-impurities. Assessment of environmental risks. St.Petersburg: Nedra Publ. 2005. 372 p. (In Russ.)

Yakutseni S.P. Deep zoning in concentration of heavy elements-admixtures in hydrocarbons. *Neftegazovaya geologiya. Teoriya i praktika*. 2010. Vol. 5. No. 2. http://www.ngtp.ru/rub/7/30_2010.pdf (In Russ.)

Yarahanova D.G. The use of horizontal wells for extraction of hard-to-recover and non-traditional hydrocarbon reserves. *Proc. Int. Sci. and Prac. Conf. «Hard-to-recover and unconventional hydrocarbon reserves: Experience and prospects»*. Kazan. 2014. Pp. 400-402. (In Russ.)

Zanin Yu.N., Zamirailova A.G., Eder V.G. Regularities in the distribution of some elements in different types of rocks of the Bazhenov suite. *Black shales: geology, lithology, geochemistry, significance for the oil and gas complex, prospects for using as an alternative hydrocarbon raw material: Proc. All-Russian Sci. and Pract. Conf*. Ed. A.F. Safronov. Yakutsk: Akhsaan. 2015. Pp. 128-132. (In Russ.)

Zueva I.N., Chalaya O.N., Kashirtsev V.A., Glyaznetsova Yu.S., Kalinin A.I. Possibilities of using high-carbon rocks of the Cuonam formation as a complex mineral raw material. *Black shales: geology, lithology, geochemistry, significance for the oil and gas complex, prospects for using as an alternative hydrocarbon raw material: Proc. All-Russian Sci. and Pract. Conf*. Ed. A.F. Safronov. Yakutsk: Akhsaan. 2015. Pp. 133-137. (In Russ.)

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RESERVOIR TYPES OF THE KASHIRIAN HORIZON OF THE MIDDLE CARBONIFEROUS WITHIN THE MELEKESS DEPRESSION AND THE SOUTH TATAR ARCH

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Abstract. At the present stage, most of the oil fields in the central part of the Volga-Ural oil and gas province, administratively located within the Republic of Tatarstan on the structures of the Melekess Depression, the South and North Tatar Arches, are at a late stage of development. Developed fields are characterized by high depletion of the main productive horizons and increase of hard-to-recover oil reserves. In order to replenish the accumulated oil production, it is required to intensify exploration for less studied horizons, which include, inter alia, the deposits of the Kashirian horizon of the Moscow stage of the Middle Carboniferous. The low degree of study for these deposits is associated with the relative importance of their study when drilling on the Devonian, Lower Carboniferous, and Vereisko-Bashkirian Middle Carboniferous deposits.

For the purposeful conduct of geological exploration in the Kashirian horizon, the study of Kashirian oil reservoirs, features of their location, and the structure of oil-bearing rocks is of great importance. The most important direction of research for solving these problems is the typification of Kashirian reservoir rocks according to their reservoir properties, structure and genesis.

Keywords: Kashirian horizon, limestones, dolomites, porosity, permeability, porous, fractured, cavernous
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The Middle Carboniferous deposits in the studied area within the Melekess Depression and the South Tatar Arch, administratively located within the Republic of Tatarstan, are represented by rocks of the Bashkirian and Moskovian stages, developed everywhere. Bashkirian stage in the studied territory is composed mainly of carbonate deposits. The Moscovian stage is represented by terrigenous-carbonate deposits of the Vereiskian horizon and carbonate deposits of the Kashirian, Podolskian, and Myachkovskian horizons. The lower boundary of the Kashirian horizon is located at the base of carbonate rocks overlapping the mudstone of the Vereiskian horizon, the roof of which, by radioactive logging, coincides with the roof of the high gamma-ray logging zone with reduced values of neutron gamma-ray logging. The upper boundary of the Kashirian deposits is confined to the base of dense rocks in the lower part of the Podolskian horizon, characterized by elevated values of gas oil contact. The thicknesses of the Kashirian deposits vary from 45 meters in the dome of the South Tatar Arch to 95 meters on the eastern edge of the Melekess Depression.

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In the structure of the Kashirian horizon, studied at the Aksubaevo-Mokshinsky, Vishnevo-Polyansky, Pionersky, Osenny (Melekess Depression), Yamashinsky, Shegurchinsky, Yersubaykinsky, Romashkino (South Tatar Arch) and other fields, six packs are allocated of carbonate, predominantly organogenic-clastic rocks, separated by regional references of chemogenic micro-grained and pelitomorphic carbonate rocks. The packs of organogenic-clastic rocks are considered as reservoirs with proven oil content and are called from the bottom up as Cks-1, Cks-2, Cks-3, Cks-4, Cks-5 and Cks-6. All six packs can be traced in most of the fields in the territory under consideration (Vishnevo-Polyansky, Aksubaevo-Mokshinsky, Shegurchinsky, Ersubaykinsky, Novo-Elkhovsky and other fields). The reference strata are conditionally indexed from bottom to top as rp-1, rp-2, rp-3, rp-4, rp-5 and are considered as impermeable layers (Fig.1).

Reference strata separating reservoir packs are represented by dense micro-grained and pelitomorphic limestones (Fig. 2) and secondary dolomites. The thickness of the reference rocks varies from 0.5 to 4.0 m.

The reservoir packs Cks-1, Cks-2, Cks-3, Cks-4, Cks-5, Cks-6 are composed of organogenic-clastic limestones, to a lesser extent secondary dolomites. Their

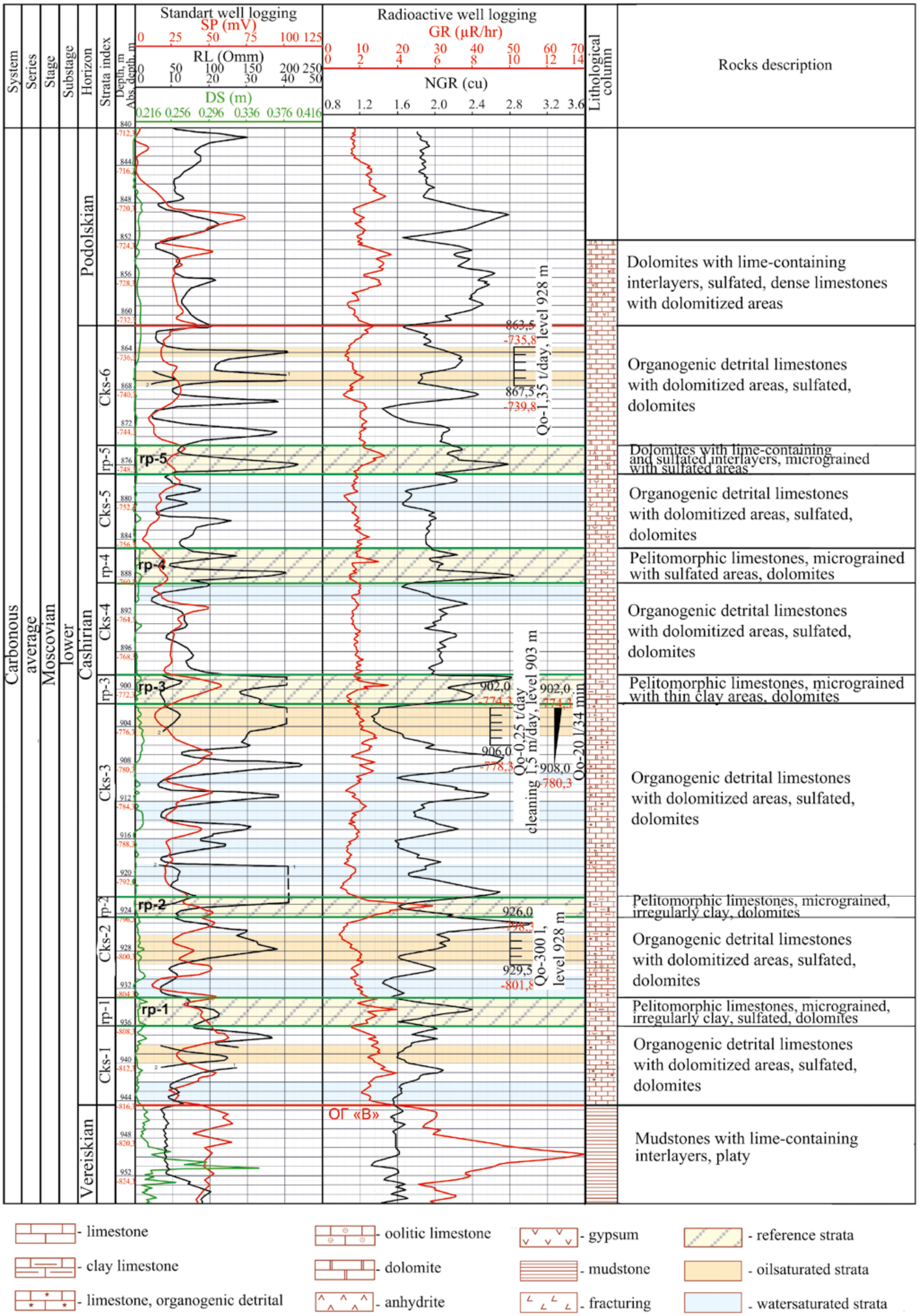

Fig. 1. Consolidated geological and geophysical section of sediments of the Kashirian horizon (eastern side of the Melekess Depression, western slope of the South Tatar Arch)

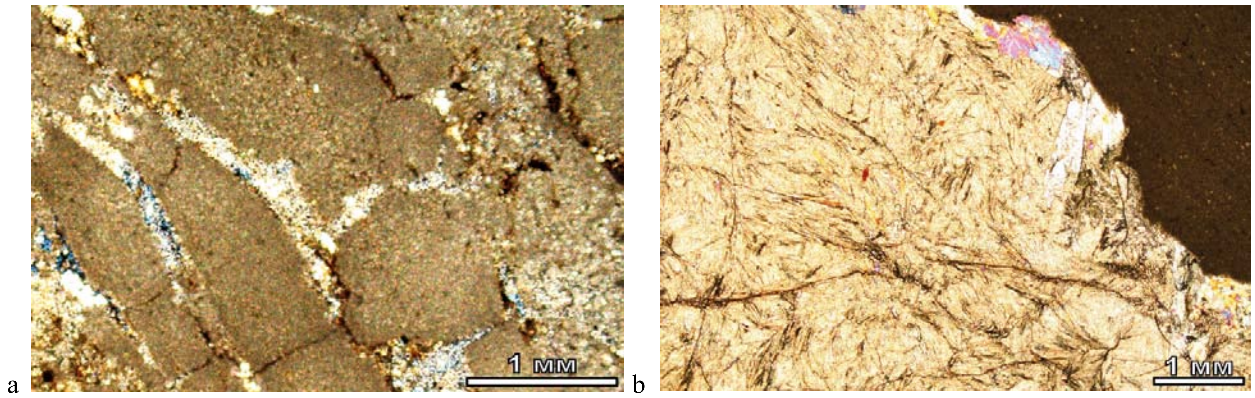

*Fig. 2. Pelitomorphic and micro-grained limestones in reference rocks. a – Pelitomorphic brecciated limestone from reference mark rp-1, well 13 of the Yamashinsky field. Void space is leached with gypsum. K_p – 1,8%, K_{per} – 0,04 * 10^{-3}μm^2. b – Anhydrite and micro-grained limestone from the reference mark rp-1, well 13 of the Yamashinsky field, K_p – 0,9%, K_{per} – 0,01 * 10^{-3}μm^2*

thickness varies from 4.4 to 31 m. Allocated reservoir packs are heterogeneous in their composition and contain both reservoir rocks and dense, recrystallized non-reservoir rocks.

Reservoir rocks in the packs are described in Vishnevo-Polyansky, Yamashinsky, Shegurchinsky and Romashkino fields (Fig. 3, 4). The rocks are represented mainly by organogenic-clastic limestones and are composed of fragments of foraminifera, brachiopods, crinoids, algae (Fig. 3). Pore-forming elements are cemented with heterogeneous mainly calcite cement. Lumps and clots of microgranular or pelitomorphic calcite are observed in some areas of limestone (Fig. 3a, 3b). The rocks are recrystallized to different degrees (Fig. 4a, 4c). In some sections rocks are fractured (Fig. 4c, 4d). In the dolomitized limestone differences, spots of fractured areas with leached pores, saturated with oil, are observed (Fig. 4d) (Khisamov et al., 2010). The described reservoir rocks were formed as a result of carbonate sedimentation under conditions of

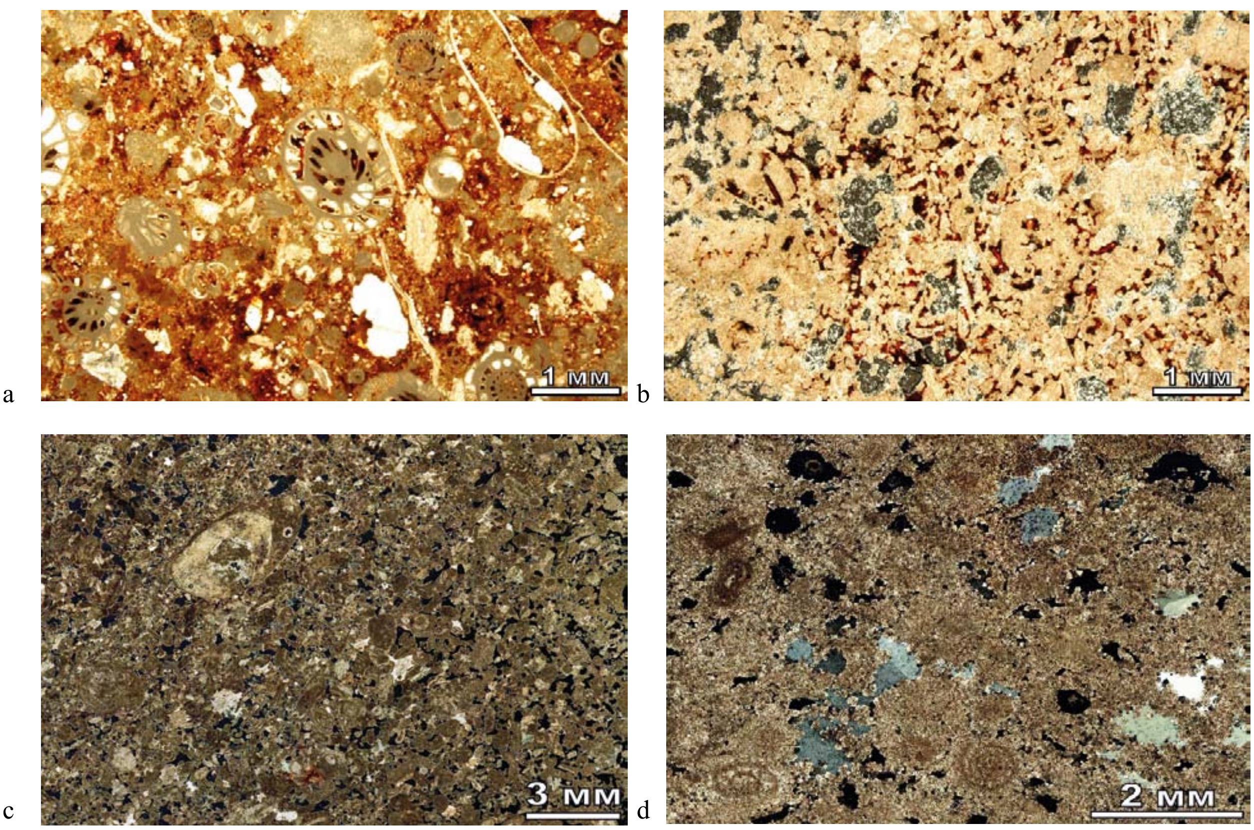

*Fig. 3. Thin sections pictures of the Kashirian reservoir rocks. a – Organogenic-clastic fusulinide limestone from the pack Cks-2, well 13 of Yamashinsky field, K_p – 11.4%, K_{per} – 2.7*10^{-3} μm^2, K_{rws} – 38%, type of reservoir is porous. b – Organogenic-clastic foraminiferous limestone from the pack Cks-1, well 13 of Yamashinsky field, K_p – 15.1%, K_{per} – 18.9*10^{-3} μm^2, K_{rws} – 31%, type of reservoir is porous. c – Organogenic-clastic thin-layered limestone from the pack Cks-3, well 2 of the Vishnevo-Polyansky field, K_p – 21%, K_{per} – 855*10^{-3} μm^2, K_{rws} – 18%, reservoir type-porous. d – Cavernous dolomite from the pack Cks-5, well 3P of Romashkino field, K_p – 17%, K_{per} – 42*10^{-3} μm^2, K_{rws} – 23%, reservoir type is cavernous-porous*

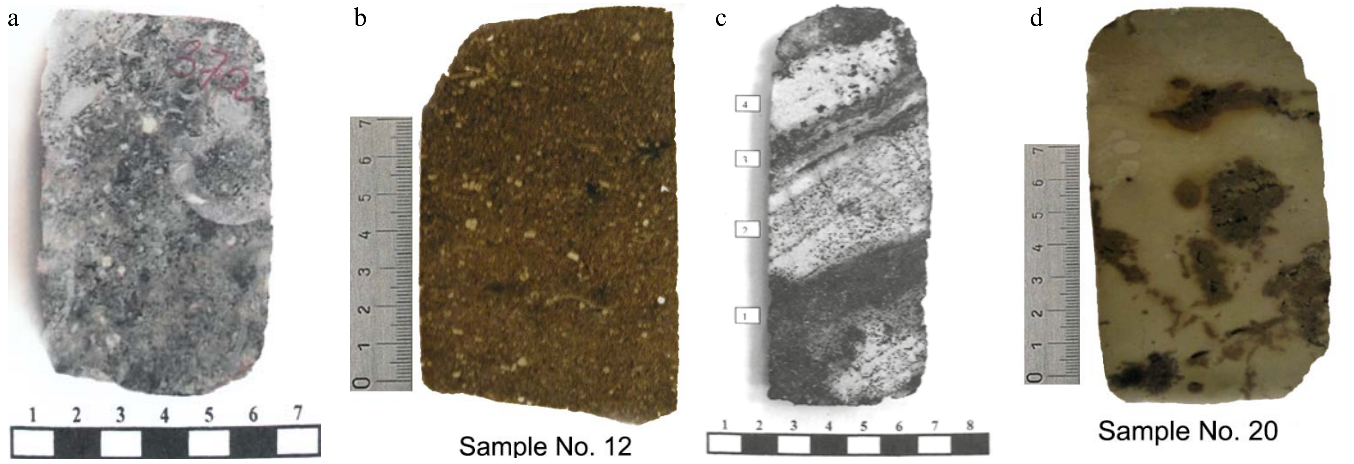

*Fig. 4. Core samples of the Kashirian reservoirs of the Vishnevo-Polyansky and Shegurchinsky field. a – Sample 37a. Organogenic-clastic recrystallized oil-saturated limestone from the pack Cks-3, well 17 of the Vishnevo-Polyansky field, K_p – 9.2%, K_{per} – 5.4*10^{-3} μm², K_{rws} – 44%, reservoir type is porous. b – Organogenic-clastic oil-saturated limestone from the pack Cks-1, well 1sh of the Shegurchinsky field, along with the pores, rare leaching cavities are noted, K_p – 12.4%, K_{per} – 6.7*10^{-3} μm², K_{rws} – 32%, type of reservoir is cavernous-porous. c – Sample 9a. Organogenic-clastic, banded-oil saturated limestone from the pack Cks-3, well 17 of Vishnevo-Polyansky field, K_p – 15.3%, K_{per} – 121.4*10^{-3} μm², K_{rws} – 28%, type of reservoir is cavernous-fissured-porous. d – Dolomitized spotted oil-saturated limestone from the pack Cks-1, well 1sh of Shegurchinsky field, K_p – 7.9%, K_{per} – 1.06*10^{-3} μm², K_{rws} – 54%, type of reservoir is fractured-porous*

an open shallow sea of normal salinity with an active hydrodynamic regime, in an environment favorable for the habitation of organisms serving as the material for the formation of organogenic limestone varieties and subsequent deposition of organogenic detrital material (Khisamov et al., 2014).

Reservoir properties were determined for reservoir rocks of the Kashirian horizon; the dependence of reservoir properties on rock types was analyzed, and the Kashirian horizon reservoir was identified and valued according to the type of void space in accordance with the genetic classification of K.I. Bagrintseva (Bagrintseva, 1999). A detailed description of the reservoir rocks and determination of their reservoir properties was carried out from the core material of Shegurchinsky, Yamashinsky, Vishnevo-Polyansky and Romashkino oil fields (Fig. 3, 4).

Most of the allocated reservoirs are of a pore type, but their capacitive space varies greatly from medium to low. Sometimes there are high-capacity pore reservoirs, which are described in detail at the Vishnevo-Polyansky field, where 80-90% of deposits are composed of debris from shells of foraminifera with a minimum content of cement (up to 5-10%), with high primary porosity, the simplest structure of void space, good voidability (Fig. 3c). Here, the processes of inherited leaching with high primary porosity, which improve reservoir properties, the secondary processes of carburization and recrystallization, which worsen the reservoir properties, are most intensively developed. Accordingly, they have the best reservoir properties – porosity (K_p) – 21%, permeability (K_{per}) – 855*10^{-3} μm², residual water saturation (K_{rws}) – 18%, and assigned to reservoirs with high reservoir properties (Fig. 3, 4).

In medium-sized reservoirs of the porous type, the primary voidness is smaller, the structure of the void space in them is more complicated, and secondary leaching processes are worse, secondary processes that worsen the reservoir properties play a big role – cementation, secondary mineral formation, recrystallization. In these rocks, clots and lumps of pelito-morphic and microgranular calcite are noted, they are more recrystallized, the content of cement is higher (up to 15-25%) (Fig. 3a, 3b). Accordingly, these porous reservoirs are characterized by lower values of reservoir properties – K_p, from 11.4 to 15.1%, K_{per} – from 2.7 to 18.9*10^{-3} μm², and K_{rws} from 31 to 38%.

The low reservoir properties of organogenic-detrital limestone in Fig. 4 a (K_p – 9,2%, K_{per} – 3,4*10^{-3} μm², K_{rws} – 44%) are associated with the presence of lumps and clots, a high degree of its recrystallization, as a result of which the primary organogenic structure is strongly altered. Such limestone is attributed to the porous reservoirs with low reservoir properties.

The Kashirian deposits are characterized by fracturing. A part of fractures is encapsulated by secondary mineral formation processes, secondary leaching processes with formation of pores and caverns are noted in the other part of fractures. Thus, in the studied rocks of the Vishnevo-Polyansky field, pores and leaching cavities are developed in the areas of inclined and horizontal microcracks, forming alternating thick and thin porous-permeable oil-saturated interlayers and strongly recrystallized dense interlayers (Fig. 4c) (Khisamov et al., 2010). Due to the system of inclined and horizontal cracks along the interlayers, along with the improvement of the capacitive properties (K_p – 15.3%), the filtration properties of the reservoirs are improved (the increase in K_{per} to $121.4*10^{-3}$ μm^2), ensured by the direction of filtration pathways. Such reservoirs are attributed by the author to reservoirs of cavernous-fractured-porous type with an average useful reservoir properties.

Occasionally microcrack formation in dolomitized limestones is observed, which may be due to secondary processes in the rocks. At the Shegurchinsky field, dolomitic limestone is a reservoir where microcracks and leaching pores filled with oil are noted (Fig. 4d). The formation of secondary porosity occurs due to leaching along the cracks. The reservoir properties are low – K_p – 7.9%, K_{per} – $1.06*10^{-3}$ μm^2, K_{rws} – 54%. Such reservoirs are attributed to the fractured reservoirs with low reservoir properties.

Rarely, as in the Vishnevo-Polyansky field, when the high primary porosity is significantly increased by secondary leaching processes, the reservoir has high reservoir properties – porosity is more than 15-16%, permeability is more than $100\text{-}300*10^{-3}$ μm^2.

In the presence of oriented microcracking in the bedding of rocks and the development of pores and leaching cavities along it, reservoirs of a cavernous-fractured-porous type are developed. In the dolomitized limestones, areas of heterogeneous microcracks with developing leaching pores are noted. Such reservoirs of the fractured-porous type are distributed, as a rule, in dense rocks and possess low reservoir properties (porosity 6-10%, permeability – the first units of millidarcy).

Conclusions

Reservoir rocks in sediments of the Kashirian horizon are confined to the packs of carbonate rocks predominantly of organogenic-detrital origin, separated by regional reference chemogenic micrograined and pelitomorphic carbonate rocks that are impermeable strata.

Reservoir rocks by the type of a void space are represented by porous, cavernous-porous, cavernous-fractured-porous, and fractured-porous type. Porous reservoirs are the most widespread, mainly associated with organogenic-clastic limestones.

Reservoir properties of reservoir rocks, depending on the primary conditions of sedimentation and secondary processes of rock transformation vary widely – from low to high. The most common are reservoirs with low and medium reservoir properties – porosity – 10-15% with permeability from the first units to tens of millidarcy.

References

Bagrintseva K.I. Formation conditions and properties of carbonate oil and gas reservoirs. Moscow: RGGU. 1999. 283 p. (In Russ.)

Khisamov R.S., Gubaidullin A.A., Bazarevskaya V.G., Yudintsev E.A. Geology of complex carbonate reservoirs of the Devonian and the Carboniferous of Tatarstan. Kazan: Fen. 2010. 283 p. (In Russ.)

Khisamov R.S., Khazipov R.G., Bazarevskaya V.G., Gazeeva F.M., Badurtdinova N.A., Doronkina I.I., Martynov A.N. Sedimentation conditions in Kashirian time in the South Tatar arch and the Melekess depression. *Geologiya nefti i gaza = Oil and gas Geology*. 2014. No. 2. Pp. 38-44. (In Russ.)

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PORE SPACE CHANGE OF VARIOUS LITHOTYPES OF THE KEROGEN DOMANIC ROCKS AT DIFFERENT HEATING RATES

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Abstract. The results of pore space changes as a result of heating Domanik Formation rock samples at different heating rates are shown. Microtomography method revealed that after heating in significant changes may arise, lens-like large pores can be formed, the number of pores and their coherence increase. It was found that changes in the pore space depend on the texture of rocks, the amount of organic matter and its degree of maturity, with all the factors must be considered together. Heating rate also influences the change in the pore space. The results should been considered in the retrieving of the natural reservoirs formation.

Keywords: Domanik Formation, pore space, samples heating, kerogen cracking
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Introduction

Currently, researchers and oil companies are paying special attention to unconventional oil and gas reservoirs, such as Bazhenov and Domanic formations. This is due to a decrease in the amount of conventional oil reserves and an increase in the share of reserves belonging to high-carbon formations. At the same time, unlike conventional reservoirs, the regularities of field distribution are not known at present for unconventional reservoirs; many wells drilled are yet dry. Therefore, the researchers are faced with the task of finding these regularities and predicting the most productive areas.

One way to understand the structure and distribution of intervals with high porosity is to develop a theory of pores generation in high-carbon formations. The works carried out abroad are usually devoted to identifying the patterns of kerogen conversion under natural conditions for the formation of oil and gas fields (Ishiwatary et al., 1979; Burnham et al., 1984; Behar et al., 1992). However, these studies consider first of all the mechanism and kinetics of hydrocarbons formation and do not consider changes occurring in the pore space due to the transformation of organic matter (OM).

Temperature, time and pressure are the main factors influencing the transformation of organic matter of the oil-parent rock, leading to the formation of new pores and changes in permeability (Bazhenova, 2000). At present, a number of experiments are being carried out, mainly to simulate the thermal impact on rocks and to investigate the transformation of voids (Jing Zhao et al., 2012; Kobchenko et al., 2011; Tisot, 1967; Korost et al., 2012; Tiwari et al., 2013, etc.). However, these works are not generalized by a single technology, they do not consider the influence of the heating rate on the simulation, and, first of all, do not consider the Domanic Formation as an object that has a structure different from other objects under study and which provokes increased interest among Russian geologists and representatives of oil companies.

In this paper, we consider the change in the internal structure of rocks, in particular, the void space, as a result of laboratory modeling of generation and primary migration of hydrocarbons. Earlier, the authors of the article carried out a number of similar experiments in which the degree of change in the pore space of samples was studied depending on the texture features of rocks and the degree of their saturation with organic matter (Gilyazetdinova, 2016).

The experiment described is based on the experience of foreign and Russian scientists (Table 1). The heating rates in these cases were selected in an average way: based on sample sizes, heating temperatures and instrumentation capabilities and programs. At the same time, the heating rate of rocks and their composition and texture, in our opinion, can play a significant role in the degree of change in the internal structure of rocks. This determined the main task of this work: the characterization and analysis of the degree of change in the rocks as a result of various heating modes of samples and setting the influence of the heating rate on the transformation of void space in various samples.

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Experiment	Formation	Corg, %	Size, cm	Temperature, °C	Heating method	Newly formed elements of pore space
Institute of Mining Technology, Taiyuan University of Technology (China), Jing zhao et al., 2012	Daqing	15,02	0,5x1	100, 200, 300, 400, 500, 600	At all temperatures were held for 30 min	Fractures, pores
	Yan'an	7,85	0,5x1			
Department of Chemical Engineering, University of Utah, Salt Lake City (United States), P. Tiwari et al., 2013	Green river	20,27	2,54x5,08	350, 425, 500	100ºC/min were heated to the estimeated temperature and were held for 24 hours	Fractures, pores
		10,33	2,54x5,08			
		0,1546	2,54x5,08			
Laramie Petroleum Research Center, Bureau of Mines, Department of the Interior, Laramie, Wyo. (United States) P. R. TISOT, 1967	Green river	0,006	1,9/3,175	510, 815	5ºC/hour to 399ºC and were held 12 hours, then heating до 510ºC and were held 2 hours	Fractures
		3,9	1,9/3,175			
		8,1	1,9/3,175			
		15	1,9/3,175			
		18	1,9/3,175			
		35,1	1,9/3,175			
Geological Faculty of Lomonosov Moscow State University, Petroleum Geology Department (Russia), D.V.Korost, 2011	Domanic	13,08	0,3	300, 400, 470, 510	10ºC/min then were held 5 min, at temp. 470, 510 2ºC/min и 5 min were held	Fractures
Physics of Geological Processes, University of Oslo, Oslo, (Norway), Maya Kobchenko et al., 2011	Green river	9,92	0,5x0,5	400	1ºC/min	Fractures

Table 1. Comparison of the rock heating modes in the experiments of Russian and foreign scientists

Methods for the study of rocks

To study the structure and composition of the rocks selected for the experiment, a complex of studies was carried out, including: X-ray diffractometry on the Rigaku Ultima-IV unit (Japan), study of thin sections on the Leica DM EP optical laboratory microscope, microprobe based on a scanning electron Microscope (SEM) "Jeol JSM-6480L" with a combined system of X-ray spectral microanalysis. Scanning electronic images are obtained in secondary electrons (surface morphology)

The next stage of the investigation consisted in scanning of cylindrical samples with a diameter of 3 mm on a computer X-ray microtomograph (microCT) SkyScan-1172. The survey was carried out with a spatial resolution of about 1.5 μm, on an Al 0.5 mm filter at a source voltage of 70 kV and a current strength of 129 μA. On the resulting x-ray sections of the sample, a darker color corresponded to a smaller X-ray density of the medium, and a lighter color – to a larger density (Stock, 2009).

The geochemical characteristics of organic matter were obtained on a Rock-Eval-6 pyrolyzator (Espitalie, 1984; Tissot and Welte, 1981; Lopatin and Emets, 1987).

Collection of samples

For the experiment, a collection of rock samples was selected from the kerogen-saturated Domanic formation of the Volga-Ural oil and gas basin with various parameters including the content of organic matter, the degree of maturity, and texture characteristics (Gilyazetdinova, 2015). Among the Domanic rocks, with a high content of kerogen and bitumen, the siliceous-carbonate rocks of the South Tatar arch (Semilukskian and Mendinskian horizons, the Franskian stage of the Upper Devonian) were chosen because of the low content of pyrite in them, which distorts the X-ray density sections (as, for example, in the rocks of the Bazhenov Formation of the Western Siberian oil and gas basin).

Samples are characterized by different contents of organic matter (from 5.66% to 30.23%), different textures and mineral composition. The rock composition is predominantly siliceous-carbonate. The composition of the samples differs, primarily, by the content of the siliceous component (Table 2).

Sample 1 is characterized by a layered texture, which is recorded due to the presence of carbonate detritus

No	Rock	Mineral composition, Main/ Silic./Carb., %	Texture	TOC, %	Degree of transformation
1	Kerogen-siliceous-carbonate	4/20/37	Laminated	30	PK3
2	Carbonate rock with kerogen	4/0/89	Laminated	6	MK2
3	Kerogen-siliceous-carbonate	2/17/64	Massive	13	PK3

Table 2. General lithological and geochemical characteristics of the samples

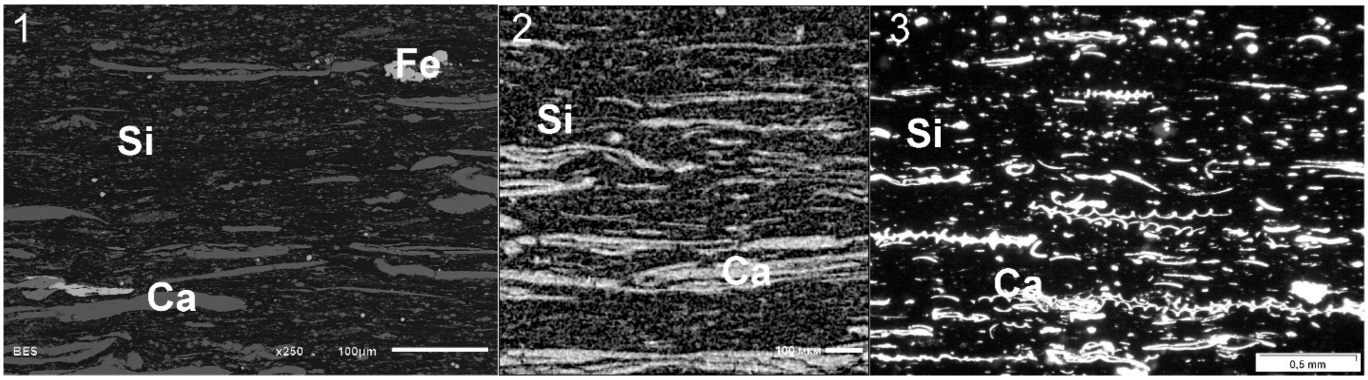

Fig. 1. Sample 1: 1 – SEM photograph, 2 – microCT cut, 3 – photograph of the section in crossed Nicol prisms

(Fig. 1). Matrix consists of a siliceous material, which is well distinguished on x-ray density microtech slices and has a weakly expressed intrinsic layered microtexture. The content of organic carbon in the sample reaches 30%.

Sample 2 is characterized by minimal values of organic carbon content (6%) among the selected samples. The rock contains organic interlayers in the carbonate matrix. The bulk of the rock is represented by a massive carbonate material, against which thin (up to 30 μm) interlayers saturated with organic matter are noted (Fig. 2).

Sample 3 has a massive texture. Bioclasts cemented with siliceous substance are distinguished in the rock composition (Fig. 3), while in the rock it is possible to assume the presence of stratification. The content of organic carbon in the rock is 13%.

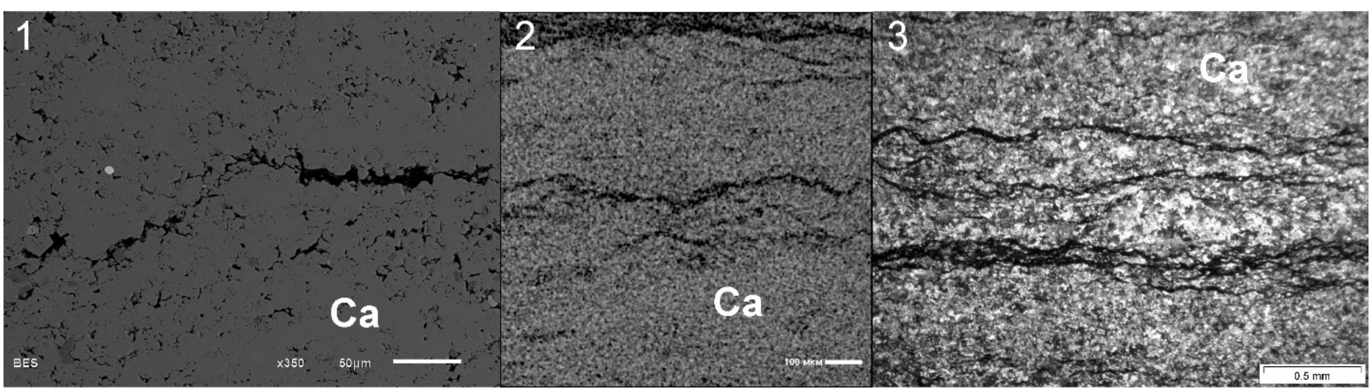

Fig. 2. Sample 2: 1 – SEM photograph, 2 – microCT cut, 3 – photograph of the section in crossed Nicol prisms

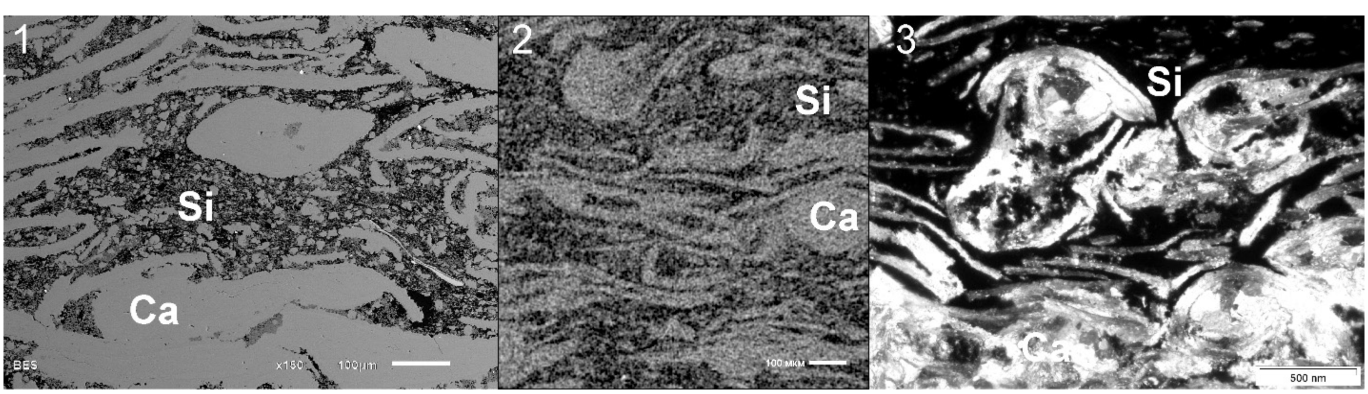

Fig. 3. Sample 3: 1 – SEM photograph, 2 – microCT cut, 3 – photograph of the section in crossed Nicol prisms

Methods of the experiment

The laboratory experiment consisted in simulating the formation of pore space by generating a shock wave in an undisturbed rock sample (a microcylinder with a diameter of about 3 mm and a height of 3-5 mm) by heating in a nitrogen atmosphere according to a given temperature program and observing changes in the pore space structure. The experiments were based on changes occurring in three duplicating cylinders of one sample placed in a RockEval 6 pyrolyzer and heated with different heating rates. At a temperature of 300 °C, the samples were held for 5 minutes, while the peak S1, characterizing the content of light hydrocarbons, was recorded. Then, heating occurred at rates of 2, 10 and 30 °C/min from 300 °C to 500 °C. The temperature of 500 °C was chosen on the basis of preliminary experiments on powders for which the parameter S2 (hydrocarbons release in the temperature range 300-650 °C) was determined and the temperature of the release peak was chosen.

To monitor changes in the construction, rock structure and pore space, a computer microtomograph was used. The color of the phase, obtained on X-ray density sections of the sample, characterizes X-ray absorption. X-ray absorption depends on the density of mineral and non-mineral components of rocks. X-ray absorption will be minimal for organic matter due to the low density of kerogen component in the rock. Taking into account the fact that in the studied rocks, empty space as such is practically absent (the OM is filled), the entire volume corresponding to the intermineral phase of the rock, that is, the void space with the minimum X-ray absorption is taken as OM.

Based on the data of the microCT, the content of OM in unchanged samples, as well as the content of OM and newly formed pores in heated samples was measured for all samples, with all other conditions being equal. The evaluation of OM/porosity was carried out using computer analysis: the separation of X-ray contrast phases on the basis of the brightnesses characteristic for them (grayscale). The volume calculation of the phase was carried out for the selected brightness corresponding to the pore space of rocks. To estimate the transformation of the void space in the sample, in particular, the calculated volumes of pore connectivity were estimated. The "connectivity" parameter characterizes the degree of connection of the emitted elements in a void space in the volume of the sample. This analysis allows us to calculate the number and size of each individual object (pores). Based on the statistical analysis, the volume fraction of the largest cluster is estimated, which characterizes the element connectivity (in this case, voids) in the rock volume (Fig. 4). The parameter "connectivity" allows estimating the degree of change in the void space, since during the rock heating, the pores, lenses and interlayers are modified and are often combined into a single system.

Results of the research

As a result of heating at different rates, there were significant changes in the matrix of the rock in sample 1. Lenticular voids appeared with the opening up to 0.3-0.4 mm (Fig. 5). At the same time, the heating rate does not affect the weight loss of the samples; the weight change was constant and amounted to about 27%. Also objects connectivity was constant, regardless of the heating rate, and was 99%. However, the different heating rates had a significant effect on the change in porosity, the number of objects in the sample, and the lenses openness. The calculated values of porosity have changed depending on the heating rate of 2 °C /min, 10 °C/min and 30 °C/min for 23, 54 and 61%, respectively. At the same time, visually the maximum capacity of the newly formed voids falls on a sample heated at a rate of 2 °C/min and equal to 0.4 mm (Fig. 5). In this sample, the largest (threefold) change was also observed in the number of void space elements – micro-voids, which were formed as a result of the OM transformation. The results of the change in characteristics as an influence of heating are given in Table 3.

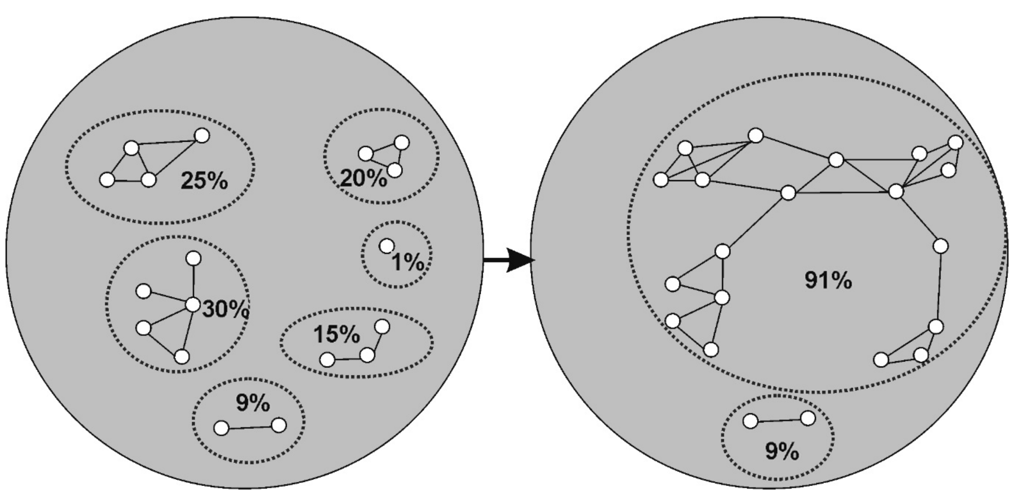

Fig. 4. Scheme of changes in the void space connectivity as a result of the sample heating

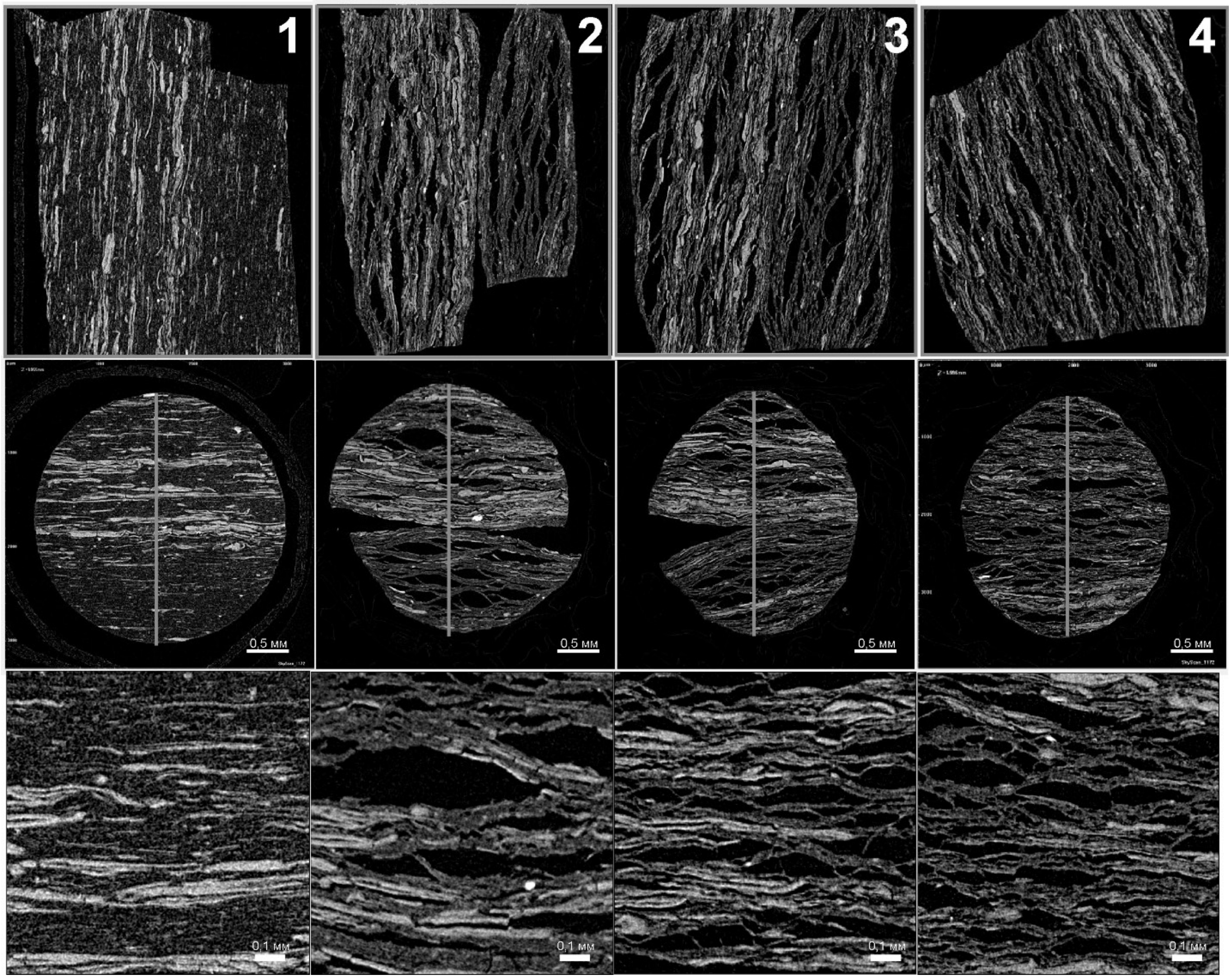

Fig. 5. X-ray density sections of sample 1 (cube edge 1 mm): 1 – unchanged sample, 2 – 2 °C/min, 3 – 10 °C/min, 4 – 30 °C/min

Heating rate	TOC, %	S1, mgHc/g	S2, mgHc/g	Porosity variation, %	Coherence, %	Number of objects (pores)	Weight variation (loss), %
raw	30	10,26	198,64	23,4	99,1	5930	26,69
2°C/min		5,32	102,5		96,48	16408	
raw	30	10,26	198,64	54,49	98,9	7050	27,81
10°C/min		5,11	120		99,1	8151	
raw	30	10,26	198,64	60,51	99,3	6023	28,57
30°C/min		3,93	97,86		99,48	9886	

Table 3. Results of sample 1heating

In the structure of sample 2, characterized by a minimum content of organic matter, the smallest changes occurred (Fig. 6). The pore connectivity remained the same and amounted to 30-35%, weight loss for all samples was about 4%, and the number of objects in the void space increased by about 20% (Table 4). It is worth noting that, just like in the first sample, the trend of variation in the calculated values of the porosity, depending on the rate of heating, was similar and amounted to 27, 55 and 55%.

In sample 3 with a massive texture, a different character of the changes was observed. In this sample, there was no significant expansion of interlayers filled with organic matter, but the void space was transformed due to the formation of new pores and channels connecting the original elements of the void space of the rock (Fig. 7). The pores connectivity in the samples increased to 85-95%, and the change in porosity with the same weight loss was 117%, 99% and 76% (Table 5). In this case, the number of free-standing elements of the void space decreased by at least 2 times.

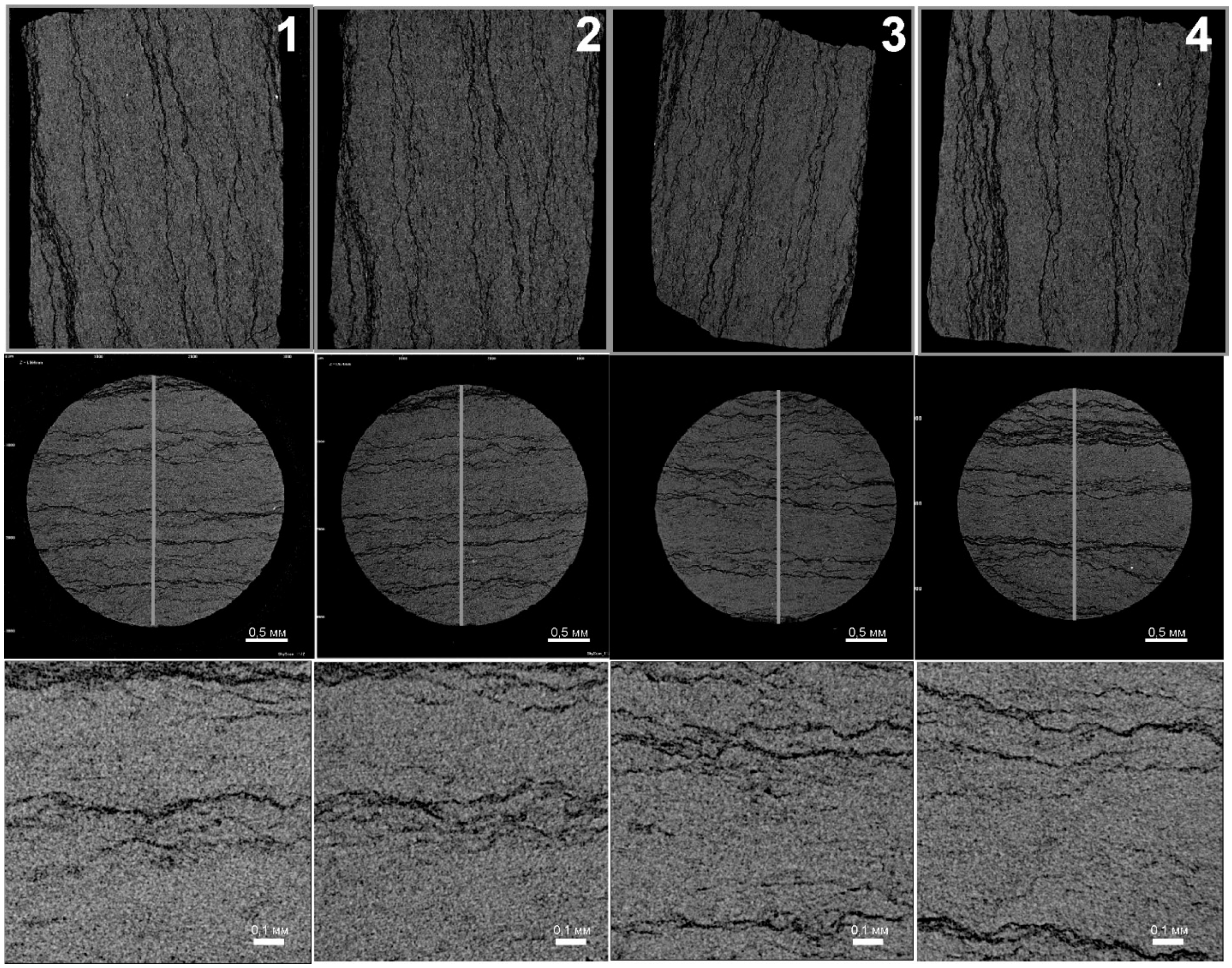

Fig. 6. X-ray density sections of sample 2 (cube edge 1 mm): 1 – unchanged sample, 2 – 2 °C/min, 3 – 10 °C/min, 4 – 30 °C/min

Heating rate	TOC, %	S1, mgHc/g	S2, mgHc/g	Porosity variation, %	Coherence, %	Number of objects (pores)	Weight variation (loss), %
raw	6	2,48	32,78	27,35	32,06	20542	3,85
2°C/min		1,44	17,29		32,32	25832	
raw	6	2,48	32,78	54,55	30,65	23502	3,04
10°C/ min		1,56	18,53		35,2	25614	
raw	6	2,48	32,78	54,71	39,6	19138	4,82
30°C/ min		1,51	19,32		39,27	23038	

Table 4. Results of sample 2 heating

The discussion of the results

As a result of the conducted experiments, a significant change in the pore space was observed, depending on the amount of organic matter. Probably, the formation of large lenses in sample 1 (Fig. 5) is associated with an increase in pore pressure in interlayers saturated with organic matter in the process of new hydrocarbons generation. Considering the organic matter content in the rock and its low maturity, the formation of new hydrocarbons leads to an anomalously high pore pressure, and, as a consequence, to rupture of interlayers, the formation of large lenticular voids.

Another pattern is observed in sample 2, the original thin interlayers, saturated with organic matter, retained their shape, no visible large deformations in the rock occurred. The low content of organic matter and its partial transformation do not lead to the formation of large visible voids. Probably, newly formed hydrocarbons migrate in a small volume in already existing interlayers, thereby releasing voids previously filled with bitumen. The volume of newly formed hydrocarbons is so small that it is not enough to cause high pore pressure in the pores and lead to the rupture of bonds. It is worth noting that in the second

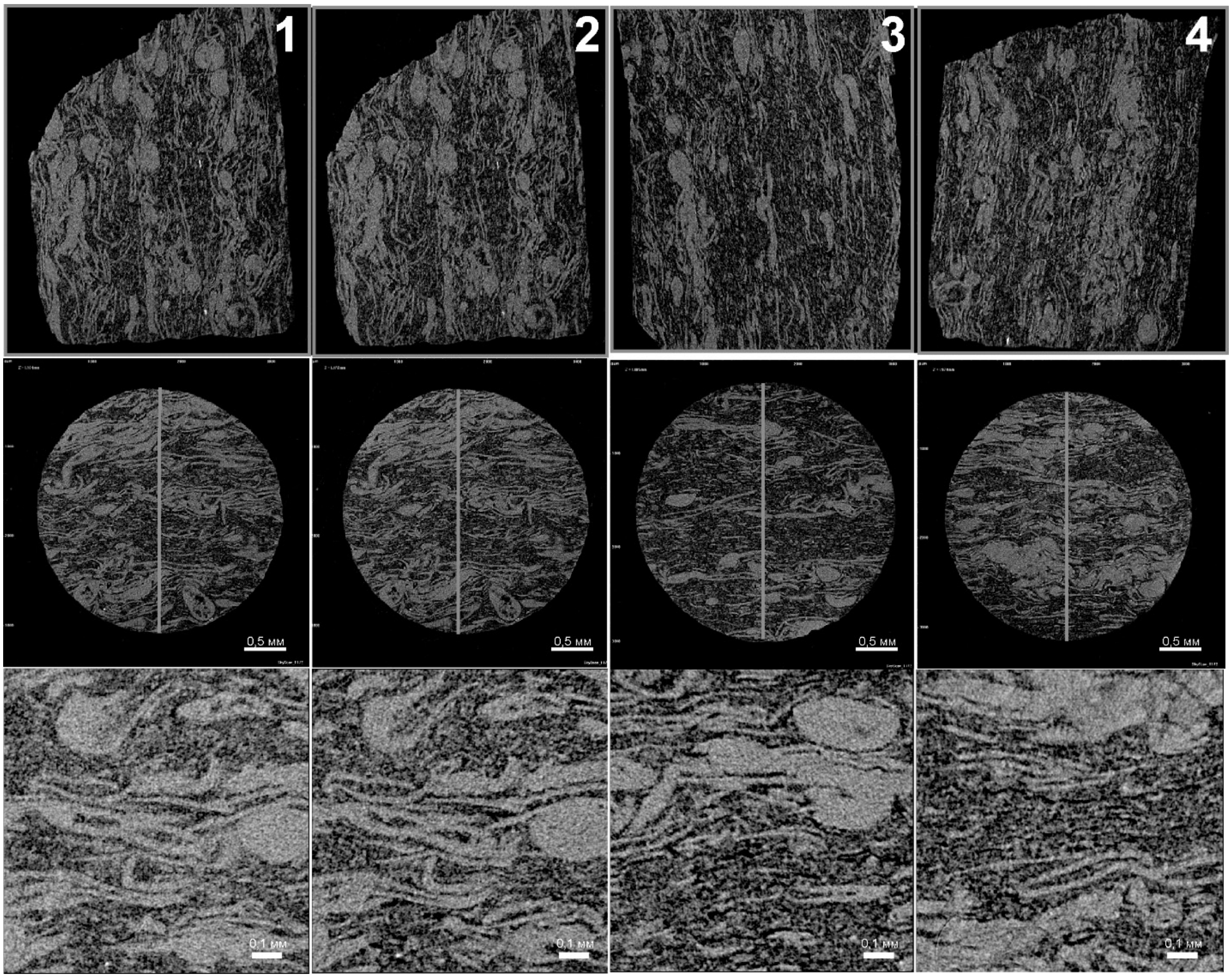

Fig. 7. X-ray density sections of sample 3 (cube edge 1 mm): 1 – unchanged sample, 2 – 2 °C/min, 3 – 10 °C/min, 4 – 30 °C/min

Heating rate	TOC, %	S1, mgHc/g	S2, mgHc/g	Porosity variation, %	Coherence, %	Number of objects (pores)	Weight variation (loss), %
raw	13	5,35	82,81	116,72	18,68	35439	9,62
2°C/ min		1,77	28,18		84,85	16767	
raw	13	5,35	82,81	98,83	75,69	75997	9,58
10°C/ min		2,91	45,63		94,52	37177	
raw	13	5,35	82,81	76,22	37,42	85844	8,45
30°C/ min		2,16	37,29		84,46	17130	

Table 5. Results of sample 3 heating

sample the organic matter had a greater maturity, a smaller generation potential (parameter S2 is much lower), which can determine a smaller volume of formed pore space. Thus, it can be concluded that the amount of organic matter and its stage of catagenesis influence the transformation of voids simultaneously (Gilyazetdinova, 2015).

As was shown above, the pattern of porosity variation for samples 1 and 2 is the same and has the appearance of an increasing function that emerges on the plateau, while for sample 3 a smooth decrease in porosity variation with increasing heating rate is observed (Fig. 8). The observed regularities are not associated with the maturity stage, since samples 1 and 2 are at different stages of catagenesis, and also do not directly depend on the composition of the samples, since in sample 3 the average content of carbonates, organic matter and silica is compared with the other two. Most probably this difference is explained by the morphology of sample 3, possibly carbonate bioclasts prevent expansion of pores, and therefore the reservoir pressure cannot create lenses.

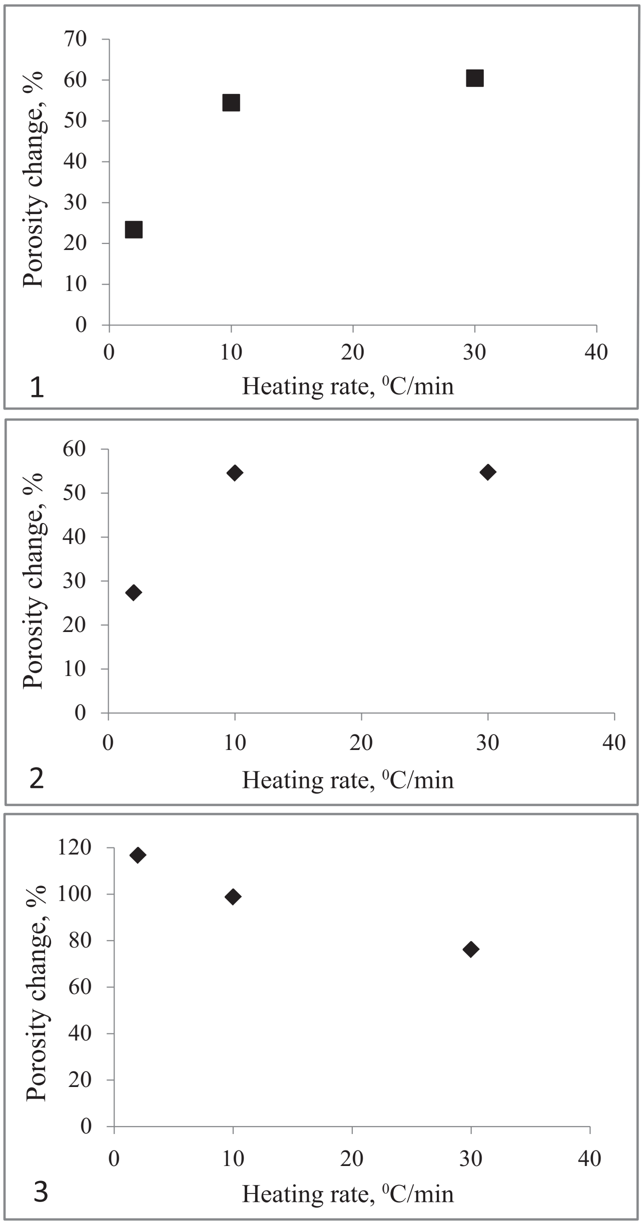

Fig. 8. Graphs of ΔKpCT dependence (porosity change) on the rock heating rate: 1 – sample 1; 2 – sample 2; 3 – sample 3

Another option is the possible inhibitory capacity of such bioclasts. Nevertheless, according to the results of the studies, the following conclusion can be drawn: the texture of the rock is an important factor affecting the formation of porous structure and, probably, influencing the degree of organic matter transformation (Gilyazetdinova, 2015).

Thus, on the basis of the work done, the following conclusions can be drawn:

1. The heating rates play a rather large role in the degree of the porous space transformation. However, these changes in different types of rocks take place in different ways. It is necessary to carry out additional experiments on rocks with different composition and texture in order to reveal direct dependences of the influence of various components and their mutual arrangement on the formation process of a porous structure. Nevertheless, the results obtained are important in modeling the process, it is necessary to take into account these factors when modeling the formation of reservoirs in Domanic deposits.

2. The degree of catagenetic transformation must also be taken into account in modeling. However, there was no direct effect on the change in pore space. At the same time, it is obvious that under the same conditions, more hydrocarbons are formed from less mature organic matter, which will lead to the formation of a larger space. Further studies should also take into account this factor.

3. The correctly selected heating mode and experimental conditions make it possible to simulate a long process of the pore space generation in the Domanic Formation in the framework of a laboratory experiment. The result obtained may prove to be the key in the search for new deposits and regulations of natural reservoirs distribution.

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References

Bazhenova O.K., Burlin Yu.K., Sokolov B.A., Khain V.E. Geologiya i geokhimiya nefti i gaza [Geology and geochemistry of oil and gas]. Moscow: MGU. 2000. 384 p. (In Russ.)

Behar F., Kressmann S., Rudkiewicz J.L., Vandenbroucke M. Experimental simulation in a confined system and kinetic modeling of kerogen and oil cracking. *Org. Geochem*. 1992. V. 19. No. 1-3. Pp. 173-189.

Behar F., Roy S., Jarvie D. Artificial maturation of a Type I kerogen in closed system: Mass balance and kinetic modeling. *Organic Geochemistry.* 2010. V. 41. Pp. 1235-1247.

Burnham A.K., Happe J.A. On the mechanism of kerogen pyrolysis. *Fuel*. 1984. V. 63. Pp. 1353-1356.

Espitalie J., Bordenave M.L. Rock-Eval pyrolysis. In: M.L. Bordenave (Editor) Applied Petroleum Geochemistry. Technip ed., Paris. 1993. Pp. 237-361.

Gilyazetdinova D.R., Korost D.V. Transformation of void space in the simulation of the generation of hydrocarbon fluids in the example domanic horizon of the Souf-Tatar arch. *Moscow University Geology Bulletin*. 2015. No.5. Pp. 78-86. (In Russ.)

Ishiwatary R., Fukushima K. Generation of unsaturated and aromatic hydrocarbons by thermal alteration of young kerogen. *Geochimica et Cosmocimica Acta*. 1979. V. 43. Pp. 1343-1349.

Jing Zhao, Dong Yang, Zhiqin Kang, Zengchao Feng, A micro-ct-study of changes in the internal structure of Daqing and Yan'an oil shales at high temperatures. *Oil Shale*. 2012. Vol. 29. No. 4. Pp. 357-367. doi: 10.3176/oil.2012.4.06

Kobchenko, M., H. Panahi, F. Renard, D. K. Dysthe, A. Malthe-Sørenssen, A. Mazzini, J. Scheibert, B. Jamtveit, and P. Meakin , 4D imaging of fracturing in organic-rich shales during heating. *J. Geophys. Res*. 116. B12201. doi:10.1029/2011JB008565.

Korost D.V., Nadezhkin D.V., Akhmanov G.G. Void space of oil-source rock during the generation of hydrocarbons: laboratory experiment. *Moscow University Geology Bulletin*. 2012. No.4. Pp. 32-37. (In Russ.)

Lopatin N.P., Emets T.P. Piroliz v neftegazovoy geologii [Pyrolysis in oil and gas geology]. Moscow: Nauka. 1987. 143 p. (In Russ.)

Stuart R. Stock, Microcomputed Tomography, methodology and applications. Taylor & Francis Group. 2009.

Tisot P.R. Alterations in Structure and Physical Properties of Green River Oil Shale by Thermal Treatment. *Journal of chemical and engineering data.* 1967. 12. Pp. 405-422.

Tisso B., Vel'te D. Obrazovanie i rasprostranenie nefti [Generation and distribution of oil]. Moscow: Mir. 1981. 501 p. (In Russ.)

Tiwari P., Deo M., Lin C.L., Miller J.D. Characterization of oil shale pore structure before and after pyrolysis by using X-ray micro CT. *Fuel.* 2013. 107. Pp. 547-554.

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IDENTIFICATION OF ZONES AND AREAL EXTENT OF WEATHERING CRYSTALLINE BASEMENT IN THE ARCHEAN-LOWER PROTEROZOIC CRUST OF THE SOUTH TATAR ARCH

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Abstract. Based on the data of geophysical surveys and deep drilling the depth to the crystalline basement and its weathering upper layer at the eastern flank of the South Tartar Arch varies from 1650 to 2500 m. Against the ongoing depletion of hydrocarbon reserves in the Paleozoic reservoirs of the region the basement becomes a promising exploration target. However the study of its architecture, composition and areal extent is largely hindered by so far very limited coring in this interval. In previous research correlation of core data and wireline logs was used for petrophysical characterization and identification of zones in a vertical profile of the upper weathering layer of the basement in the deep parametric test wells 50 Novournyak and 2000 Tyimazy with most complete core recovery. These characterization criteria have been utilized for analysis of 750 deep wells drilled in Bashkortostan within the South Tatar Arch which is bounded in the south by the Serafimovsko-Baltaevskiy Graben. In 340 wells based on wireline and production logs the upper weathering layer of the basement revealed certain distinct features of vertical zonation. The analysis resulted in thickness maps for Zone B and combined thickness maps for Zones B + C where the weathering basement is characterized by two morphological types – linear-areal and linear-fractured. The findings support the initial assumption that the obtained petrophysical characteristics may be applied to identify the weathering crystalline basement in wells with no core.

Key words: basement, crystalline rocks, hypergenesis, weathering crust, zone, core, areal extent
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The productivity of the weathering crust, both ancient and young platforms, has been proved in many oil and gas basins of the world, including the West Siberian (fields of Shaimsky swell and Krasnoleninsky arch), the South Mangyshlak (Oymasha), the northern side of the Dnieper-Donetsk avlakogen (Yuliyevsky, Khukhrinsky, and others). The presence of this geological formation in the sections of wells drilled in the western areas of the Republic of Bashkortostan was indicated in the 50s of the last century (Timergazin, 1951). The crystalline basement lies at depths of 1650-2500 m within the most hypsometrically elevated part of the eastern slope of the South-Tatar arch, and under the conditions of a sustainable reduction in the resource base of hydrocarbons in conventional Paleozoic complexes, its weathering crust may represent an undoubted petroleum search interest. However, the study of its structure, material composition, and specific features of the areal development is complicated by a small selection of cores from a given interval of the section.

In the paper (Amelchenko, Ivanova et al., 2016) on the example of parametric wells 50 Novournyak (NUN) and 2000 Tyimazy (TMZ), zones of weathering crust are identified using field geophysical data. Based on the comparison of the core material and logging data, a vertical profile of the weathering crust of the South-Tatar arch basement was constructed, in which the zones of successive changes in crystalline rocks under the influence of hypergenic factors from the initial disintegration of the original substrate to the final products of its decomposition are traced from below and their logging characteristics are outlined. The indexing of the zones is accepted by (Syungeevsky, Khafizov, 1999).

Zone "A" – unchanged in the ground surface mother rocks of the basement, which are characterized by high values of apparent resistance – 625 Ohm*m (lower in the section they can significantly increase, for example, in the silted intervals or decrease in zones of tectonic dislocations). In the well 50 NUN (the most representative complex of logging is performed here), the roof of the zone is clearly identified from the depth

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of 2462 m also from the sidewall log, which differs uniformly in different patterns, varying in the range 550-7000 Ohm*m; neutron gamma-ray logging – the values reach 7 cu; microprobe readings (micropotential and microgradient sondes) reflecting tight rocks. The acoustic logging curve is kept near 160 μs/m, and the induction curve is kept at 90 Ohm*m.

Above the surface of the basement, its weathering crust has been exposed in the sections of the wells, in the vertical profile of which, from below upwards the following zones are identified:

Zone "B" is the zone of initial disintegration, which corresponds to the first stage of rock discontinuity. The effect of factors of physical weathering leads to the emergence of multidirectional fracturing and microcracking, the degree of their occurrence increases from the bottom up. With the penetration of surface waters containing oxygen into cracks, the processes of hydration and oxidation begin. Mechanical changes in the state of the rocks are reflected in the logging by the reduction of the apparent resistance diagrams (from 625 to 125 Ohm), sidewall logging (in the well 50 NUN from 25,000 to 100 Ohm*m), the increase in the interval time of the longitudinal waves. In the lower part of the zone, tight rocks are still recorded on the microprobe, but intervals of discrepancy between the micropotential and microgradient sondes are already observed above.

Zone "C" is continuation zone of disintegration and initial decomposition. Further mechanical destruction leads to an increase in the reaction surface and intensification of geochemical processes that ensure the decomposition of silicates and aluminosilicates, and leaching of sodium and calcium. On the logs, the bottom of the zone corresponds to the apparent resistance value-125 Ohm*m; up the section, the values of the apparent resistance drop off step-by-step up to 40-50 Ohm*m and lower. The interval travel time of longitudinal waves increases (in the well 50 NUN up to 240 μs/m), in the lower half of the zone the cavernogram is usually kept near the face value, at the top – it can show an increase in the well diameter characteristic for coarse clastic rocks.

Zone "D" is the zone of final decomposition. It is composed of clay minerals of hydromica-kaolinite composition, which are a product of weathering of acidic metamorphic rocks – plagiogneisses and granite-gneisses, discovered in most wells of the South-Tatar Arch; in the clay mass fragments of undecomposed crystalline rocks are noted. According to the logging, it is distinguished by deep cavities, abnormally low apparent resistance readings (U-shaped recording is observed), lowering of neutron gamma-ray logging to 1-1.3 cu; the increased values of natural gamma activity from the spectral gamma-ray logging data are explained by the presence of thorium and potassium.

Zone "E" is a residual zone, represented in various degrees by washed clastic material (fragments of source rock, grains resistant to weathering of minerals). It is allocated in well 50 NUNs in the range of 2443-2427 m according to the increased content of thorium and potassium, which indirectly indicates its connection with the underlying "D" zone and belonging to the weathering crust.

Using the revealed logging characteristics of the weathering crust zones, we studied materials on 750 deep wells drilled in the territory of the South-Tatar Arch, confined by the Serafimovsko-Baltaevsky graben from the south; in 340 of them, the weathering crust was identified.

The crystalline rocks unchanged by hypergenesis, the roof of which is indicated by the readings of the apparent resistance at 625 Ohm*m, were installed only in 147 wells out of 340. The passage through zone "A" was from less than 1 to 69 m and only in two wells – wells 50 NUN and 2000 TMZ – the basement rocks were penetrated to a depth of 538 and 2204 m, respectively.

The raised core is mainly represented by the differences between biotite plagiogneisses and granite-gneisses; amphibolites, quartz diorites, granodiorites, plagiogranites, and gabbro-diabases were more rarely encountered.

Zone "B", with which the profile of the weathering crust itself actually begins, is penetrated in 271 wells. It should be kept in mind that it is certainly present in the sections of those 69 wells that were stopped by drilling in the overlying zone "C". The wide areal distribution of the zone of initial disintegration is explained by the fact that the occurrence of fracturing in crystalline rocks is ensured by the establishment on the territory of continental conditions and does not depend directly on the climate and the relief. In contrast to it, the formation of zones of initial and final decomposition of the vertical weathering crust profile ("C" and "D") takes place against the background of a warm moist climate and a relatively leveled but dissected basement surface.

Zone "B" is found most confidently by logging, as it is located in the range of apparent resistance values from 625 to 125 Ohm*m. The revealed thickness varies considerably (from 1 to several tens of meters); the largest value – 112 m – is marked in the well 12 BLT. From the bottomhole part of the section (interval 2367-2370 m, core 2.0 m) dark gray and dark red differences of biotite plagiogneisses, slightly weathered, with numerous formless cracks; on the fractures there are chlorite, kaolinite spots (drilling log). Dark gray, fractured sillimanite-biotite plagiogneisses were removed from the overlying interval (2296.2-2300.9 m, core 2.0 m). Micro-study shows that the rocks are changed – sillimanite is replaced by fibrous and flaky kaolinite (forms pseudomorphs in sillimanite), and

Fig. 1. Fractured core from well 181 VIU. Interval 1864-1869 m

plagioclases – with sericite; cracks are made of limonite and chlorite (Timergazin, 1959).

In the well 181 VIU zone "B" has a thickness of 29 m and is penetrated in its upper part, since the interval 1840-1869 m is characterized by relatively low readings of apparent resistance – from 210 to 125 Ohm*m. Fractured garnet-biotite plagiogneisses are raised from the bottomhole zone (Fig. 1).

In view of the fact that zone "B" is located at the very bottom of the vertical profile of weathering crust, it can continue to develop even with erosion of the upper zones, reaching significant thicknesses. In addition, if the well is located near tectonic faults, hydrothermal fluids are imprinted on its formation (Razumova, 1977). Under their influence, the rock-forming minerals of crystalline rocks change with the formation of scapolite, quartz, calcite, microcline, etc.

Zone "B" is established in sections of all 340 wells. In 271 of them it is completely covered and its thickness is 3-65.5 m. In 69 wells completed by drilling in the zone of initial decomposition, the penetrated thickness varies in significant ranges – from 1 to 25-30 m; in fact, it can be much larger. The core and sludge raised from the upper part of the zone are often characterized in drilling logs as crystalline eluvium or deluvium, in the lower part there are markedly fractured rocks.

The bottom of the zone is clearly identified by the apparent resistance value of 125 Ohm*m; upward along the section, the apparent resistance diagram is reduced to 40-50 Ohm*m and lower (often step-like, sometimes sharply within 2-3 m). Roof is identified by standard logging uncertainly, especially when the substance is well developed and the upper part of the section is represented by small clastic rocks. In this case, it is difficult to distinguish it from the overlapping terrigenous deposits of the Paleozoic or pre-Devonian, even in the presence of core descriptions. As a rule, the position of the roof in the "C" zone is recorded by the rise of natural gamma activity in the spectral gamma-ray logging, caused by an increased content of potassium and thorium. The method of gamma spectrometry until recently was not included in the compulsory complex of logging and was performed only in wells 50 NUN and 181 VIU. Zone "C" in the first well was described in detail in the paper (Amelchenko, Ivanova et al., 2016); in the section of well 181, roof is clearly identified at a depth of 1818 m by a high total content of potassium and thorium.

In the well 12 BLT zone "C" is allocated by logging in the interval 2246-2258 m and is composed of polymictic gravels with large fragments of pink feldspar and meat-red color (drill log). Gravelites overlap with sediments of the Kaltasinskian formation of the Lower Riphean. The thickness of zone "C" is 12 m; it is disproportionate in comparison with the underlying zone of initial disintegration (> 112 m), which suggests an intensive erosion of the upper part of the weathering crust in the Pre-Kaltasinskian.

As for the "D" zone, its establishment in sections with a sufficient degree of certainty is possible only by rock material and spectral gamma-ray logs, which records the continental character of clay formations (Ferthl, 1983). The diagram of apparent resistance is characterized by typical values for clay rocks with low values (up to 10-20 Ohm), and cavernogram – by a significant increase in the diameter of the well.

In the well 28 TMK the allocation of zone "D" according to logging is confirmed by sludge: from the interval 1777.5-1788 m the clay is red-brown with grains of quartz and feldspar. This well is one of the few where the successive changes in crystalline rocks from the source substrate (zone "A") to the clay zone have been established based on the rock material (Fig. 2). The total thickness of the weathering crust is 124 m, of which 69 m are in zone "B" and 43 m – in zone "C", marked by deluvium of crystalline rocks. The vertical profile ends with a 12-meter clay zone. The increased thickness of the weathering crust is explained by the well location in the contact zone of the main intrusion (in the magnetic field it corresponds to an anomaly with an intensity of more than 1200 nT) with the host rocks.

Clay zone in the well 377 SRF according to logging data is recorded at depths of 2974-3012 m. According to (Timergazin, 1959), greenish-gray kaolin-sericite rocks are raised from the bottom part, consisting of a "finely scaly-fibrous bulk containing relics of strongly altered plagioclase, biotite, grains of quartz and a fairly fresh microcline". The upper part of this interval is represented

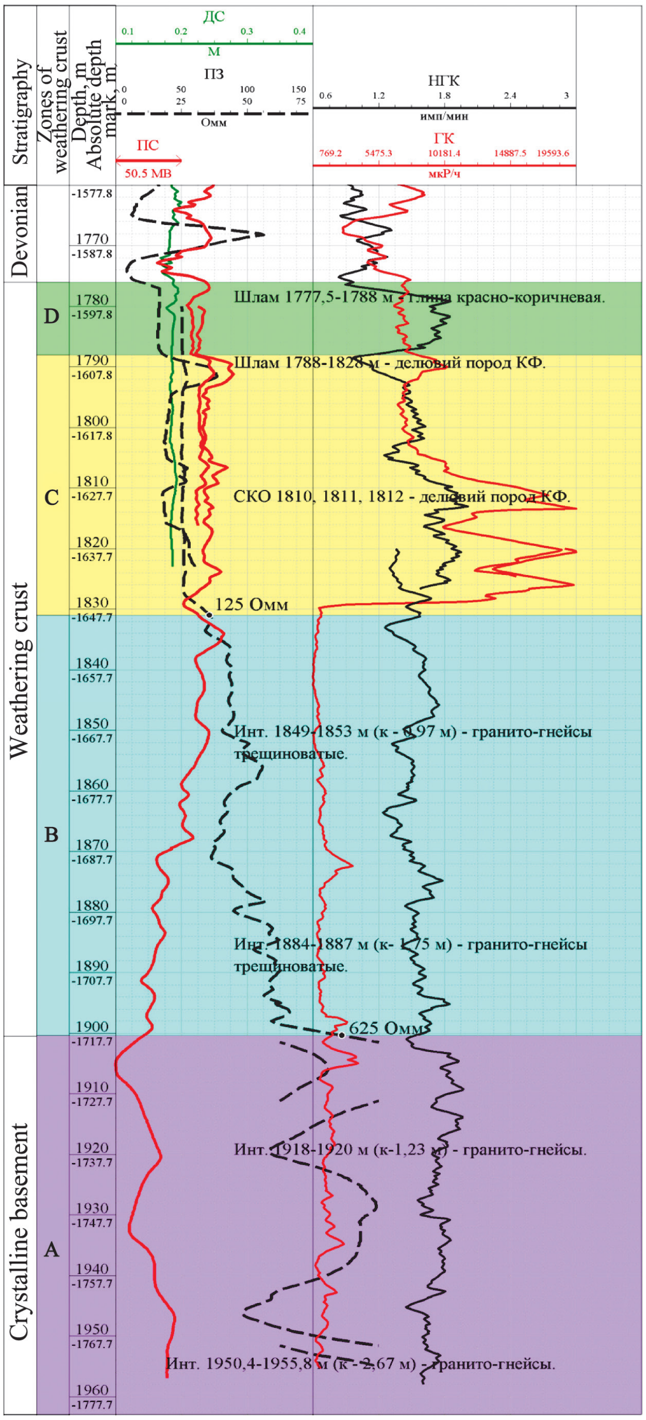

Fig. 2. The weathering crust of the South-Tatar Arch basement in the well 28 TMK

by a red-brown tight rock with rare inclusions of grains of gray quartz, pink feldspar and dark green biotite. Micro-study showed the presence of a fine-fibrous-scaly kaolin-sericite material, which amounts to 75% of the rock; it is thinly permeated with brown iron oxides and contains grains of microcline and strongly fractured quartz.

As one of the upper zones of the vertical profile of weathering crust, it is more often subject to erosion; established in only 17 wells.

A well-developed profile of the weathering crust ends with a residual zone "E", the formation of which is possible only under conditions of intensive drainage. It is composed, to varying degrees, of coarse-grained, poorly sorted sandstones with interbeds of pebbles and conglomerates washed from the clay material. The clastic material is represented by fragments of crystalline rocks and minerals most resistant to the action of hypergenic agents – quartz, microcline, zircon, rutile, magnetite, etc. The zone is difficult to distinguish from overlapping terrigenous sediments of Riphean-Vendian and Paleozoic, so it is distinguished by position in the section of established weathering crust and by correlated core and logging data. It is revealed only in well 50 NUN, where it lies on clays of zone "E". Initially, the interval 2443-2427 m was referred to the basal pack of the Tyuryushevskian formation of the Lower Riphean. However, it is distinctly separated from the overlapping Riphean sandstones by increased gamma activity (7-8 vs. 3.5 mcr/h), in the spectral gamma-ray logging provided by thorium and potassium; by a significant decrease in the curve of the neutron gamma-ray logging, which increases from 3.6 to 5 cu under the transition to the Tyuryushevskian sandstones (from a depth of 2427 m). In the middle part of the interval, a supposedly porous layer 7 m thick is distinguished, marked by a sharp increase in the interval time to 280 μs/m against 180 μs/m in its bottom. Coarse-grained terrigenous rocks of the residual zone also differ from underlying clay by higher values of apparent resistance. Apparently, the preservation of zone "E" in the well 50 NUN was provided by its relatively early burial by the most ancient in the region sedimentary rocks – the Tyuryushevskian formation of the Lower Riphean.

Conditionally, its presence is assumed over the zone "D" in wells 377 SRF in the interval 2974-2943 m according to the increased values of natural gamma activity; The curve of the gamma-ray log is similar to the diagram of well 50 NUN.

Based on the zones of the vertical profile of the weathering crust identified by the logging, maps of the "B" zone thicknesses (as most confidently identified by the logging characteristics) and the total thicknesses of the "B"+"C" zones (Fig. 3, 4) were plotted. The completed constructions make it possible to outline the main features of the development of the weathering crust along the surface of the crystalline basement of the South-Tatar Arch.

As is known from the geological literature (Koronovsky, Yakushova, 1991; Zhuravlev, 2009; Kayachev, 2014), as a rule, two main morphological types of weathering crusts are distinguished: areal and linear (linear-fractured). The weathering crust of the first type is developed over vast areas in the form of a cover, which has isometric outlines. Geometrically it is represented by two elements – width and thickness; the width is determined by the magnitude of straight

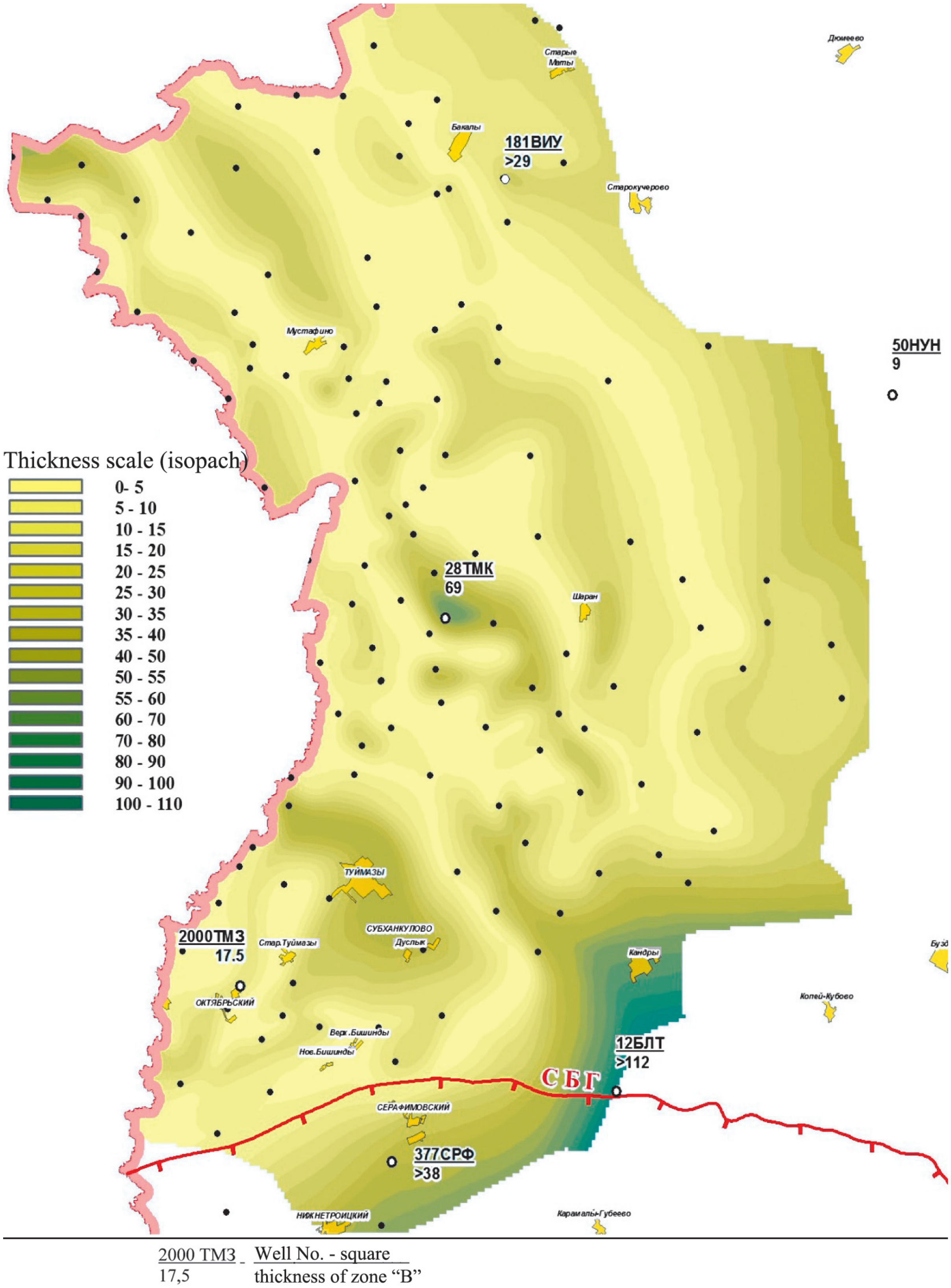

Fig. 3. Map thickness of zone "B" of weathering crust of the South-Tatar Arch (well spacing is rarefied)

lines drawn through the geometric center of the outline (Chetverikov, 2005).

The weathering crust of the second type has an increased thickness and is confined to areas of tectonic dislocation of a linear nature. There are three characteristics – length, width and thickness in the geometry of linear-fractured type of the weathering crust.

Analyzing isopachite maps, we come to the conclusion that within the investigated territory the weathering crust of the surface type in its classical sense (values of width relatively close to congruent) is not observed. The presented constructions testify to the dominance of the weathering crust of linear directivity, which is subdivided into linear-areal and

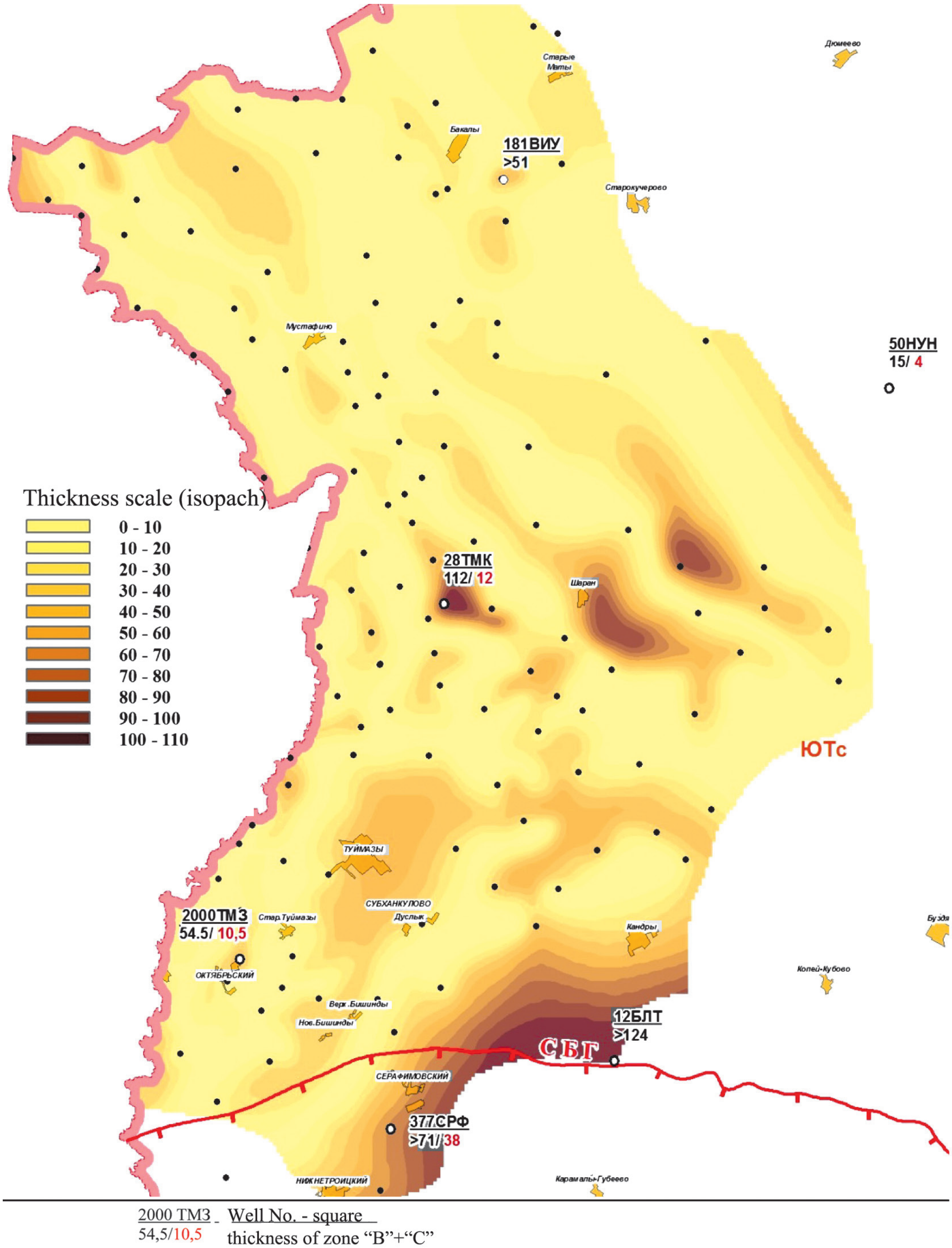

Fig. 4. Map of total thicknesses of zones "B" + "C" of the weathering crust of the South-Tatar Arch basement (well spacing is rarefied)

linear-fractured, having a thickness, width and much exceeding the last in length.

The linear-areal type is characterized by the hose-like development and insignificant thickness – 1-10 m. Three lengthy strips of weathering crust of this type are mapped on the thickness map of zone "B": western, central and eastern. They have sinuous outlines in the plan and strike with an azimuth of the order of 45-55° NW; at a considerable extent (60-70 km) they are characterized by extremely variable widths – from 1 to 6-10 km. A small submeridionally oriented fragment of linear-areal weathering crust (length 16 km, width – 2-4 km) is allocated in the outermost south-west of the territory.

From west to east, alternating strips of linear-areal weathering crust with the same elongated and narrow areas with increased thickness of hypergenically altered crystalline rocks (linear-fractured weathering crust) are observed.

Linear-areal type of the weathering crust, obviously, corresponds to areas with aligned and slightly dissected relief of the basement surface, which does not provide sufficient drainage, because of which the hypergenic factors did not have deep penetration into the crystalline rocks (thickness of the weathering crust is up to 10 m). The slopes of the peneplaines were characterized by an intensive washing regime, so here the weathering crust of a greater thickness – 11-25 m and more was formed.

Linear-fractured weathering crust marks axial zones of long-lived faults (well 12 BLT) and contact zones of rocks of various composition (well 28 TMK). The increased fracturing accompanying tectonically dislocated areas not only facilitates the penetration of hypergenic agents to a significant depth; hydrothermal solutions also rise along them. Thus, crystalline rocks are exposed to both exogenous and endogenous factors. According to a number of researchers (Leonov, Tsekhovsky et al, 2014), in the lower zones of the linear-fractured weathering crust, the transformation of crystalline rocks is dominated not by hypergenesis, but by "... processes associated with a tectonic or tectonic-hydro-thermal regime".

The weathering crust has a considerable thickness, 64 m, in the section of the parametric well 2000 TMZ, which is explained not only by the long period of its formation (taking into account the pre-Devonian age), but also by the location in the vicinity of disjunctive dislocation, as indicated by fracturing and fragmentation zones marked in the core, glide mirrors. In another parametric well 50 NUN, despite the confinement to the Neftekamsko-Sophyisky submeridional fault, the thickness of the full weathering crust profile is almost 2 times less – 35 m, which is apparently due to the early sealing of it by the Lower Riphean sandstones.

The maximum thicknesses of linear-fractured weathering crust are marked in well 377 SRF (> 109 m) and 12 BLT (> 124 m) located in the zone of Seraphimovsky-Baltayevsky graben. This is an penetrated thickness, since both wells were stopped by drilling in zone "B" and did not establish its lower limit. K.R. Timergazin indicates the change of rocks under the endogenous processes, in particular the appearance in well 377 SRF of such hydrothermal minerals as garnet, albite, quartz, calcite, pyrite, etc.

On the map of the total thicknesses of the "B"+"C", the northwest orientation of isolines also dominates and the alternation of the hose-like strips of the weathering crust of the linear-areal and linear-fractured type is preserved, although their configuration undergoes certain changes.

Comparison of thickness maps, in which, in general, the pattern of isopachitis is consistent, indicates a unified orientation of tectonic processes during the formation of weathering crust of the crystalline basement. The predominance of the northwestern orientation of isolines with an azimuth of 45-55° NW indicates on an earlier (probably pre-Riphean) age of tectonic faults of this strike.

The elements of the northeastern orientation (orthogonal to the above) appear on individual sections in the southern part and only on the map of total thickness, which allows us to assume a later laying of the corresponding disjunctive dislocations.

Conclusions

1. Based on the comparison of rock material and logging data, logging characteristics for zones of the weathering crust of crystalline rocks are determined.

2. Application of the revealed characteristics in consideration of materials on 750 wells drilled on the eastern slope of the South-Tatar Arch allowed to record vertical zonation of the weathering crust in 340 wells according to the field geophysical data.

3. The completed constructions made it possible to outline the main features of the development of the weathering crust along the surface of the crystalline basement and to establish linear-areal and linear-fractured types of it.

4. The results of the conducted studies prove the possibility of using the identified logging features to establish zones of weathering crust in the sections of wells even in the absence of core material.

References

Amel'chenko N.B., Ivanova T.V., Ivanov D.I., Masagutov R.Kh. Weathering Crust of the Basement in Parametric Wells 50 Novournyak and 2000 Tuimazy in the South-Tatar Arch. Georesursy = Georesources. 2016. V. 18. No. 3. Part 2. Pp. 212-217. DOI: 10.18599/grs.18.3.11

Chetverikov L.I. Geokinematika kory vyvetrivaniya [Geokinematics of the weathered crust]. *Proceedings of Voronezh State University. Geology* 2005. No. 1. Pp. 11-17. (In Russ.)

Fertl V.Kh. Spektrometriya estestvennogo gamma-izlucheniya v skvazhine [Spectrometry of natural gamma radiation in the well]. *Neft', gaz i neftekhimiya za rubezhom* [Oil, gas, petrochemistry abroad]. 1983. Pp. 3-8. (In Russ.)

Kayachev N.F. Oil and gas potential of the basement and its contact zone with sedimentary cover deposits within the Nepa arch of Eastern Siberia. *Materialy 10 Ural'skogo litologicheskogo soveshchaniya «Virtual'nye i real'nye geologicheskie modeli»* [Proc. 10th Ural lithological meeting «Virtual and real geological models»]. Ekaterinburg. 2014. Pp. 73-75. (In Russ.)

Koronovskiy N.V., Yakushova A.F. Osnovy geologii [Basic concepts of geology]. Moscow: Vysshaya shkola. 1991. 416 p. (In Russ.)

Leonov M.G., Tsekhovskiy Yu.G., Przhiyalgovskiy E.S., Poleshchuk A.V., Lavrushina E.V. Polygenic nature of granite clastites: Communication 1. Exogenic and tectonic postmagmatic disintegration of granite massifs. *Litologiya i poleznye iskopaemye = Lithology and Mineral Resources*. 2014. No. 1. Pp. 89-112.

Razumova V.N. Drevnie kory vyvetrivaniya i gidrotermal'nyy protsess [Ancient weathering crusts and hydrothermal process]. Moscow: Nauka. 1977. 156 p. (In Russ.)

Syngaevskiy P.E., Khafizov S.F. Formatsiya kory vyvetrivaniya v osadochnom tsikle Zapadno-Sibirskogo basseyna [Formation of weathering crust in sedimentary cycle of the West Siberian basin]. *Geologiya nefti i gaza = Geology of oil and gas*. 1999. No. 11-12. Pp. 22-30. (In Russ.)

Timergazin K.R. O metamorficheskikh porodakh fundamenta platformy, vskrytykh Chekanskoy skv. № 1 [On the metamorphic rocks of the basement platform, exposed by Chekanskaya well No. 1]. *Bashkirskaya neft'* [Bashkirian oil]. 1951. No. 3. Pp. 8-14.

Timergazin K.R. Dodevonskie obrazovaniya Zapadnoy Bashkirii i perspektivy ikh neftegazonosnosti [Pre-Devonian formations of Western Bashkiria and oil and gas potential]. Ufa: GGI BFAN SSSR. 1959. 311 p.

Zhuravlev E.G. Oil and gas pools in weathering crusts on the sedimentary basin basement. *Litologiya i poleznye iskopaemye = Lithology and Mineral Resources*. 2009. No. 3. Pp. 329-334. (In Russ.)

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SUBSTANTIATION OF THE FAULT-BLOCK STRUCTURE FOR EFFECTIVE ADDITIONAL EXPLORATION AND DEVELOPMENT OF THE WEST-KOMMUNARSKY FIELD

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Abstract. While the seismic exploration and methodological geological interpretation of geological data for drilling various wells and other types of research are improved for a significant part of the fields being developed in the Samara Region, the reliability of the structure of geological and recoverable oil and gas reserves increases. The complication of the structure and multiple recalculations of reserves at a number of fields are due to the introduction into the development of undiscovered to the required conditions of complex geological fields and licensed areas. The example of the West-Kommunarsky field shows how its geological structure becomes more complex as its study becomes more extensive. Thus, the oil reservoir in the Lower Paschian sediments, according to the created integrated model, has horizontal positions, but with different levels of water-oil contact in adjacent blocks separated by downthrows. The justification of disjunctive dislocations, which have been planned but not tracked due to their uncertainty in seismic data and determination of their main characteristics, was performed by stratigraphic correlation of well sections using the rules of projective geometry and confirmed by other traditional methodical methods. With each new tectonic movement along the strike-slip, a near-faul fracture of rocks is formed parallel to it, as a reflection of geodynamic stresses and energy-intensive processes in the downthrows and strike-slips of rocks along the fault plane. Near-fault regular changes in the fracturing of rocks and the dependence of well productivity on their location relative to the disjunctive make it possible to predict the latitudinal reservoirs zonation in near-fault area: fractured, porous-fractured, fractured-porous and porous types. Such a dialectical process of movement towards a real model of the field ensures the reliability of revised reserves and updated technological documents for the development of fields.

Keywords: strike-slip, disjunctive dislocations, well productivity, fault-block model, water-oil contact
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Introduction

The reliability of geological and recoverable oil and gas reserves structure increases with the improvement of seismic exploration means and geological interpretation methods for drilling wells of various purposes and other types of research for the significant part of the fields under development in the Samara Region. The complication of the structure and multiple recalculations of reserves at a number of fields are due to the introduction into the development of fields and licensed areas unexplored up to the required conditions and complicated in the geological structure (Ashirov et al., 2001). As a result, the structure of complex hydrocarbon reservoirs is specified (sometimes drastically) at the stage of development due to the drilling of a large number of production wells. Such a dialectical process of movement towards a real model of the field ensures the reliability of specified reserves and updated technological documents for the development of fields.

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Brief geological description of the field

The field is confined to the western side of the Buzuluk depression at the regional level along the surface of the crystalline basement and the terrigenous Devonian. Deposits of the Devonian, Carboniferous, Permian, Neogene and Quaternary ages, located on the surface of the crystalline basement of the Archaean age, participate in the geological structure of the field. The total thickness of the sedimentary cover reaches 3290 m. The productive Staroskolskian and Pashian horizons are composed of sandstones interbedded with siltstones and clayey rocks. Sandstones are quartzous, fine-grained. The productivity of sandstones is associated with the formations D-I, D-II, D-III. The reservoir under consideration in the DIII formation (total thickness 11.0 ... 31.4 m) lies at an average depth of 3187 m.

The West-Kommunarsky field is located within the Kinel district of the Samara region. A detailed study of the features of its geological structure was carried out with the goal of creating, as far as possible, a reliable geological and hydrodynamic model and justifying the real indicators in the forthcoming technological documents for its development.

Previously, when the degree of the field exploration was insufficient, the formations in question were modeled in a plicative variant with an inclined water-oil contact (immersion in the west direction). According to the data of seismic prospecting, north-north-eastern strike faults, confining the reservoir in a structural-tectonic trap, are clearly identified and reflected in the resulting structural maps. Presumably, this fault is accompanied (feathered) by disjunctive dislocations with insignificant amplitude of rocks displacement along the dislocation plane. Fragmentary tracking of these faults, as well as small amplitude of their displacement in the dislocation plane, were below the sensitivity threshold of the seismic survey equipment at some sites. For this reason, most of the disjunctive dislocations are not represented on maps by reflective horizons (Fig. 1).

After drilling exploration and production wells, the geological structure of the field was repeatedly clarified in view of more complex (block) structure of oil deposits. The process of multivariate study of deposits began and continues including manual and computer reconstructions of the structural plans of the sedimentary cover, including the fault-block version presented below.

The ratio of structural plans of the basement and the platform cover

The crystalline basement has played a decisive role in the formation of the sedimentary cover tectonics, composed of highly metamorphosed, magmatic and sedimentary rocks of the Archean and Lower Proterozoic. The basement is divided by numerous faults into blocks of various shapes and sizes. Two ancient orthogonal systems of dislocations are distinguished – of sublatitudinal and ex-meridian strike – in the sediments of the basement and the platform cover within the area of the study. The movement of blocks along faults directly or indirectly affects the formation of such tectonic structures as graben-like troughs and horst-like raised zones (Fig. 2). A number of signs of fracture tectonics and tectonic movements of rocks along faults have been established (steep fall of rocks, repetition of horizons in a section, development of jointing in rocks, occurrence of volcanic inclusions among sedimentary deposits, presence of linear magnetic and gravitational anomalies, etc.). The presence of pronounced disjunctive dislocations is established throughout the section of the terrigenous deposits of the Devonian in the zones of Devonian graben-like troughs (Shashel, 1998).

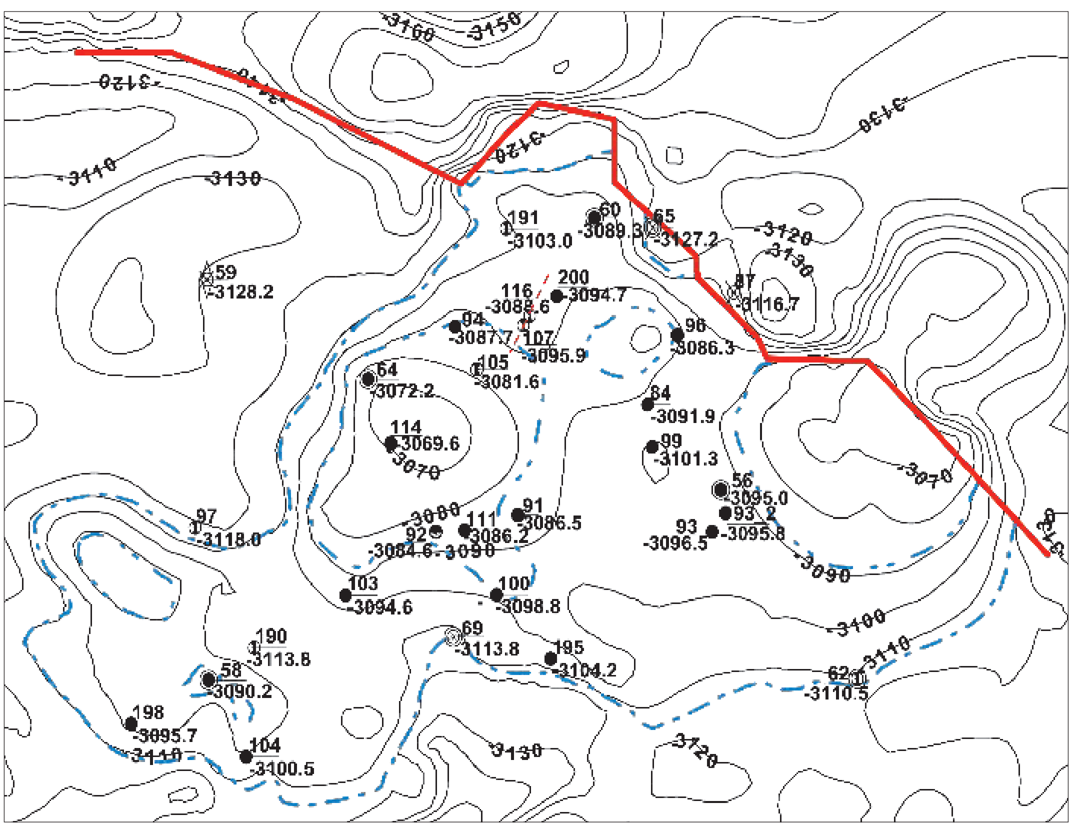

Fig. 1. Structural map for the roof of the productive formation D-III of the Starooskolskian horizon in a plicative version. 1 – external and internal contours of oil content; 2 – downthrows

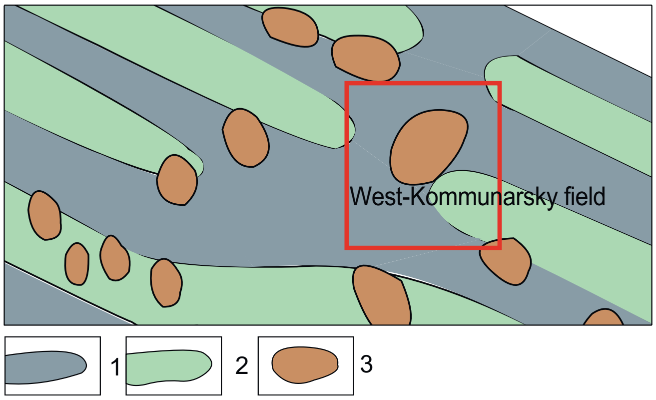

Fig. 2 – The map fragment of the tectonic and oil geological zoning of the Samara region (the area of the West-Kommunarsky field). 1 – Devonian graben-like troughs; 2 – horst-like raised zones; 3 – oil fields

The main tectonic factor controlling the morphology of structural elements of grabens are narrow, linear, sublatitudinal and parallel strike-slips, which limit it and are the sides. The fault planes of strike-slips are directed towards each other and have a steep fall, being extensions of disjunctives in the basement.

As shown by similar studies in other regions, a joint approach to the modeling of hydrocarbon deposits from the viewpoint of geology and development makes it possible to more accurately approach the modeling of reservoir boundaries, the estimation of hydrocarbon reserves and the optimal location of producing wells (Bochkarev, Bochkarev, 2016; Karpov, 2011; Kopylov et al., 2015; Lobusev et al., 2014b).

New geological model of the deposit

As the drilling volumes increased and new modifications of geophysical works were applied, the structure of the field became more complex than it seemed at the early stages of the research. The structural-tectonic field composition is clarified below by analyzing the resulting seismic survey materials along the reflecting horizons as close to productive strata as possible, and by using standard methods for establishing and tracing discontinuous faults (projective geometry, profiles, etc.) (Bochkarev, Bochkarev, 2016; Karpov, 2011).

When sediments were correlated, particular attention was paid to those parts of the deposit section where a sharp change in the thickness occurred in a narrow inter-well space along the linear zones of uncertain interpretation (loss of sensitivity) of disjunctive tectonics from seismic data. The analysis involved 35 wells. In the places of the proposed monitoring of faults, adjacent pairs of wells were put on different sides of the dislocations. A pair of wells No.107-116 and No.127/2-56 was chosen as an example of the downthrow and graben-like structural elements.

The regional reference A “ostracod limestone” served as a comparison line for linking the analyzed strata, differing in lithological composition from the above and below underlying sediments, consistent in thickness and area and clearly recorded in the logging diagrams. The boundaries of roof and base of the compared productive formations are identified on the geological profiles of selected pairs of analyzed wells (Fig. 3).

To correlate the D-III formation of the Staroskolskian horizon, Mullin clays and “ostracod limestone” were used as the reference surface, which are clearly traced throughout the area and have a specific configuration of the logging curves. The pack 1 (Fig. 3) is mainly represented by clayey rocks and siltstones. The pack 2 corresponds to the D-III formation, which is represented by sandstones and siltstones and is allocated confidently on the background of enclosing rocks. The overlying layer of clay (pack 3) serves as the cover of the D-III formation. The thickness of the D-III formation varies from 22.8 to 37.6 m. The pack 4 corresponds to the regional benchmark “ostracod limestone”, for which high indications of resistance and neutron gamma-ray logging are typical, as well as reduced values of gamma-ray logging. The upper part of the Zhivetskian formation is represented by clayey deposits (bundle 5), which are characterized by regional consistency. These deposits are distinguished by high values of gamma-ray and self-potential, low resistance in the logging diagrams. Deposits of the Pashian horizon, mostly composed of sandstones and siltstones with interlayers of clay, are divided into packs 6 ... 9. The pack 6 includes reservoirs of the D-II formation, the pack 8 – reservoirs of the D-I formation. The section between the formations D-I and D-II is represented by a clay pack confidently allocated by logging diagrams (pack 7). The cover of formation D-I is clay (pack 9).

The method of projective geometry, proposed by the Canadian geologist T.B. Heights, based on the rule of the “complex ratio of four points”, as well as other methodical techniques, was applied in this work in order to establish and confirm in the inter-wellbore space of disjunctive dislocations represented by downthrows and strike-slips. The absolute marks of the roof and the base of the same formations in two adjacent wells were analyzed, between which a disjunctive was assumed. Points that are in a projective relationship form a bundle of straight lines intersecting in accordance with the Heights law at a single point M, called the design center; and the connection of “four points” is the desired temporal chronostratigraphic correlation of the sections of two neighboring wells (Bochkarev, Bochkarev, 2016; Kopylov et al., 2015; Lobusev et al., 2014a).

The projective four-point ratio method identifies section intervals that have different thicknesses in the investigated wells. At the same time, an increase in thickness is observed in the lowered block, which is typical for consedimentary downthrows.

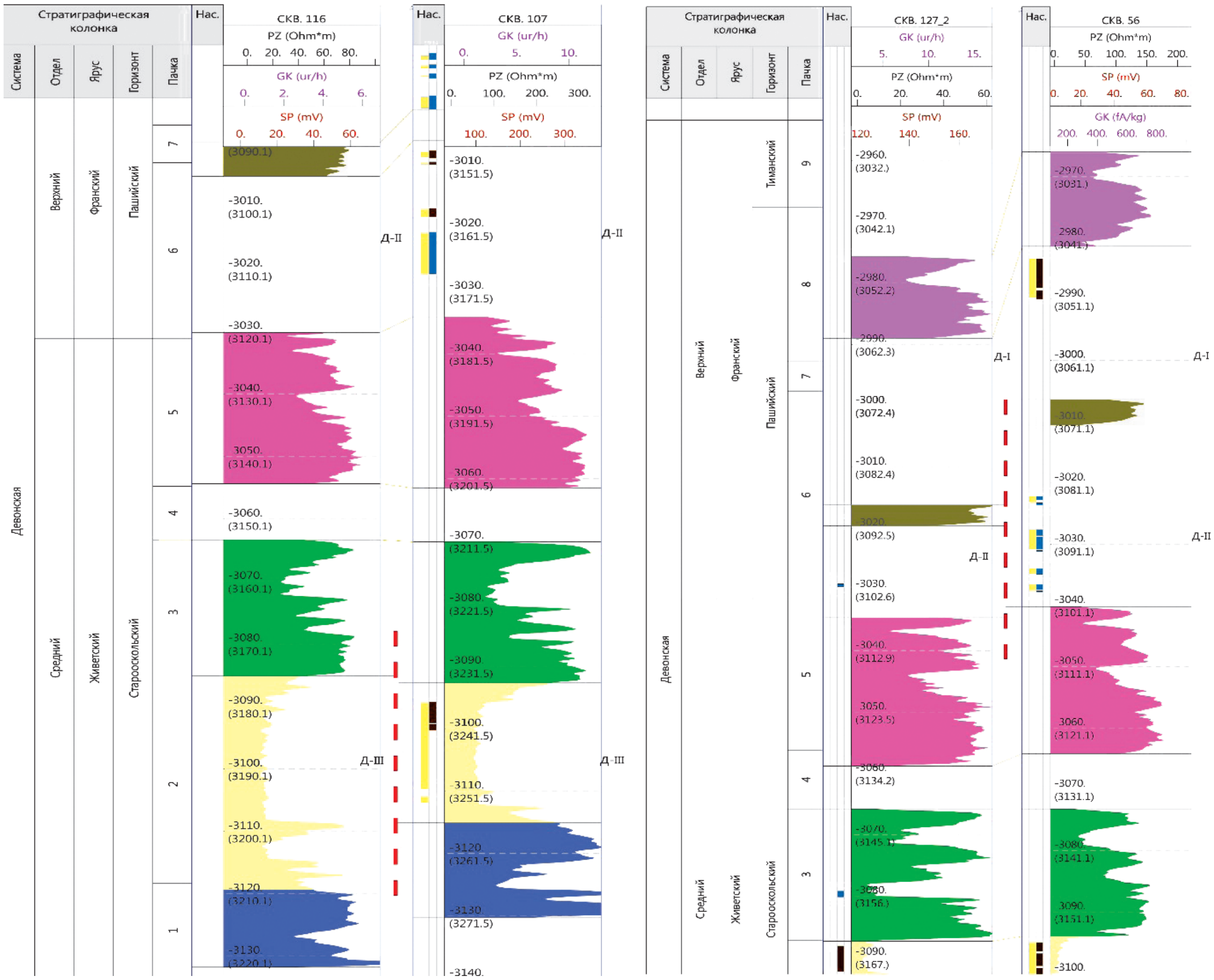

Fig. 3. Correlation of the chronostratigraphic reference marks of the productive formation D-III in pair wells No. 116 – No. 107 and No. 127_2 – No. 56

The presence of two projection centers M1 and M2 as a result of joining chronostratigraphic references, is a direct indication of tectonic dislocations. According to the four points connection rule, only one design center M is obtained at best for a pair of wells between which there is no discontinuous dislocation. The results of the correlation of productive formations D-III and D-II are shown in Tables 1, 2. The correlation analysis of the section according to the rule of the projective ratio of four points is shown on the example of two pairs of wells Nos. 116-107 (on the left for the productive formation D-III) and Nos. 127/2-56 (on the right for the D-II formation) (Fig. 4). According to the principle of projective geometry, as a result of the connection of chronostratigraphic references, two design centers M1 and M2 for the analyzed pairs of wells were obtained in each considered case, which indicated the presence of a dislocation between the given wells. Section and analysis of formation continuity in wells Nos. 107 and 116 and in wells Nos. 127/2 and 56 are shown in Fig. 5 and 6. For the first pair of wells, the displacement amplitude of rocks in the fault plane was 8 m, for the second – 11 m.

As a result, within the area of the field, small-amplitude disjunctive dislocations were confirmed, as planned by seismic prospecting and identified by geological data. As the drilling volumes increased and new modifications of geophysical operations were applied, a more complex structure of the field began to be revealed than was imagined at the early stages of the research. On the fragment of the map along the basement disjunctive dislocations, horsts and grabens have the same strike as the rocks fracturing revealed in the cover deposits according to different data (Fig. 2, 7).

Two blocks can be allocated in a large scale: northern (A) and southern (B), separated by micrograben (II) (Fig. 7, 8). The slip in the dislocations of graben II was 750 m, and the graben itself was also recorded by the presence of “structural shoulders” and the contraction of

Chronostratigraphic references	Legend	Depth of absolute marks of references by wells, m	
		well 116	well 107
Cover roof for the formation D-III	A/A1	-3063.3	-3070.1
Roof of the formation D-III	B/B1	-3084.9	-3092.5
Bottom of the formation D-III	C/C1	-3119.1	-3114.9
Bottom of the clay formation of Vorobyovsky horizon	D/D1	-3131.5	-3130.5

Table 1. The correlation results for the productive formation D-III (wells No. 116 – No. 107)

Chronostratigraphic references	Legend	Depth of absolute marks of references by wells, m	
		well 127/ 2	well 56
Cover roof for the formation D-II	A/A1	-3015.9	-3006.0
Roof of the formation D-II	B/B1	-3019.3	-3010.6
Bottom of the formation D-II	C/C1	-3034.5	-3040.2
Bottom of the clay formation of Mullinsky horizon	D/D1	-3058.7	-3064.0

Table 2. The correlation results for the productive formation D-II (wells No. 127/2 – No.56)

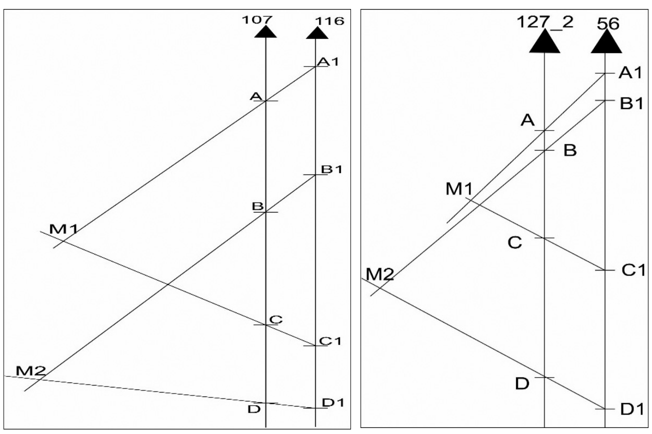

Fig. 4. Checking the correlation of the section according to the projective ratio rule of "four points" for the wells No. 116 – No. 107 (on the left for the productive formation D-III) and No. 127_2 – No. 56 (on the right for the D-II formation)

multiple isohypes (Bochkarev and Bochkarev, 2016). The presence between the enlarged blocks (A and B) of graben (II) divides the once unified field into two unconnected oil clusters. The northern block is 21 m above the southern one by the maximum hypsometric levels on the structural plan, which causes different levels of water-oil contact for the same productive formations: in the northern – minus 3103 m, in the southern – minus 3112 m (Fig. 7, 8). In the grabens productive deposits are replaced by pelitic material and productive formations are represented by non-reservoirs (porosity decreases to boundary values and less, the effective oil-saturated thickness is zero) (wells 65, 87, 69, 97). Well 190 penetrated the downthrow at the level of the productive formation, penetrating it only partially (2.2 m).

Long-term disjunctive dislocations at the level of productive formations are accompanied by zones

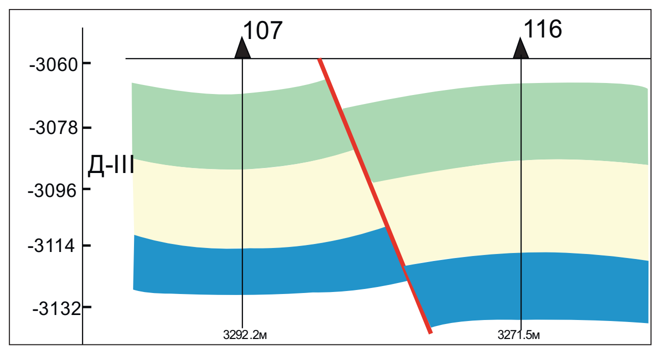

Fig. 5. Geological section through the wells 107 and 116 and the proposed downthrow location for the productive formation D-III

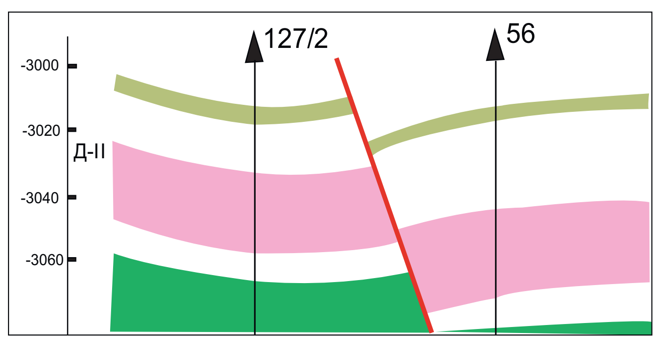

Fig. 6. Geological section through the wells 127/2 and 56 and the proposed downthrow location for the productive formation D-II

of abnormally high tectonic stresses, which, due to confined areas of normal-fault increased fracturing and maximum oil production rates, are an important area of geological exploration for oil in the region (Shashel, 1998). The role of cracks in the reservoir properties of D-II formation of the West-Kommunarsky field predominates so much that a purely fractured reservoir type can be diagnosed for them.

With each new tectonic movement in the strike-slip,

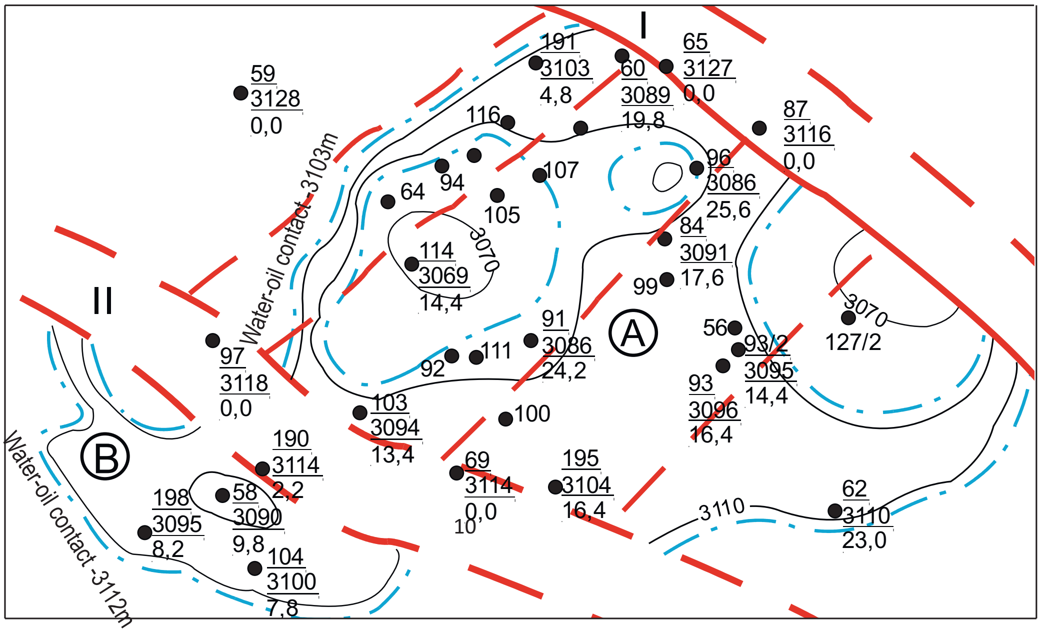

Fig. 7. The fault-block model 2D for the roof of the productive formation D-III of the West-Kommunarsky field

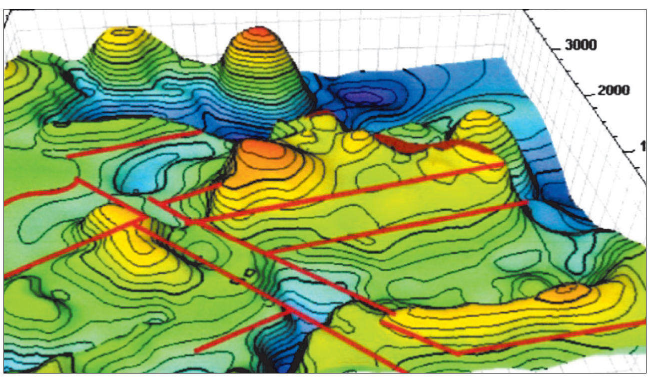

Fig. 8. Geological model 3D for the surface of the productive formation D-III in the fault-block structure of the West-Kommunarsky field

normal-fault fracturing of the rocks is formed in parallel, as a reflection of geodynamic stresses and energy-consuming processes in the strike and slip of rocks along the fault plane. This is evidenced by the effectiveness of creating a branched system of cracks in hydraulic fracturing (Golf-Rakht, 1986; Karpov, 2011; Kopylov et al., 2015).

Ashirov K.B. and others in the studied fields of the Samara region indicate an active flow of light oil through the zones of fault fragmentation into the deposits, the presence of which is fixed in normal-fault wells (Ashirov et al., 2001). Along with this, the studies of regular changes in the physical properties of rocks (decrease in porosity, increase in density and fracturing of rocks) and growth in well productivity towards the disjunctive dislocation have been initiated in sandy-siltstone reservoirs, which makes it possible to predict, in parallel to the disjunctive strike, the consistent zoning of reservoir types: fractured, porous-fractured, fractured-porous and porous types (Bochkarev, Bochkarev, 2016).

Conclusions

1. In-depth tectonic analysis and attracted methods for detecting low-amplitude dislocations made it possible to identify, and in some cases confirm downthrows previously identified from seismic data and to substantiate the fault-block structure of the West-Kommunarsky field. A system of Devonian graben-like deflections of the northeastern strike, genetically related to the horst-graben structure in the basement, has been allocated.

2. Horizontal levels of water-oil contact in the allocated enlarged blocks of the field are justified. It is pointed out that it is possible to form a normal-fault natural fracturing of rocks; its effects on the formation of various types of reservoirs (fractured, porous-fractured, and fractured-porous) are emphasized. Noting the important role of disjunctive dislocations in the structure of fields, it is necessary to attract additional methods for their study (gravimagnetic and tracer studies, hydrodynamic wells and results of reservoir pressure measurements in adjacent blocks, the results of recording the image of micro-lateral logging in wells on the FMI device and cross-dipole broadband acoustic logging, and others) in order to clarify their location and to reveal the patterns of change in rock properties and the productivity nature in normal-fault areas on the considered and other fields in the region.

3. The obtained results should be taken into account when specifying development projects, hydrodynamic modeling and choosing methods of bed stimulation.

References

Ashirov K.B., Borgest T.M., Karev K.L. Obosnovanie prichin mnogokratnoi vospolnyaemosti zapasov nefti i gaza na razrabatyvaemykh mestorozhdeniyakh Samarskoi oblasti [Substantiation of the reasons for the multiple replenishment of oil and gas reserves in the developed fields of the Samara Region]. *Izvestiya Samarskogo nauchnogo tsentra RAN. Geologiya, gefizika i geokhimiya* [Bulletin of the Samara Scientific Center of the Russian Academy of Sciences. Geology, geophysics and geochemistry]. 2001. No. 1. Pp.167-173. (In Russ.)

Bochkarev V.A., Bochkarev A.V. Sbrosy i neftegazonosnost' [Discharges and oil and gas potential]. Moscow: VNIIOENG Publ. 2016. 428 p. (In Russ.)

Golf-Rakht T. D. Osnovy neftepromyslovoi geologii i razrabotki treshchinovatykh kollektorov [The fundamentals of oilfield geology and the development of fractured reservoirs]. Moscow: Nedra Publ. 1986. 608 p. (In Russ.)

Karpov V.A. Razlom – kak ob'ekt izucheniya pri neftegazopoiskovykh rabotakh [Fault – as an object of study in oil and gas exploration]. *Nedropolzovanie XXI vek* [Subsoil use – XXI Century]. 2011. No.6. Pp. 66-70. (In Russ.)

Kopylov V.E., Bronskova E.I, Bochkarev A.V. Utochnenie geologicheskogo stroeniya Vostochno-Pereval'nogo mestorozhdeniya dlya effektivnoi razrabotki zalezhi Ach1-2 [Clarification of geological structure of the East-Perevalnoye field for the effective development of the Ach1-2 deposit]. *Neftepromyslovoe delo*. 2015. No.10. Pp.4-9. (In Russ.)

Lobusev A.V., Lobusev M.A., Antipova Yu.A., Osin D.A., Strakhov P.N. Vozmozhnosti ispol'zovaniya dannykh seismorazvedki dlya prognozirovaniya kollektorskikh svoistv produktivnykh otlozhenii Tympuchikanskogo mestorozhdeniya [Possibilities of using seismic data to predict the reservoir properties of productive deposits of the Tympuchikansky field]. *Territorija NEFTEGAZ = Oil and Gas Territory*. 2014a. No.3. Pp. 18-23. (In Russ.)

Lobusev A.V., Lobusev M.A., Strakhov P.N., Novyi podkhod k otsenke i prognozu produktivnosti neftegazonasyshchennykh porod [A new approach to the assessment and forecast of productivity of oil and gas saturated rocks]. *Akademicheskii zhurnal Zapadnoi Sibiri* [Academic Journal of Western Siberia]. 2014b. No.2(51). Vol. 10. Pp. 45-47. (In Russ.)

Shilov G.Ya Dostovernaya identifikatsiya razlomov – klyuch k povysheniyu effektivnosti neftegazopoiskovykh rabot [Authentic identification of faults is the key to increasing the efficiency of oil and gas exploration]. *Nedropolzovanie XXI vek* [Subsoil use – XXI Century]. 2012. No.6. Pp.60-63. (In Russ.)

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MODEL OF THE SOUTH-TEGYANSKY FIELD OF HEAVY OIL

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Abstract. The article considers the geological structure of the South-Tegyansky oil field, which until now remains underexplored. Geological and field characteristics, results of various estimates of geological and recoverable reserves and resources are given. Based on the seismic survey data and comparison of subhorizons XIa, XIb and XIc thicknesses in well sections, an upthrust model of the reservoir structure was proposed in the location of the only industrial well P-102. It is shown that the imposition of sub-horizon XIc with improved reservoir properties in the well section and increased fracturing of the upthrust area cannot increase the well productivity by almost an order of magnitude, so the assumption is made about deep feeding of the reservoir through disjunctive dislocations. Geochemical indicators of oil composition and distribution of molecules-biomarkers may indicate a mixed Devonian-Permian genesis of the oil in the South-Tegyansky field. A conclusion is drawn on the high potential of the subsalt Mid-Paleozoic deposit complex.

Keywords: Anabaro-Hatagskaya anticline, Upper Paleozoic, Mid-Paleozoic, oil field, halokinesis, uplift, oil-gas perspective

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Introduction

Currently, within the continental shelf of the Laptev Sea, large-scale seismic surveys are carried out by various subsoil users (PJSC Rosneft, JSC Gazprom and others). High prospects of oil and gas content in the Laptev Sea shelf are noted by many researchers. But it should be borne in mind that the Arctic shelf is the most inaccessible in terms of carrying out geological exploration both for climatic and transport-infrastructure conditions. At the same time, the coastal part of the Laptev Sea remains an extremely poorly explored area of the Siberian Platform. Here exploration for oil and gas was carried out in two main stages. At the first stage, in the 40-50's of the last century, the organization "Glavsevmorput" carried out prospecting for oil and gas in the Anabar-Khatanga interfluve to provide fuel for vessels plying along the Northern Sea Route. During these works, two small oil fields were discovered on the territory of the Republic of Sakha (Yakutia) – South-Tegyansky and Chaydakhsky. At the second stage, in the 80-90's of the last century, a network of CDP profiles with a total length of 6570 km was completed and several deep wells drilled. The results of these works did not lead to the discovery of an oil and gas field.

At the same time, taking into account industrial inflows and a certain volume of oil production from the South-Tegyansky field, we consider it expedient to clarify the model of the structure, complete additional exploration and make a calculation of the reserves.

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Formulation of the problem

The South-Tegyansky field is located within the Anabar-Khatanga saddle, which, in our opinion, is part of the Lena-Anabar trough. The field is confined to the brahinanthclinal fold of the sublatitudinal strike with the same name. Its dimensions along the Lower Cretaceous sediments are 19×6 km, the amplitude is 700 m. Fold axis forms two domes – east and west, separated by a saddle, while the eastern dome is above the western one for about 200 m. Penetrated by deep drilling section of the field is represented by the Upper-Lower Mesozoic terrigenous deposits. Quite thick clastic-carbonate of the Middle Paleozoic (up to 1 km), carbonate Lower Paleozoic (up to 1.3 km) and the Precambrian cover are expected to be developed in the unopened portion.

The industrial oil and gas potential of the South-Tegyansky field is associated with sediments (the horizon) of the roofing part of the Lower Kozhevnikovskian Formation of the Lower Permian. The productive horizon XI with a total thickness of 70-90 m lies in the depth interval 1580-1720 m. The maximum inflow of 15.3 m^3/day of oil was received in the well P-102, laid on the western dome. From the same well, an inflow of gas up to 1445 m^3/day was obtained. In other wells on the western dome, the flow rates vary from 0.1 to 2 m^3/day. On the eastern dome, oil inflows do not exceed 0.3 m^3/day. The density of oil is high from 0.930 to 0.970 g/cm^3, an average of 0.950 g/cm^3 (Kalinko, 1959).

The XI horizon is divided into three sand subhorizon – XIa, XIb, XIc with a thickness of 10 to 49 m, with improved reservoir properties relatively separating them from mudstone layers with thicknesses up to 12 m. Sandstones are finely grained, in varying degrees, clayey and silty, weakly cemented by clay – micaceous-siliceous and carbonate cement. The subhorizon XIa was penetrated in the P-102 well in the interval of 1583-1605 m, XIb – 1617-1630 m, XIc – 1639-1670 m. The subhorizon XIb has the best reservoir quality. The open porosity of the sandstone in this horizon reaches 26%, an average of 11%, the permeability reaches 0.068 μm^2, with an average value of 0.004 μm^2. The reservoir pressure in the middle of the productive interval 1617-1630 m is 14.27 MPa, the reservoir temperature is 32.4 °C.

Total recorded cumulative production of the well was about 2085.15 tons of crude oil, of which, from 12.1948 to 08.1952 year – 1789 m^3 of oil (1789×0.95 = 1699.55 tons) and in the period from 06.1996 to 08.2002 year – 385.6 tons.

First a rough estimate of geological and recoverable reserves and resources of the Lower Permian reservoir in the Western dome of the South-Tegyansky field on C_2 category was performed by Trust "Krasnoyarsk-neftegazrazvedka" in 1976, in the volume of 3990/399 thousand tons of oil and 610/61 million m^3 of dissolved gas (recovery ratio was was assumed to be 0.1). Volumes of free gas contained in the gas cap of the deposit, because of the lack of parameters, were not counted. The following estimation of geological reserves of oil was carried out in 1996 (Safronov et al., 1996) in the volume of 6946 thousand tons on C_2 category, recoverable – 2083 thousand tons. And 1448 thousand tons and 434 thousand tons (the recovery ratio was taken equal to 0.3), respectively – on C_1 category (in the radius of drainage of the P-102 well).

Thus, the calculation of oil reserves of the South-Tegyansky field with approval in the State Balance of the Russian Federation has not been carried out to date. The objective reasons for this situation are insignificant inflows from wells (no more than 2 m^3/day), except for P-102, and insufficient knowledge of the oil reservoir model. A number of researchers have suggested that there is no active oil deposit, and oil enters the P-102 well through a fault from deep seams (deep source). The main argument in favor of this assumption is the anhydrous oil flowing of the P-102 well.

The aquiferous complex of the Upper Paleozoic-Mesozoic deposits of the geological region has been studied very poorly. The few data available indicate the low reservoir energy of the productive horizon XI.

Based on the available geological, geophysical and geochemical data, we will try to show the most approximate to the natural structure model of the South-Tegyansky oil field.

Experimental part

We have considered the thickness of subhorizons XIa, XIb, XIc at the field, given in the primary data (Puk, Kopylova, 1955). Table 1 shows the depths and thicknesses of subhorizons XIa, XIb, XIc. Figure 1 shows the change in the thicknesses of subhorizons XIa, XIb, XIc in wells drilled on the western dome of the South-Tegyansky field.

As can be seen from Table 1 and Figure 1, the thicknesses of subhorizons XIa, XIb and XIc differ significantly from the others in the well P-102. In all wells except P-102, horizon XIa has a small thickness, XIb – maximum and XIc – average; while in the well P-102 all three subhorizons have commensurable

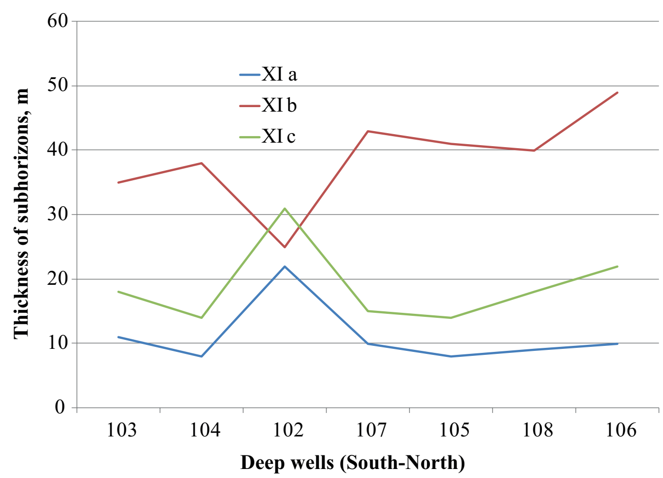

Fig. 1. Graph of the thickness variation of subhorizons XIa, XIb and XIc in the productive horizon XI. South-Tegyansky area

well	XIa			XIb			XIc		
	roof	bottom	thickness	roof	bottom	thickness	roof	bottom	thickness
102	1583	1605	**22**	1611	1636	**25**	1639	1670	**31**
103	1599	1610	11	1613	1648	35	1660	1678	18
104	1643	1651	8	1660	1698	38	1704	1718	14
105	1607	1615	8	1616	1657	41	1666	1680	14
106	1642	1652	10	1655	1704	49	1709	1731+	22+
107	1661	1671	10	1680	1723	43	-	-	
108	1576	1585	9	1590	1630	40	1640	1658	18

Table 1. Depth and thickness of subhorizons XIa, XIb, XIc

thicknesses (22 m, 25 m, 31 m). The thickness of the subhorizon XIa was increased 2 times, the subhorizon XIb thickness was decreased noticeably relative to other wells, and the thickness of subhorizon XIc was increased 1.5 times.

In our opinion, these differences can be due to superposition of the section parts due to the upthurst dislocations. It seems unlikely to have a quite sharp change in the thickness of sand interlayers in a limited area of sedimentation (the first hundreds of meters), even in coastal-marine conditions. The presence of faults in the area of the well P-102, including the upthrusts, was reliably established by the latest seismic surveys in 2012 (Fig. 2, A). This disjunctive dislocation for the western dome has the form of a central or axial downthrow to the middle of the sediments, bounded by the reflecting horizons VII and VIb (the middle Carboniferous-Tuskakhstian formation of the Lower Permian). However, it is central only in the sediments of the Middle and Upper Paleozoic of the western dome, and in the layers of the Riphean and the Lower Paleozoic it is shifted to the southern periphery of the fold. The vertical displacements of the layers are 100-200 m. Fig. 2 (A and B) shows that from a depth

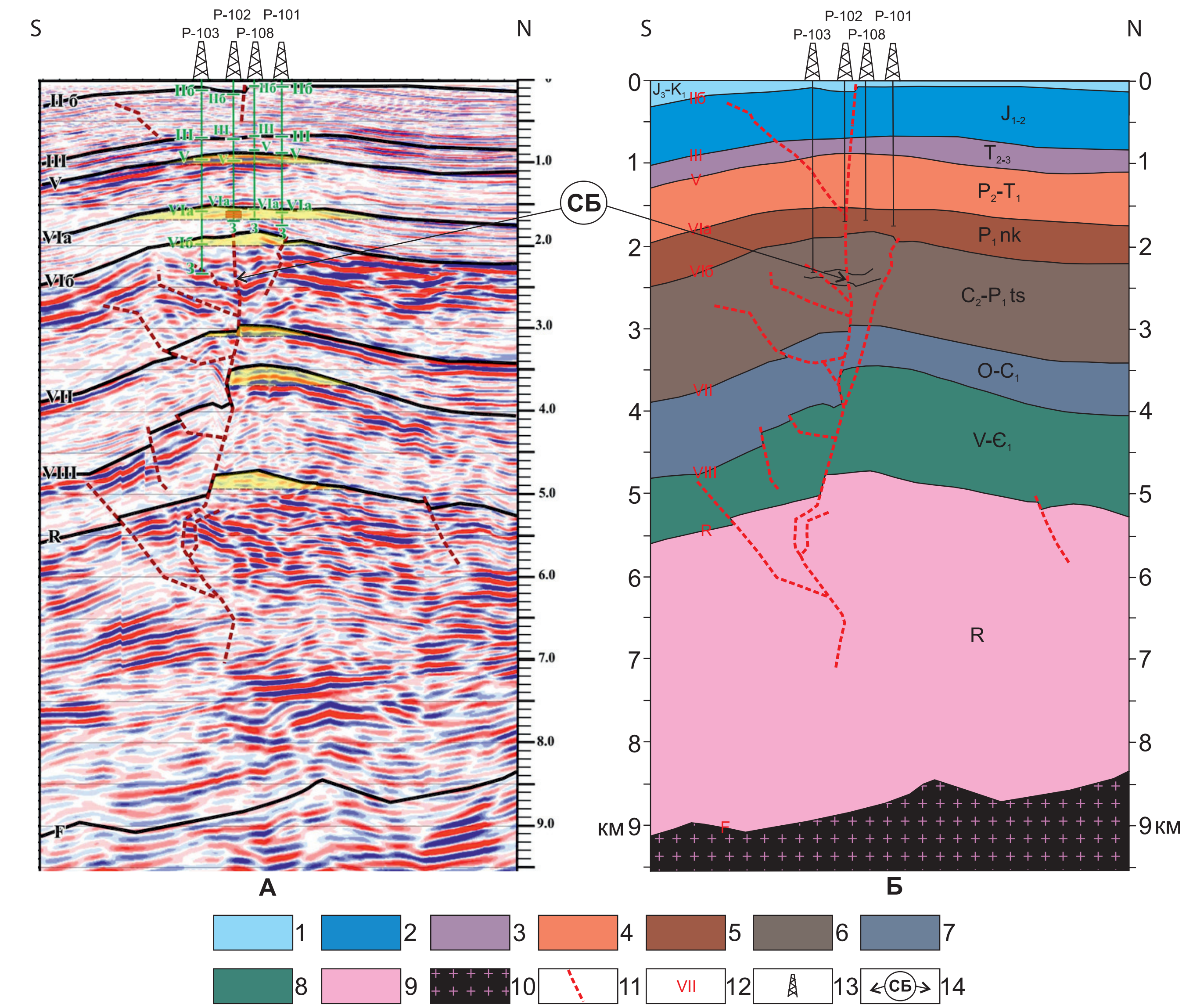

Fig. 2. Seismogeological section across the western dome of the South-Tegyasnky structure (profile section 050311 according to the materials of the State Research Center of the Federal State Unitary Enterprise "Yuzhmorgeologiya", 2012) with the additions of the authors. Legend: deposits: 1 – Upper Jurassic-Lower Cretaceous, 2 – Lower-Middle Jurassic, 3 – Middle-Upper Triassic, 4 – Upper Permian-Lower Triassic, 5 – Lower Kozhevnikovskian Formation of Lower Permian, 6 – Upper Carboniferous-Lower Permian (Tustakhskian Formation), 7 – Ordovician- Lower Carboniferous, 8 – Vendian-Lower Cambrian, 9 – Riphean; 10 – the basement; 11 – disjunctive dislocations; 12 – indices of reflecting horizons: IIb – roof of Lower-Middle Jurassic deposits; III – roof of Middle-Upper Triassic sediments; V – roof of Upper Permian-Lower Triassic deposits; VIa – roof of Lower Kozhevnikovskian Formation of the Lower Permian; VIb – roof of Middle Carboniferous – Tustahskian Formation of the Lower Permian; VII – the roof of the Ordovician-Lower Carboniferous, VIII – the roof of the Vendian-Cambrian deposits; R – the roof of Riphean deposits; F – the surface of the crystalline basement of the Archaean-Middle Proterozoic; 13 – deep wells; 14 – the transition zone of upthrust to downthrow

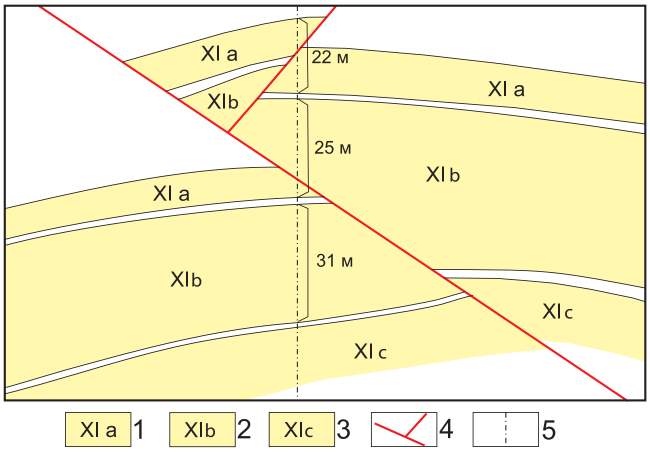

Fig. 3. Principal model of the deposit in the area of the P-102 well. Legend: 1 – subhorizon XIa, 2 – subhorizon XIb, 3 – subhorizon XIc, 4 – disjunctive dislocations, 5 – axis of the P-102 well

of 2.4 km the disjunctive dislocation takes the form of an upthrust. From the interval of productive horizon XI in the south direction, an additional disjunctive dislocation (upthrust) appears, where the fault plane is inclined to the south, the amplitude of the upthrust is small – 30-40 m. This disjunctive dislocation of the northwest strike does not complicate the eastern dome of the South-Tegyansky area.

In addition, in the descriptions of core material, numerous glide mirrors and crushing zones are established, which indicate about subhorizontal displacements (Kalinko, 1959). The schematic diagram of the section formation penetrated by P-102 well opened due to upthrusts is modeled and shown in Fig. 3.

The proposed reservoir model can cause a slight increase in the productivity of the P-102 well due to the imposition of the subhorizon XIb with improved reservoir properties and due to the zone of increased fracturing near the upthrust.

At the same time, since the specific drained volume of the well has practically not changed, the increase in productivity is almost one order of magnitude more likely due to another factor. It is highly probable that in the increased production rate of the P-102 well, the decisive role is played by deep feeding of the deposit through the established disjunctive dislocation from the subsalt Middle Paleozoic deposits. In any case, geochemical data does not contradict this assumption.

According to our data, the oil of the South-Tegyansky field refers to heavy (922-960 kg/m^3), sulphurous (2.16%), highly resin oil. The content of the gasoline fraction is 11%, in its composition 54.2% – of methane hydrocarbons, 29.4% – naphthenic and 16.5% – aromatic.

Saturated hydrocarbons are characterized by the alkanes predominance of normal structure (61%), and among them – relatively high-molecular homologues (Σn.k.-nC20/ΣnC21-k.k.=0.74), the presence of squalane, a significant content of 2- and 3- methylalanes (24%) and isoprenoids (15%), in their composition, phytan predominates over the pristane (pristane/phytan = 0.63).

In the topped oil fraction, hydrocarbons account for 51.5%, among them methane-naphthenic hydrocarbons are slightly higher than naphthenic-aromatic hydrocarbons (MH/HA = 1.16). Resins account for 29.2% with practically the same content of benzene and alcohol-benzene components (15.6% and 13.6%, respectively). Asphaltenes make up 8.4%.

Among the peculiarities of the polycyclic hydrocarbons of this oil, it is worth noting the significant content of tricycloalkanes (26.6%) and low – of moretanes, which is typical for the oils of the ancient deposits of the Nepa-Botuoba oil and gas basin generated by aquatic OM. The predominance of adiantane over hopane in the composition of pentacyclic hydrocarbons may indicate about the accumulation of petroleum-based OM in the conditions of carbonate or carbonate-evaporite facies (Connan et al., 1986; Peters et al., 2005). The presence of gamma-cerane in pentacyclanes is characteristic for conditions of increased salinity of the formation of the initial OM.

It should be noted that regrouped steranes (diasteranes) play an important role in the composition of the steranes of the South-Tegyansky oil, their ratio to regular steranes is 0.28-0.52. This distribution character of sterane hydrocarbons is usually considered as a sign of the terrigenous nature of the source deposits (Peters, Moldowan, 1993; Rubinstein, 1975).

Thus, a number of geochemical parameters, such as low values of pristane/phytane ratio, high concentrations of gamma-cerane and squalane, the predominance of adiantane over hopane indicate about the formation of source rocks in a sharply saline lagoon basin. Here, oil-source deposits of the Middle Paleozoic could be domanicoid by the type of the Lower Frasnian D_3 stratum, represented by massive black marine clay limestones with interlayers of limestones and calcareous mudstones.

At the same time, the ratio of diasteranes to regular steranes indicates about a predominantly terrigenous composition of the initial OM, which is characteristic of the lagoon-continental sedimentation with a wide development of the lake-marshy facies.

In general, the peculiarities of the composition and distribution of biomarker molecules, taking into account all the geochemical data, suggest that the source of the South-Tegyansky oil generation could be the OM of the mixed composition of the Devonian-Permian area of oil and gas generation (Kashirtsev, 2003; Kashirtsev et al., 2013). Like the other naphtides of the Anabar-Khatanga saddle, the Nordvkisky oil (T_2), oil shows of

Yuring-Tumus Peninsula (J_2) and the North-Suolemsky Well 2 (P_2), the South-Tegyansky oil "originates mainly from OM of the Devonian salt-bearing complex. The contribution of Upper Paleozoic oil-bearing rocks is less significant" (Kashirtsev et al., 2013).

The discussion of the results

The formation of oil reservoirs at the level of the Lower Kozhenikovskian Formation in the studied geological region apparently began with the formation of anticlinal traps due to tectonic activation in the Lower Triassic period, with the imposition of halokinesis processes of Devonian salt deposits. After the Late Permian-Early Triassic tectonic activation was completed, the described area was lowered and the formation of the deposits continued until the late Cretaceous mainly due to lateral migration. Subsequent renewal of differentiated tectonic movements that continued in the Cenozoic resulted in partial destruction of the traps both at the level of the Lower Kozhevnikovskian Formation and at the level of the subsalt sediments of the Middle Paleozoic, as evidenced by numerous epigenetic naphthyde spots over the fractures that occur in the Mesozoic deposits from a depth of 70 m (Kalinko, 1959).

In our opinion, at the present time the destroyed reservoir at the lower level of the Kozhevnikovskian level, fueled by hydrocarbons from the lower parts of the section, can be productive only in certain near-fault zones. At the regional level, significant accumulations of oil and gas in the Middle Paleozoic potential oil and gas bearing complex can be confined to the crypto-diapir structures formed due to halokinesis of salt deposits without the formation of significant disjunctive dislocations.

Conclusion

To clarify the prospects of the oil and gas potential in the lower part of the section of the studied geological region (from the Riphean to the Middle Paleozoic) and to establish the model of the South-Tegyansky field, it is proposed to drill a well with a depth of up to 5 km. Before drilling a well, it is expedient to clarify the structural plans of the subsalt deposits.

Drilling a well may also allow the calculation of oil and gas reserves in the field and put it on the State Balance of the Russian Federation.

According to the geological area in question, the main prospects for oil and gas potential are likely to be associated with the subsalt Middle Paleozoic complex of sediments.

References

Connan J., Bouroullec J., Dessort D., Albrecht P. The microbial input in carbonate-anhgidrite facies of a sabkha paleoenvironmant from Guatemala: A molecular approach. *Organic Geochemistry*. 1986. V. 10. Pp. 29-50.

Kalinko M.K. Hystory of geological development and prospects of oil and gas potential of Khatanga depression. Leningrad: Gostoptekhizdat. 1959. 353 p.

Kashirtsev V.A. Organic geochemistry of nafthides of the East Siberian platform. Yakutsk: YaF SO RAN Publ. 2003. 160 p. (In Russ.)

Kashirtsev V.A., Kim N.S., Fursenko E.A., Dzyuba O.S., Fomin A.N., Chalaya O.N. Genesis of oils and oil shows of the Anabar-Khatanga saddle (Arctic sector of the Siberian platform). *Geology and mineral resources of Siberia*. 2013. No. 1(13). Pp. 54-63. (In Russ.)

Peters K.E., Moldowan J.M. The biomarker guide. Prentice Hall, Englewood Cliffs, New Jersey. 1993. 363 p.

Peters K.E., Walters C.C., Moldowan J.M. The biomarker guide. 2nd ed. N.Y. Camburidge Univ. Press. 2005. 1155 p.

Puk P.S., Kopylova T.N. Basic data on the geological structure and oil content of the Anabar-Khatanga interfluve. Report, Book 5. Leningrad. 1955. (In Russ.)

Rubinstein I., Sieskind O. and Albrecht P. Rearranged sterenes in a shale: Occurrence and simulated formation. *Journal of the Chemical Society*. Perkin Transaction 1. 1975. Pp. 1833-1836.

Safronov A.F., Kungurov V.M., Stepanov R.T. Yuzhno-Tigyansky oil field. *Sb. trudov I Mezhd. konf.: «Znanie – na sluzhbu nuzhdam Severa»* [I Int. Conf. "Knowledge – to the needs of the North": Collected papers]. Yakutsk: Severoved. 1996. Pp. 167-169. (In Russ.)

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THE APPLICATION OF BIOGEOPHYSICAL STUDIES IN THE SEARCH FOR OIL FIELDS

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Abstract. The article gives an analysis of qualitative and quantitative indices of biogeophysical anomalies (BGPh-anomalies) recorded over oil deposits, obtained as a result of experimental and methodological work on the oil fields studied in detail. By the degree of intensity and complexity of the BGPh-anomalies registered in digital form with special equipment developed by the authors, a set of qualitative and quantitative features has been developed that make it possible to determine the genetic type of the structural trap of the identified oil deposit, and, under favorable conditions, the depth of its occurrence.

BGPh-anomalies of the "tectonic fault" type, their influence on the "oil deposit" type of BGPh-anomalies have been studied. The limiting values of the watercut in the exploited oil reservoir are determined, when exceeding, the oil reservoir ceases to create a BGPh-anomaly such as "oil deposit", which can be used for the areal monitoring of oil fields. The minimum thickness of the oil-saturated reservoir is determined, which creates an anomaly of the "oil deposit" type. Based on this analysis, it is assumed that the BGPh-anomalies arise only over oil deposits, potential for industrial development.

Keywords: biogeophysical method, oil deposit, tectonic fault, seismuc structure
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Academic Note

In the academic journal, the millennium was marked by the discovery of a large silver field in Germany by dowsers, after which a thaler with a frame was released (Maksimov, 1970). Acknowledgment of dowsing merits in the XVIII century was the decree of Catherine II to include divining rod in the Petrozavodsk's coat of arms (Frantov, Glebovsky, 1987).

The beginning of publications about the possibility of using the divining rod method for the water search in the USSR refers to the beginning of the twentieth century. Here the work of Professor I.A. Kashkarov of the Tomsk Polytechnic Institute should be noted, as well as the works of V.A. Guskov, I.I. Ginzburg.

In 1973 the International Society for the Study of Instrumental Research of Biofields was organized, where the questions of dowsing were also considered.

The Ministry of Geology of the USSR organized in 1967 a meeting at the All-Union Institute of Mineral Raw Materials on dowsing with the participation of eight institutes, where the terms BPhE(biophysical effect) and BPhM (biophysical method) were approved.

The first All-Union seminar on BPhE was held in 1968, the second – in 1971, in Moscow, the third – in 1976 in Tomsk, the fourth – in 1979 in Riga, the fifth – in 1981 in VSEGINGEO. The results were 445 publications in the collections of the library of the Academy of Sciences of the USSR; a bibliography on BPhE was compiled. In the 1980s, the effect of the biolocation method was fully recognized by the USSR Academy of Sciences.

A letter from Academician O.A. Ovchinnikov, vice-president of the Academy of Sciences of the USSR, notes: "The Academy of Sciences of the USSR have considered issues related to the dowsing method and finds that the application of this method will yield appreciable savings in the national economy, and the need for its further study does not cause doubts" (Sochevanov, 1984).

In the work "Biogeophysical method of prospecting and exploration of oil fields", a working hypothesis of the origin of Biogeophysical (BGPh) anomalies over oil deposits is given, based on the electromagnetic nature of this phenomenon (Mardanov et al., 2015).

In the work "Electromagnetic field as a cause of the emergence of the biophysical effect", references are given to the connection of BPhE with electromagnetic fields and ionization of air (Sochevanov et al., 1975).

Introduction

At present, the seismic survey method, aimed at finding positive structures, is the most generally recognized and reliable method for searching for oil

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fields. However, seismic exploration has one significant drawback: in identified seismic structures, oil may not exist, and the seismic structures themselves may be false, caused by velocity anomalies in the overlying sediments. Therefore, recently there has been an increased interest in methods aimed at direct search for oil deposits. Such methods include the biogeophysical method.

Biogeophysical method, which in previous centuries was called "Divining rod method" was widely used in the Middle Ages, in particular, most of the ore deposits of gold, silver, copper, lead, antimony, iron, coal in Western Europe were discovered thanks to the application of this method (Maksimov, 1970, Sochevanov et al., 1987). In ancient times the BGPh method was called dowsing, this phenomenon was known more than 4000 years ago. It boils down to the fact that some people, when passing over aquiferous or ore zones, observe a deviation or rotation of a clamped woody branch in the hand.

Recent studies show that biogeophysical anomalies can be detected not only over ore deposits, but also over oil fields (Mardanov et al., 2015).

For direct searches for heavy oil fields, JSC "Tatneft" in May 28, 2014 received patent No. 2551261 "Method for mapping structural uplifts in the upper part of the sedimentary cover and predicting heavy oil deposits". Summary of the invention: Electromagnetic waves emit and receive signals reflected from the interfaces of the sounded medium. Herewith structural maps of the uplift, as well as temporary seismic sections of the reflected boundaries of the upper part of the sedimentary cover are preliminarily constructed; geophysical studies of the wells, core materials are studied.

Another method of direct searches for hydrocarbon deposits is the overvoltage prospecting method, patent No. 2391684 dated April 22, 2008. "Method of geoelectric exploration of oil and gas fields with the forecast of hydrocarbon saturation".

In contrast to the biogeophysical method, the radar method of patent No. 2551261 has a significant drawback – a narrow field of application, requiring detailed study of the field by drilling, seismic survey, and the patent No. 2391684 drawback is a low resolution for all electrical survey methods, low reliability.

1. Methods and technology of the BGPh method

At present, the authors have developed and applied the original technique and technology for the production of BGPh-studies of oil, which allows recording anomalies using a semi-automatic digital recorder combined with a GPS sensor. Depending on the intensity of the biophysical field, the frame in the hands of the operator performs a rotational motion with a certain force. The recorder converts this rotational force into millivolts, which allows the resulting material to be digitized and processed promptly using a specially designed computer program. With the use of the developed technology, it became possible to digitally quantify the level of intensity of BGPh-anomalies. Since the intensity of the BGPh-field is not obtained directly by measuring electromagnetic or other geophysical parameters, but indirectly, on the resultant maps, the intensity is denoted in conventional units (cu). This allows not only to identify and delineate oil deposits, but also to distribute the studied area according to the degree of prospects into several categories. The most promising can be considered those areas where the identified intense GGPh-anomalies such as "oil deposit" coincide with the positive seismic structures of the target oil-bearing horizons.

2. Interpretation of the results of BGPh-studies

With the increase in the number of areas studied by the BGPh-method in the search for oil deposits, the authors made significant progress in interpreting the results of the field survey. During the last six years, experimental, methodical and production work was carried out at 57 facilities located mainly in the Volga-Ural oil and gas province.

In order to resolve the interpretation issues in 2014-2015, the BGPh-method was carried out in two detailed areas of the Alekseevsky and Bavlinsky oilfields located on the south-eastern slope of the South-Tatar Arch.

2.1. The first polygon for solving the problems of interpretation of the BGPh-anomalies was the experimental and methodological work on the central part of the Alekseevsky oil field, which is being developed for more than twenty years (Fig. 1).

The unified oil deposit, which is in operation for more than 20 years, according to the data of the BGPh-study is divided into two parts; the division occurs along a tectonic fault line 150-250 meters wide, coinciding with the riverbed of the Kuehlga River, with a steep northern side.

All wells, of which industrial oil is currently produced, are in the outline of the BGPh-anomaly such as "oil deposit". Wells that, because of the water cut in the reservoir, have been transferred to the reservoir pressure maintenance regime, are located behind the outlines of the BGPh-anomalies.

In the central part of the BGPh-anomaly such as "oil deposit", a zone with an intensity of 60-80 cu is allocated; this zone corresponds to the contour of oil deposits in the carbonate Devonian sediments D3*fm*, which are located under the reservoir in the Tournaisian sediments C1*t*.

Only in one well No. 6440, which is located outside the BGPh-anomaly such as "oil deposit", oil is produced with a flow rate of 4m^3/day and it is located near the tectonic fault. This corresponds to the hypothesis of the

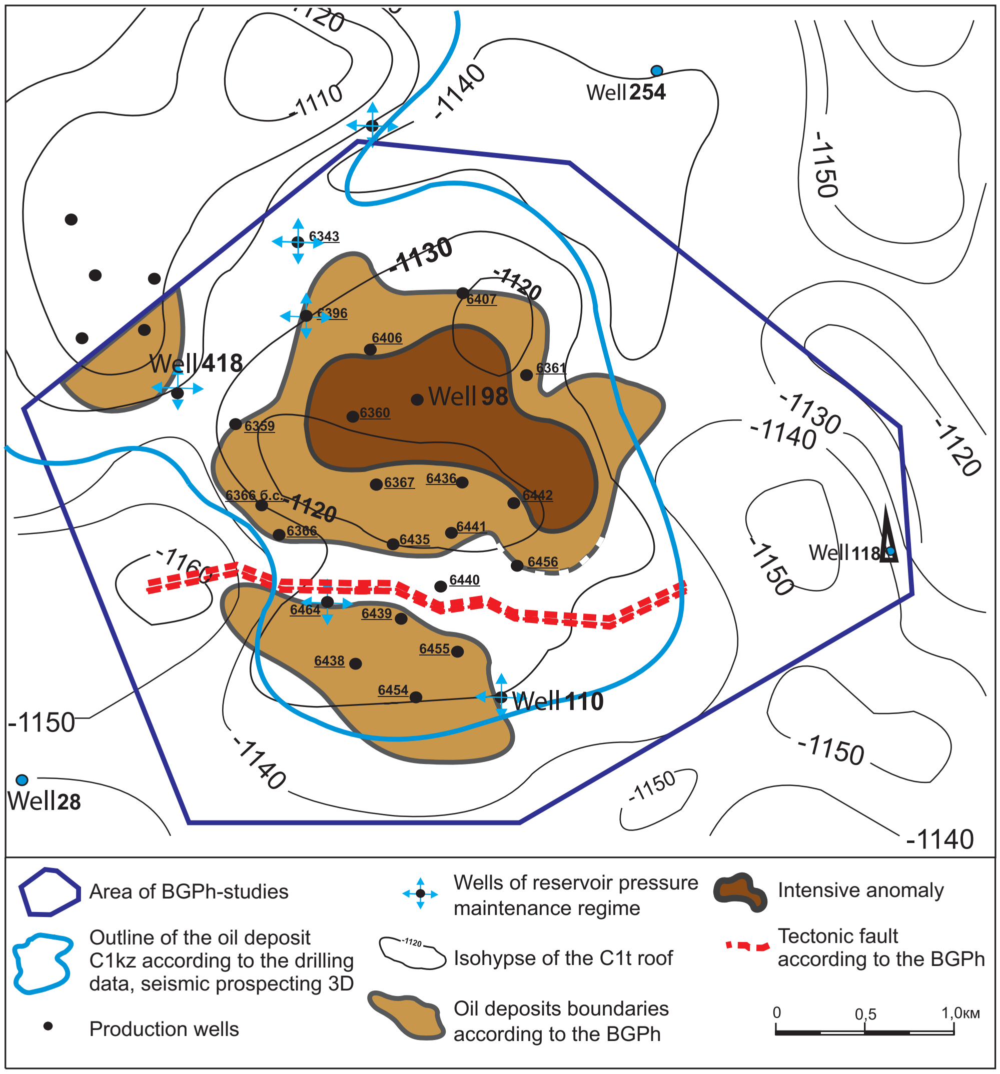

Fig. 1. Results of BGPh-studies at the Alekseevsky oil field.

origin of BGPh-anomalies over oil deposits, according to which the BGPh-anomaly from the tectonic fault breaks the BGPh-anomaly over the oil deposit (Mardanov et al., 2015).

2.2. The second polygon for solving the problems of interpreting the BGPh-anomalies was pilot works at the Sabanchinsky oil field developed since 1974. The map compiled on the basis of the results of the BGPh-studies is shown in Fig.2.

On the area of BGPh-studies, according to the available geological information, it was assumed initially that there is one vast oil deposit with a complex configuration. As a result of the work, six BGPh-anomalies of the “oil deposit” type of various sizes were identified.

In the central part, an extensive BGPh-anomaly with an intensity of 30-50 cu was found, within which one zone with an increased intensity of values and two zones of absence of the BGPh-anomaly of the “oil deposit” type was identified. After applying the revealed contours of anomalies to the development map of the field, it was found out that zones of anomaly absence within the deposit can be caused either by the absence of industrial oil (insignificant thickness of oil-saturated reservoir, with low reservoir properties – as in wells 2196, 1749, 2159, 2158) or the presence of “washed” productive zone in the area of wells 2163, 2165. 20 years ago, at the beginning of operation they produced oil up to 5t/day, but then, due to watering, they were transferred to the reservoir pressure maintenance regime. In the center of “oil-free zone” there are wells 2163, 2165. In the well 2161 the water-cut is 83%; in the well 2172 the water-cut is 92.4%.

A zone with an increased intensity of 50 to 70 cu was found in the area of well 2168, and in the very center of this zone the intensity of the BGPh-anomaly reaches a maximum value of 90 cu. After the conducted pilot works, the following features were emerged:

- zone with an intensity of 50-70 cu is caused by an oil deposit of increased thickness in the Tulskian-Bobrikovian deposits C1;

- zone with an intensity of 90 cu refers to a deeper, terrigenous Devonian D_3. Its dimensions are small – 200x200 meters. At the same time, it is known that several producing wells from the terrigenous Devonian deposits are exploited in this region, and the

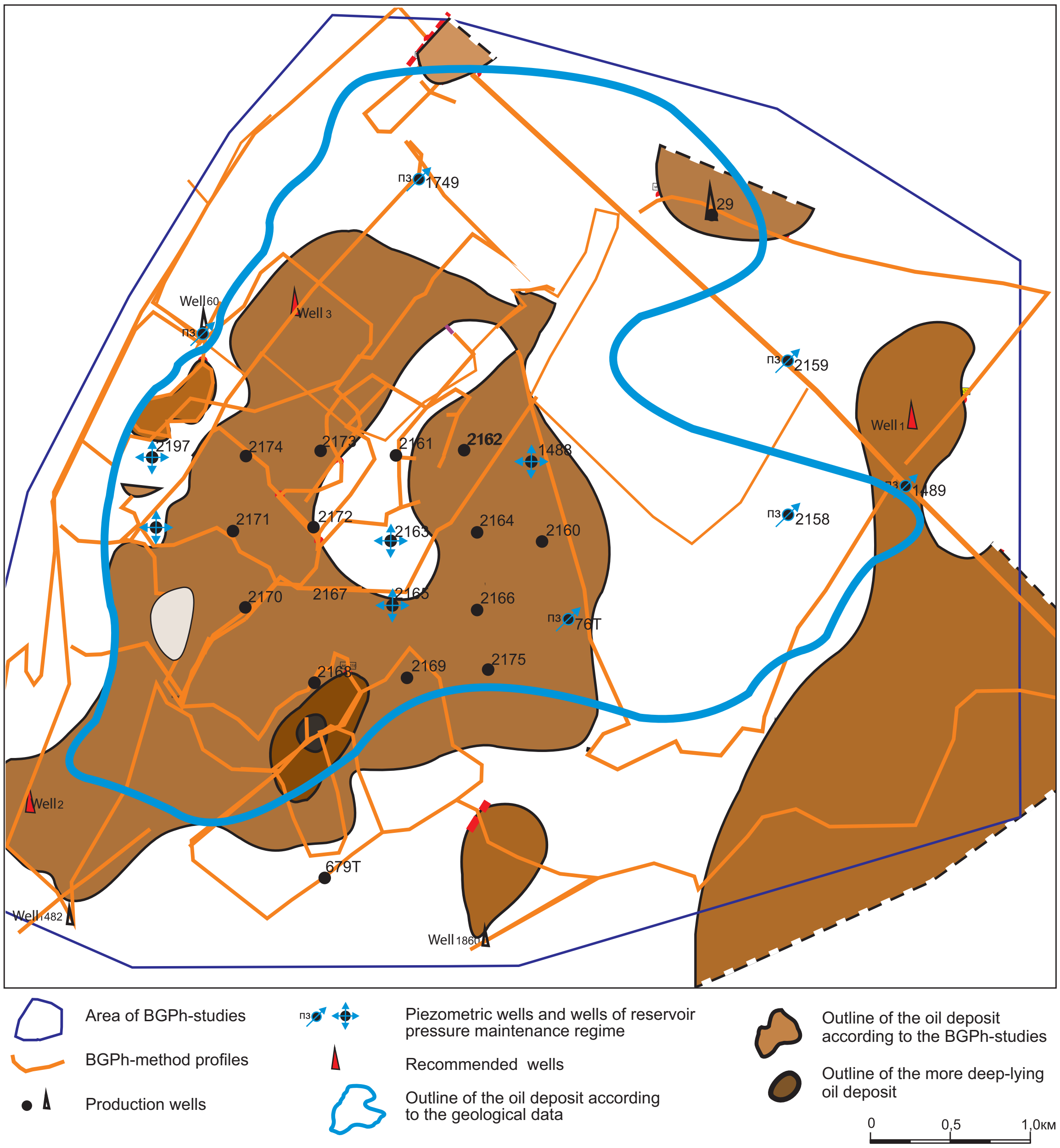

Fig. 2. Results of the BGPh-studies at the Sabanchinsky field

BGPh-studies, however, only note medium-intensity anomalies related to the lower Carboniferous. The explanation of this phenomenon is that these wells have been producing oil for many decades, and the water cut of the production reaches 98-99%. With such a water-oil ratio, the operator of BGPh-studies does not reveal the oil deposit.

As a result of the pilot production works conducted at the Sabanchinsky field, the following was revealed:

- BGPh-studies conducted on the area of old deposits, identify areas with industrial oil, where the water cut of the products does not exceed 75-80%;

- The BGPh-method under favorable conditions makes it possible to determine the presence of a second, more deep-lying oil deposit under the upper deposit and to contour it;

- The presence in the geological section of several oil-saturated reservoirs with an interval of several hundred meters leads to the formation of a high-intensity BGPh-anomaly.

3. Determination of the quality of oil reservoirs

In 2015, BGPh-studies were carried out at Shuganskoy, Komuninsky, and Pokrovsky uplifts of the Muslyumovsky section of OJSC Mellyaneft to clarify the contours of the developed deposits and identify new oil deposits. All the tasks were successfully solved. It is interesting to consider the results of drilling a horizontal well 186g, the horizontal part of the trunk of which is beyond the boundary of the BGPh-anomaly of “oil deposit” type (Fig. 3). According to the logging conclusion, the oil saturation of the C1*tl* reservoir in the horizontal part of the trunk with length of 130 meters is in the range of 55-60%, clay content – from 4.5 to 7.5%. As a result of the well tests, it was possible to obtain only a small amount of technical water, there is

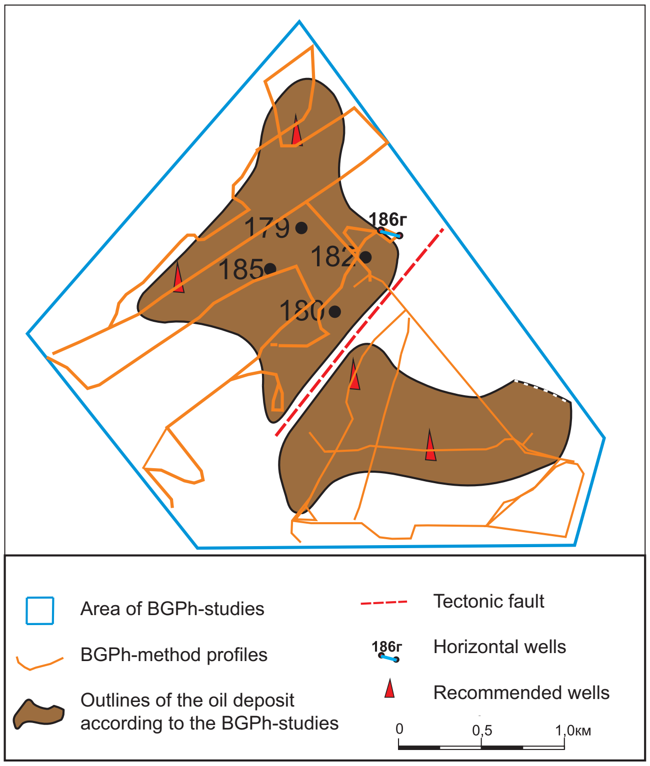

Fig. 3. Results of the BGPh-studies on the Pokrovsky uplift

no inflow of reservoir fluid. At the same time, it is known that production wells No. 179, 180, 182 and 185, located in the central part of the oil deposit, have penetrated the oil-rich reservoir C_1*tl* with clay content not exceeding 3.5%, and oil has been successfully produced for a long time. Thus, we can assume that the BGPh-method allows to indirectly determine reservoir properties of the formation.

The fact that within the oil reservoir of the structural type, identified by seismic prospecting and drilling, the BGPh-method identifies zones of BGPh-anomaly absence, can be explained by a change in reservoir properties – in terrigenous rocks by increased clayiness, in carbonate reservoirs – by dense areas.

After analyzing the results obtained and comparing them with the geological structure and hydrodynamic parameters of the studied sections of the fields, the following conclusions can be drawn.

1. At present, the technical level achieved at LLC NPF LOZA allows to register the BGPh- anomalies in digital form, continuously along the working profile. The intensity of the BGPh-anomaly is measured in conventional units (cu), in the range from 0 to 100 cu. As experience shows, gradation is enough in five intervals with values: 0-20; 20-40; 40-70; 70-90 and above 90 cu.

2. BGPh-anomaly such as "oil deposit" appears almost vertically over the outer contour of the oil deposit, with an accuracy of 50-100 meters.

3. In a detailed study of an oil field in long-term operation, local zones with high water cut (over 80%) are allocated as zones of absence of an "oil deposit" anomaly.

4. If the injection well is located inside the oil reservoir contour, the area that is "washed" by injected water is allocated as a zone of absence of an "oil deposit" anomaly.

5. The fact that within the oil reservoir of the structural type, identified by seismic prospecting and drilling, the BGPh-method identifies zones of absence of the BGPh-anomaly, can be explained by a change in reservoir properties – in terrigenous rocks by increased clayiness, in carbonate reservoirs – by dense areas.

6. If the thickness of the oil-saturated reservoir is less than 1.5-2 meters, it is not allocated as an "oil anomaly".

7. In some cases, inside the BGPh-anomaly such as "oil deposit" with an average intensity of 30-40 cu, zones are allocated with an intensity of 60 cu, and sometimes up to 90 cu. This happens in those cases when one or several oil deposits are located under one deposit, several hundred meters deeper. For example, in the case of a fragment of the Alekseevsky field (Fig. 1), discussed above, a zone with an intensity of 30-50 cu refers to the contour of the oil deposit in the sediments C1*kz*, and the anomaly with an intensity of 60-80 cu along the contour coincides with the contour of oil deposits in the carbonate sediments of the Upper Devonian (D_3*fm*).

4. Identification of tectonic faults

When searching for oil deposits by BGPh-studies, anomalies such as "tectonic fault" are often detected. This occurs as follows: an anomaly of the "oil reservoir" type disappears, after some distance an anomaly of the "tectonic fault" type appears. The width of the zone of the tectonic fault is from several meters to hundreds of meters. Quite often the anomaly "oil deposit" ends on a tectonic fault. If the oil anomaly is extensive, an anomaly of the "oil deposit" type appears again after the "tectonic fault" anomaly. The width of the absence zone of "oil deposit" anomaly along the tectonic fault in most cases coincides with the steep slopes of ravines.

The explanation of this phenomenon is possible: it is well known that ravines and rivers occur in places of tectonic faults. Anomalies of the "tectonic fault" type are mainly confined to ravines and river valleys. It is generally believed that a zone of destruction is formed along the inclined (subvertical) plane of the tectonic fault, where, due to the displacement of the rock layers, fragmentation occurs, and the rock cracks become more fractured. Hydrothermal streams circulate for a long time along this subvertical zone of destruction, which cause secondary mineralization in the near-fault zone. Ultimately, this leads to the formation of an inhomogeneously densified subvertical plane. The presence of such an anomalous object screens the anomaly emerging above the oil deposit (Fig. 1, 3). Since destruction and secondary mineralization in the tectonic fault zone does not occur in the same way everywhere, a

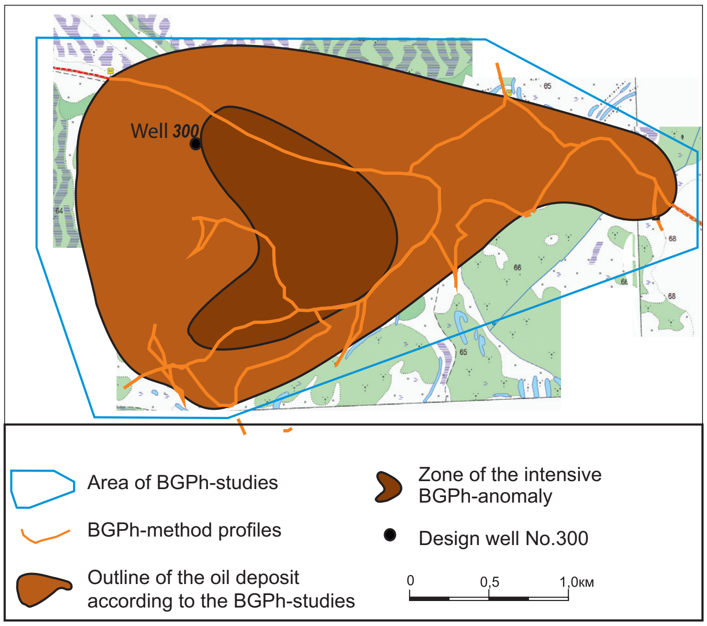

Fig. 4. Results of the BGPh-studies at the Tlanchi-Tamaksky section. Note: Well No. 300 was drilled in the spring of 2014, the oil deposit in C1bb was penetrated. The total capacity of oil-saturated reservoirs is 10 m

screen that prevents the formation of a BGPh-anomaly also arises of different qualities. Therefore, the zone of absence (screening) of the oil anomaly along the tectonic fault varies in width.

In the scientific literature devoted to the study of tectonics in the Volga-Ural oil province, the identification and tracing of tectonic faults within oil deposits has not yet been systematized and described. Modern seismic exploration does not notice small faults as a result of multiple summation of traces. This can be clearly seen from the time cuts applied to seismic records, where tectonic faults from seismic exploration, above the terrigenous Middle Devonian, are practically not distinguished. Geochemistry gives some scatter of data that is "spread out" over the area. It is known that discrete methods of fixation cannot uniquely identify small faults, especially when there is no vertical displacement of the seams. The BGPh-method allows to continuously trace the nature of the change in the anomalies of the "tectonic fault" type and as a result, it makes it possible to isolate both large tectonic faults having a deep origin, and neotectonic ones having a local character.

5. Effectiveness of the use of BGPh-studies

To illustrate the effectiveness of the use of BGPh-studies in forecasting the prospects of seismic structures, a few more examples are given below.

Tlanchi-Tamaksky section is located to the west of the village of Tat.Suksi in the Aktanyshsky district. In 2013, as a result of the studies carried out by the BGPh-method, one large anomaly of the oil deposit type was singled out with the aim of predicting the oil

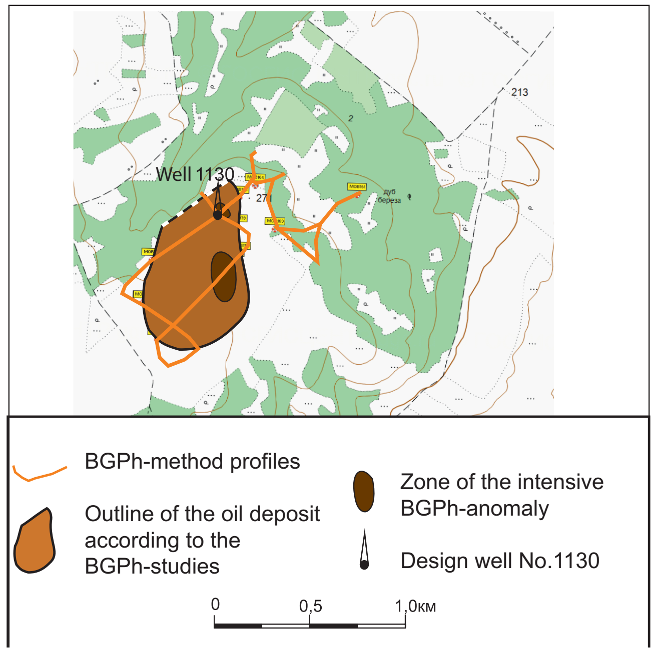

Fig. 5. Results of the BGPh-studies at the Petrovsky section. Note: Oil-saturated reservoirs in C_{1kz} and in carbonate Devonian sediments were identified in 2015 as a result of drilling

prospect of the Tlanchi-Tamaksky section. The size of the detected anomaly is 4x2 km, in the central part of the anomaly there is a section of increased intensity, with a high degree of prospects, with dimensions of 1x1.5km. The design well No.300 is located within the anomaly (Fig. 4).

Petrovsky section of the Bavlinsky field is located to the south-west from the village of Petrovka in the Bavlinsky district. In 2014, as a result of the research carried out by the BGPh-method, an anomaly of the "oil deposit" type with two intensive areas and a size of 0.6x1.0 km was singled out for the prospective evaluation of oil prospectivity by the design point for well No.1130. The design drilling point is located within the intensive zone of the oil anomaly (Fig. 5). A forecast was made about the prospects for identifying oil-saturated reservoirs in the Lower Carboniferous and Devonian sediments.

In addition to the above examples, there are still a significant number of studies that confirm the high efficiency of the BGPh-method in the search for oil deposits, these works are included in Table 1.

Table 1 includes 97 investigated structures at 37 sites. Based on the results of wells testing, including previously drilled wells, the success rate of 141 wells is 94%. In addition, on the territory of the Samara, Orenburg, Ulyanovsk, Perm, Chelyabinsk and Kurgan Regions and in the Republics of Tatarstan, Bashkortostan, an additional study was conducted on 14 licensed sites, the results of which, for reasons of confidentiality of information, are not included in Table 1.

	Field, area, objective	Results of the BGPh-study	Drilling results	Efficiency(%)
1	2	3	4	5
1	Bavly Oil and Gas Production Department, forecast for the well No. 1130	Oil anomaly was identified in the area of design well No. 1130	In 2015 exploration well No.1130 has penetrated the oil reservoirs C1 and D3	100
2	Andreevsky section, forecast for the well No. 2263	Oil anomaly was identified at 150 m away from designed bottomhole well No. 2263	In 2015 exploration well No.2263 was drilled at 150 m away from BGPh-anomaly, there were no oil-saturated reservoirs	100
3	Korobkovsky section, outlining of the identified oil deposit	Deposits were outlined around well No. 2248 and 2258, three more oil anomalies were identified	All 10 production wells are located in the area of oil anomalies	100
4	Sabanchinsky field, clarifying the contours of the fields	Outlines of the oil anomalies correspond to the current deposit outlines in C1bb with water-cut 80%	There are 26 wells on the studied area. Almost all wells with water-cut not exceeded 80% are located in the outline of oil anomalies	90
5	Yuzhno-Ashalchinsky field, searching for bitumen	3 oil anomalies of the “oil deposit” type were identified in the area of bitumen field	Anomalies correspond to the most perspective field zones	80
6	Tlanchi-Tamaksky section, predicting the oil prospect	Oil anomaly was identified with a size of 4x2km in the area of design well No. 300	In 2014 exploration well No. 300 has penetrated the oil reservoir with thickness Δh=10 m in $C_{1бб}$	100
7	Aznakaevsk Oil and Gas Production Department, Vostochno-Iryasovsky uplift	2 oil anomaly were identified with a size of 0,25x1,0 km and 0,4x0,6 km, well No. 292 is located in the zone a oil anomaly	In 2017 drilling of exploration well No. 292 is planned	
8	Tumutsky field, forecast for the 3 areas for the wells No.40216, 40217, 40218, 20152, 20154	Oil anomalies were identified on the dome areas of seismic structures	In 2017 well No. 20152 was drilled on the BGPh-anomaly boundary, in Terrigenous Devonian oil was produced - $3m^3$/day	100
9	Muslyumovsky section, forecasting the seismic structures on the 8 areas	19 seismic structures were analysed on the total area of 50 sq.km. Among them 18 anomalies were identified on the 12 structures and 7 structures were without anomallies	In 2016 well No. 40099 was drilled with industrial oil. Well No. 186g was drilled beyond the BGPh-anomaly, no fluid. 21 oil-produced wells are located within the oil anomalies	100
10	Domoseevsky section, forecasting the seismic structures on the 8 areas	16 seismic structures were analysed on the total area of 28 sq.km. Among them 12 oil anomalies were identified on the 11 structures and 5 structures were without anomallies	5 exploration wells are located on the studied area. All wells correspond to the results of BGPh-anomalies. Drilling of new wells is at the design stage.	100
11	Arovsky section, Repusblic of Bashkortostan, outlining of the Petryaevsky oil deposit	1 oil anomaly was identified and outlined, transfering the design well No.10 to the center of anomaly was recommended	In 2016 in the well No. 10 oil-saturated interval was identified with Δh=22 m in Domanic horizon. Two hours of testing gave film of oil	80
12	Alekseevsky field, forecasting the seismic structures	12 seismic structures were analysed on the total area of 40 sq.km. Among them 10 oil anomalies were identified on the 8 structures and 4 structures were without anomallies	64 wells are located on the studied area. 62 wells correspond to the results of BGPh-studies. 2 wells with oil production are located beyond the anomalies	97
13	Orekhovsky license section, forecasting the seismic structures	28 seismic structures were analysed on the total area of 120 sq.km. Among them 21 oil anomalies were identified on the 20 structures and 8 structures were without anomallies	35 wells drilled after the BGPh-studies are located on the studied area. Among them 27 wells correspond to the BGph-studies results, 8 wells with oil production were drilled beyond the anomalies	77

Table 1. Results of the BGPh-studies on identification of objects that are promising for oil reserves

Conclusions

The scope of the research allows us to substantiate that the biogeophysical method makes it possible to identify and outline oil deposits with high reliability.

1. The application of the BGPh-method at the reconnaissance stage allows choosing perspective areas for setting up seismic operations, thereby reducing the financial costs and terms of work.

2. The use of the BGPh-method in the area where seismic operations have already been conducted, seismic structures for prospecting and evaluation drilling have been identified and recommended; it is possible to classify these structures as promising (where there are anomalies such as "oil deposit") or in the category of unpromising, where such anomalies are absent.

3. BGPh-studies conducted on the area of old deposits, identify zones with industrial oil, where the water cut of the products does not exceed 75-80%. Therefore, the areal monitoring of the developed field can be conducted in order to identify "washed" zones, as well as isolated areas ("bypassed oil"), which are not affected by operation.

4. The BGPh-method, under favorable conditions, makes it possible to determine the presence of a second, more deep-lying oil deposit under the upper deposit and to delineate it.

5. If the thickness of the oil-saturated reservoir is less than 1.5 meters, it is not detected by the BGPh-method.

6. The BGPh-method allows to determine the quality of the reservoir within the oil deposit.

In conclusion, the BGPh-method can be also used as an express analysis of the prospects of licensed areas for hydrocarbon raw materials put up for auction by the Ministry of Natural Resources of the Russian Federation.

The BGPh-method can be stated as one of the most promising methods of prospecting oil fields, which includes the ability to carry out works at any time of the year, the absence of costs for farmland waste, the speed of work, and the high accuracy of reservoir boundaries allocation.

References

Mardanov M.Sh., Podavalov V.B. et al. Biogeophysical method for searching and exploration of oil fields. *Uchenye Zapiski Kazanskogo Universiteta. Seriya Estestvennye Nauki*. 2015. V.157. Pp. 20-35. (In Russ.)

Maksimov I.M. The Millennium of discovery. *Geologiya rudnykh mestorozhdenii* [Geology of ore deposits]. 1970. No.5. Pp. 108-112. (In Russ.)

Sochevanov N.N., Stetsenko V.S., Chekunov A.Ya. Use of the biolocation method in prospecting for deposits and geological mapping. *Radio i svyaz'* [Radio and communications]. 1984. (In Russ.)

Sochevanov N.N., Matveev V.S. EElectromagnetic field as the cause of the biophysical effect. Physical, mathematical and biological problems of the impact of electromagnetic fields and ionization of air. "Nauka" Publ. V.II. 1975. (In Russ.)

Frantov G.S., Glebovskii Yu.S. Zanimatel'naya geofizika [Interesting geophysics]. "Nedra" Publ. 1987. P. 130. (In Russ.)

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INVESTIGATION OF THE PILOT INDUSTRIAL WORKS EFFICIENCY ON THE INFILL WELL SPACING ON THE BASHKIRIAN DEPOSITS OF SOKOLKINSKY FIELD WITH THE USE OF THE GEOLOGICAL-TECHNOLOGICAL MODEL

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Abstract. In this paper, to assess the effectiveness of pilot industrial works on the infill well spacing in the Bashkirian deposits of Sokolkinsky field, factors affecting the final technological indicators are identified. It is possible to refer the following factors to such category: the number of simultaneously commissioned wells in the element; selection of the optimal development element (five-point, nine-point, etc.); organization of the reservoir pressure maintenance system (the ratio of production and injection wells); the time interval for the reservoir pressure maintenance system in the development element. The proof of this fact is the results analysis of the three options considered, which makes it possible to determine how the development system, the ratio of production and injection wells, and the time of wells transfer for injection affect the production of oil.

Key words: infill well spacing, pilot industrial works, development element, flow filtration lines, interference, efficiency, geological-technological model

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Justification of site selection for the pilot works

The deposit II of the Sokolkinsky uplift was considered to carry out studies for the efficiency of pilot works on the infill well spacing. The deposit II is located in the southern part of the field, confined to the Sokolkinsky uplift and penetrated by 73 wells. Up to seven separate effective carbonate interlayers are distinguished in the carbonate stratum, the total oil-saturated thickness of which varies from 0.8 m to 14.2 m.

In wells Nos. 775, 787 and 913, an interval testing of the Bashkirian sediments was carried out; industrial oil inflows were produced with a flow rate of 3.2 to 6.1 tons per day. Water-oil contact is determined from the bottom of the lower oil-saturated layer in the well No. 808 at an absolute elevation minus 648.5 m. Analysis of the geological and geophysical data shows that the oil-water contact has not been established in the deposit. All effective carbonate interlayers contact the tight rocks. The highest position of the aquifer roof (wells Nos. 787, 2764, 2798) and the lowest hypsometric position of the bottom of the oil-saturated interlayer (wells No. 2810, 2814) were recorded at an absolute mark of minus 648.5 m. As a result of all of the above, the absolute elevation of water-oil contact is set at minus 648.5 m. The size of the deposit II is 2.95×2.4 km, the oil net pay is 34.6 m (Pereschet zapasov nefti .., 2009) (Fig. 1).

In order to improve the accuracy of predictive calculations of development options, a geological and technological model of the Bashkirian deposits of the Sokolkinsky field was constructed (Dopolnenie k tekhnologicheskoi skheme ..., 2015).

Filtration modeling was carried out with the help of computational programs realizing the numerical solution of the equation system describing the filtration of formation fluids and injected agents taking into account their interaction with the rock.

The hydrodynamic model was built using ROXAR's Irap RMS software packages – Tempest 7.2.

Geometric parameters of the resulting grids are presented in Table 1. Using the filtration model to adapt the development to the known dynamics of oil and water production, the functions of the modified phase permeabilities for each development object are selected.

The general view of the model on the example of a cube of porosity, permeability and initial oil saturation is shown in Fig. 2.

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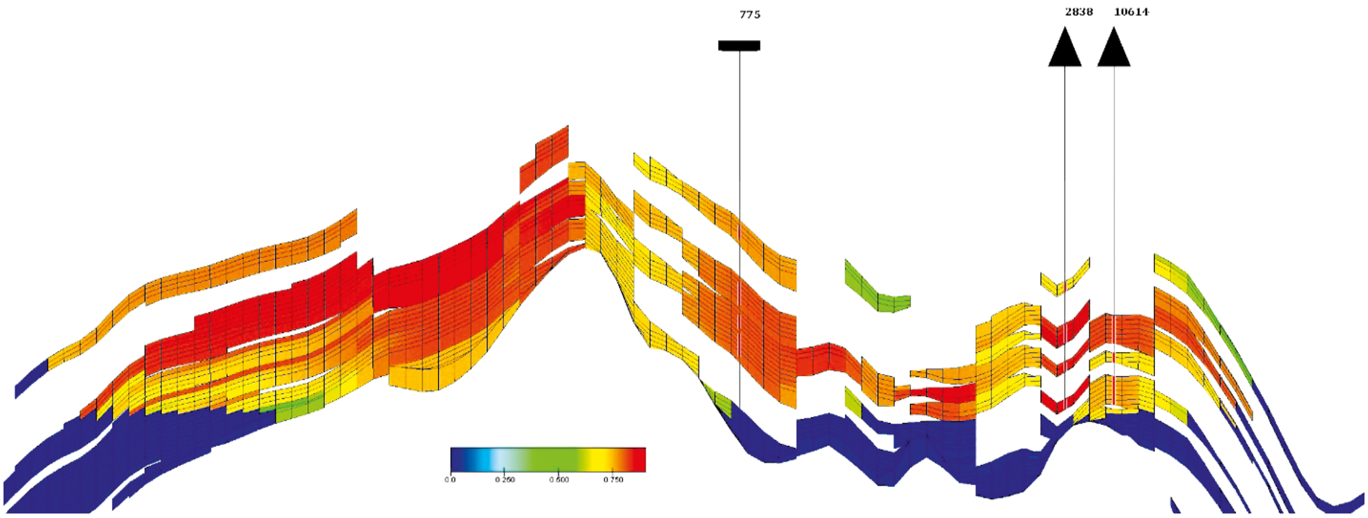

Table 1. Basic comparative characteristics of a three-dimensional reservoir model

Deposit	Model	Size of modeling area, km	Number of grid cells in three directions			Horizontal size of grid block, m	Vertical size of grid block, m	Number of active model blocks
			NX	NY	NZ			
Bashkirian	Geological	9×10	181	208	73	50×50	0,01-0,34	360 445
	Filtration	9×10	181	208	73	50×50	0,01-0,34	360 445

Fig. 1. Distribution of current oil saturation in a section along the line of wells Nos. 775,2838,10614

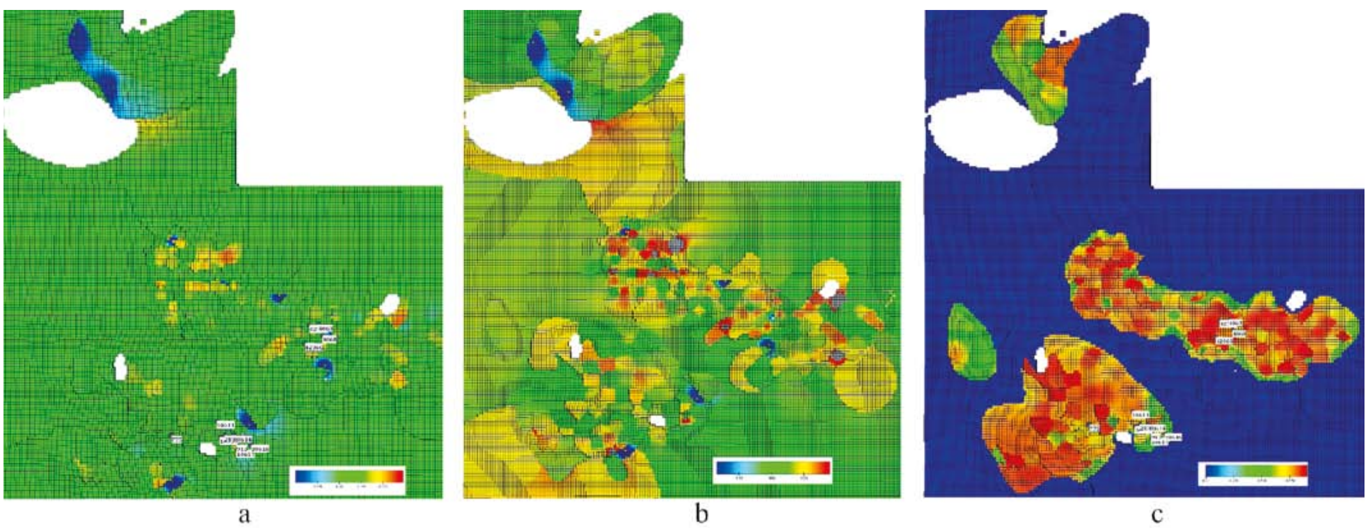

Fig. 2. Distribution of parameters (top view): a) porosity; b) permeability; c) initial oil saturation

Based on the results of adaptation of the geological and technological model, maps of current mobile reserves have been constructed (Fig. 3).

The analysis shows that in the southwest of the deposit II of the Sokolkinsky uplift, a site with rather high current mobile reserves prevails.

The site chosen for pilot works for infill well spacing within a six-meter isohypses will cover 1292 thousand m3 with geological reserves of 1550 thousand tons.

For the most complete development of residual oil reserves in this section of deposit II, drilling of 34 producing wells along a 150 x 150 m fill-in pattern Δ was proposed (Dopolnenie k tekhnologicheskoi skheme ..., 2015).

A schematic location of the project wells is shown in Figure 4.

Analysis of pilot works for the hydrodynamic modeling on the infill well spacing

With a view to calculating the forecasted technological development indicators, a development period was determined up to 2050. In 2016, 16 wells were to be introduced from infill drilling: in the following, in 2017 – 11, 2018 – 4, 2019 – 3. The results of the first forecast hydrodynamic calculations showed that drilling of 34 design wells leads to a sharp drop in reservoir pressure both in the calculated area and over the entire deposit II of the Sokolkinsky uplift.

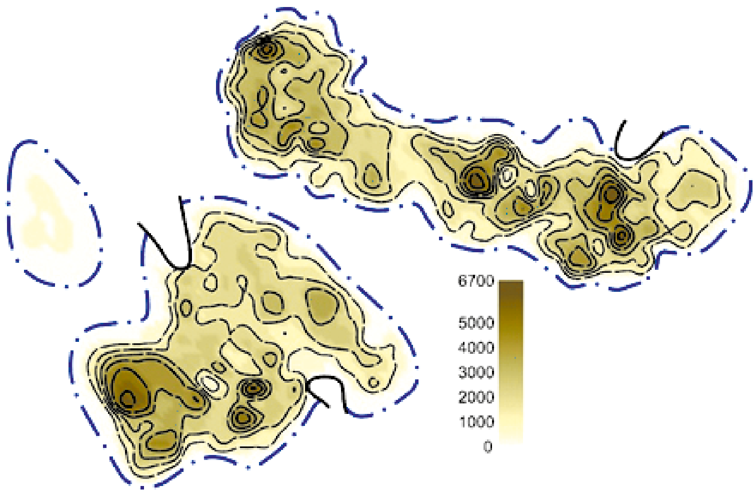

Fig. 3. Distribution of density of current mobile reserves

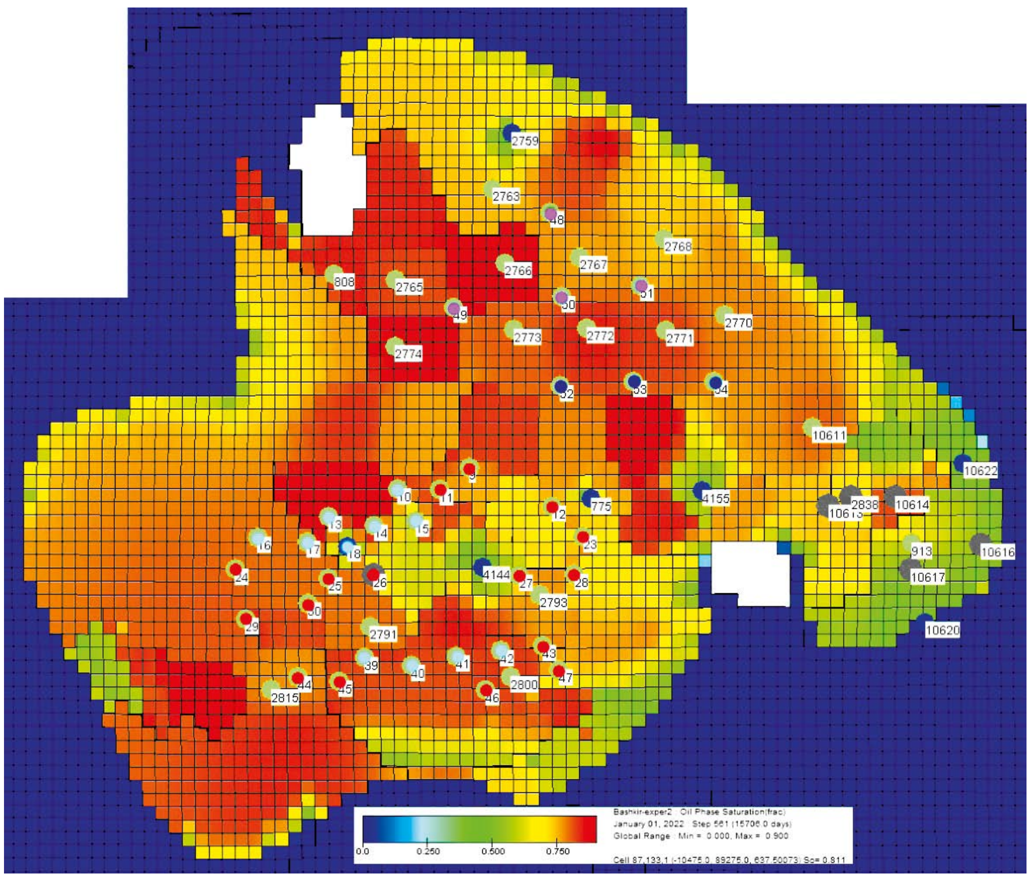

Fig. 4. Schematic location of project wells for drilling by years

Based on this, the option was considered for transferring 15 wells to water injection at certain intervals, depending on the pressure drop and the drop in oil production. In the upper part of the reservoir, wells are planned to be placed along a 5-point development system; in the lower part (area of well No. 775) focal flooding is planned. The layout of the development elements is shown in Fig. 5.

To assess the effectiveness of a particular development option, it is necessary to consider a number of factors that affect the final technological indicators, i.e. on accumulated oil production (Abdulmazitov, 2004; Zakirov, 2002; Shchelkachev, 1984).

The following factors can be attributed to this category:

- the number of simultaneously commissioned wells in the element;

- selection of the optimal development element (five-point, nine-point, etc.);

- organization of the reservoir pressure maintenance system (the ratio of production and injection wells);

- the time interval for the reservoir pressure maintenance system in the development element.

The proof of this fact is the analysis of three options considered, which makes it possible to determine how the development system, the ratio of production and injection

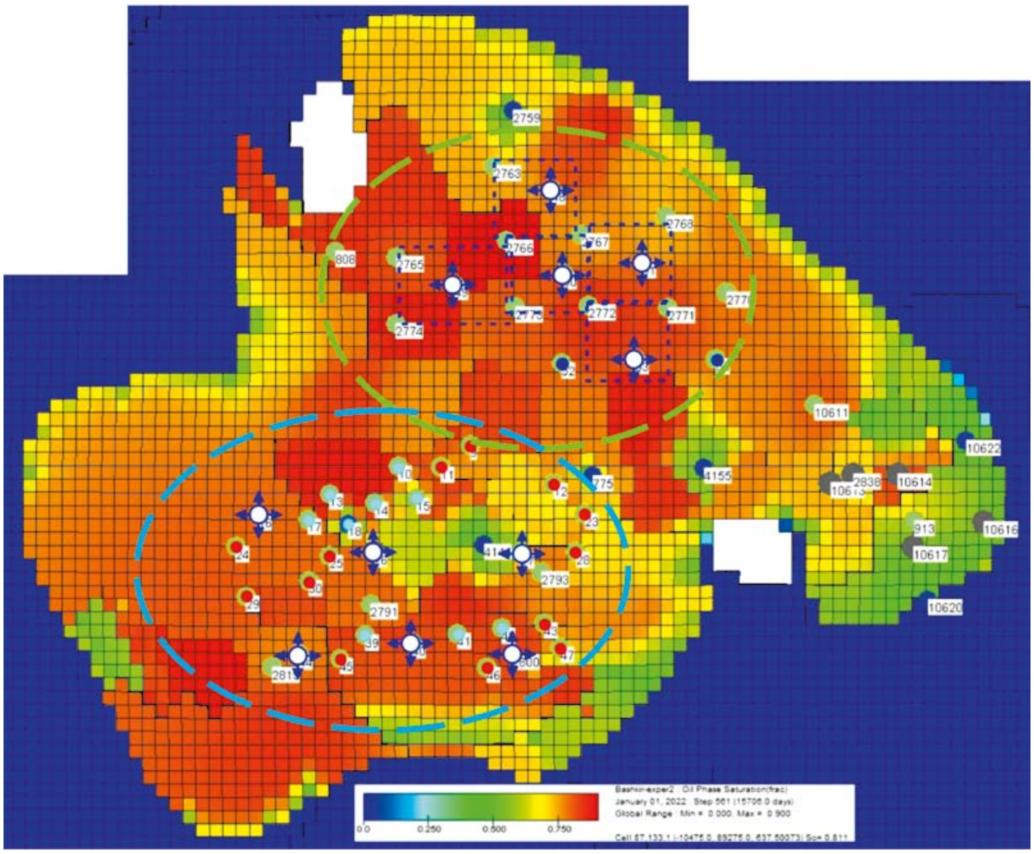

Fig. 5. Layout of the development elements

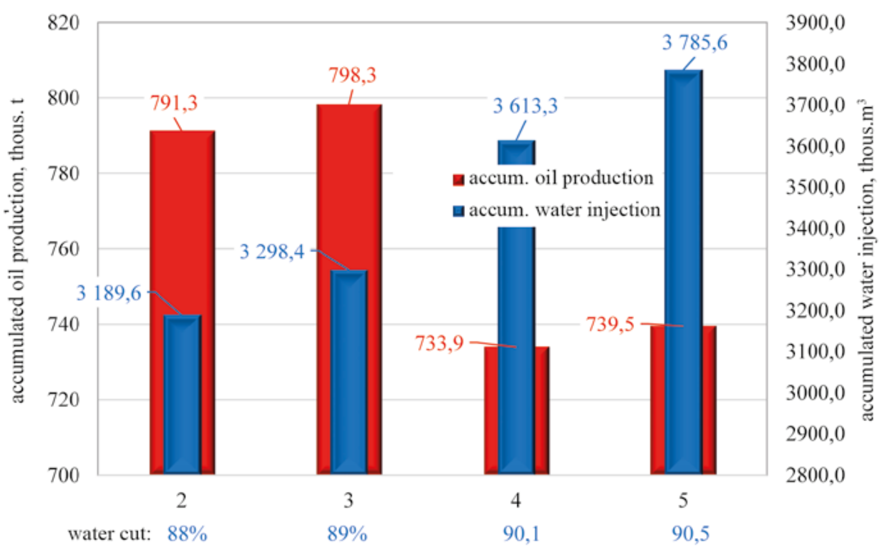

Fig. 6. Dynamics of accumulated production by groups of wells put into operation for certain years

wells, and the time of transferring wells into injection affect the production of oil. Figure 6 shows the dynamics of accumulated oil production and accumulated water injection wells in the Sokolkinsky uplift by the options. It can be noted that the commissioning of a group of fill-in wells, as well as the transfer of wells into injection, significantly affect the accumulated oil production and water cut (Abdulmazitov, 2004, Obobshchenie opyta razrabotki ..., 2005).

In the options with the organization of reservoir pressure maintenance system at the initial stage of development (options 4,5) the accumulated oil production is less than in the options with the transferring group of wells into injection in the middle stage of development (options 2,3). Accordingly, in options 4 and 5 water injection into the reservoir is greater than in options 2 and 3. The distribution of oil saturation at the end of development (2050) by options is shown in Fig. 7a-d.

It is believed that when filling-in the existing well pattern by drilling additional wells, interference occurs between the wells, i.e. wells depending on the geological structure (distribution of porosity, permeability) create interference in oil production (Zakirov, 2002; Schelkachev, 1984).

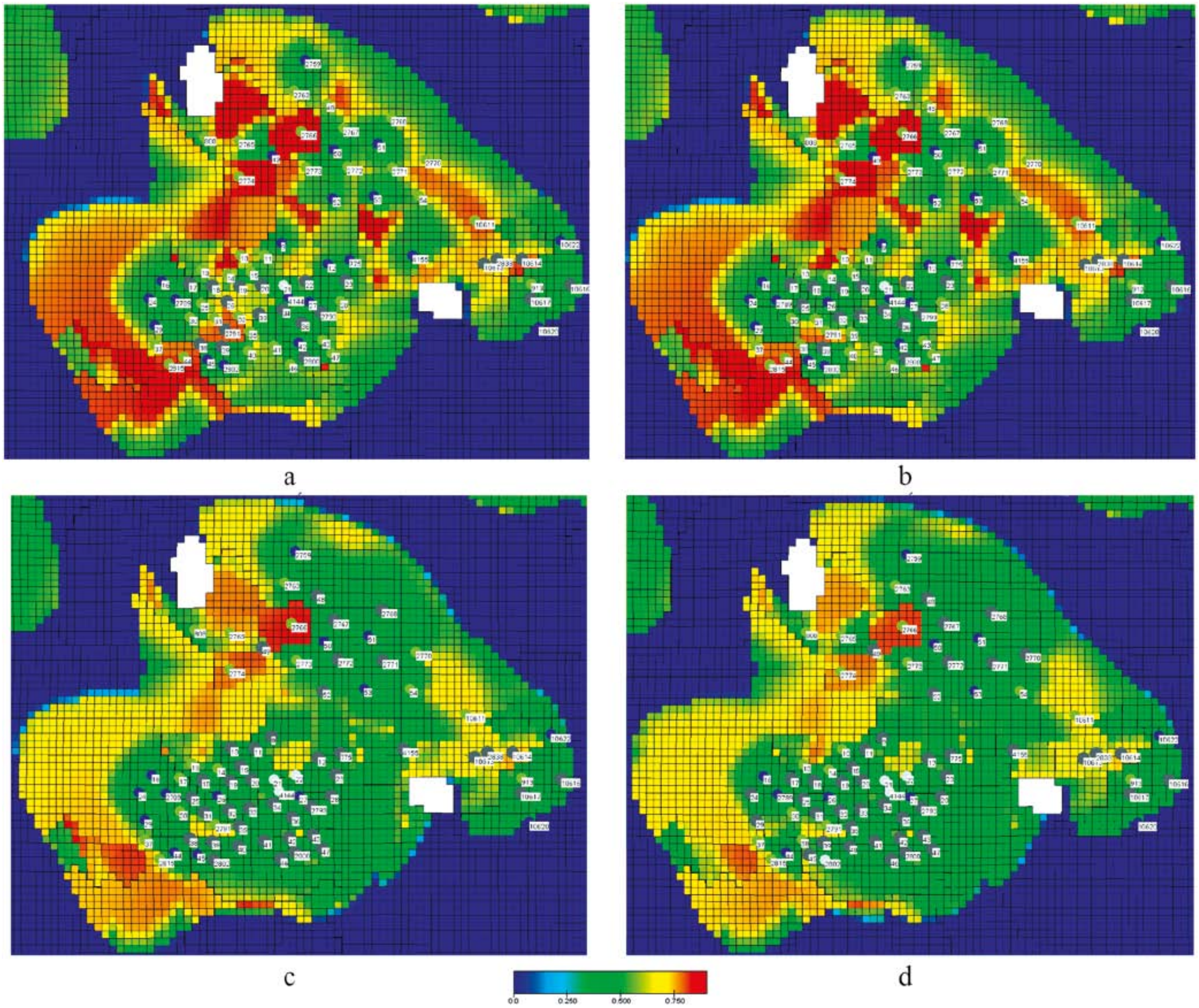

Fig. 7. Distribution of oil saturation at the end of the development by options (top view): a) 2, b) 3, c) 4, d) 5

Confirmation of this fact is in detailed analysis of the development of pilot sections of oil-bearing oil deposits with infill drilling (Yamashinsky, Bureikinsky and Shegurchinsky fields), which show the influence of interference on oil well flow rates (Abdulmazitov, 2004, Obobshchenie opyta razrabotki ..., 2005).

Proceeding from this, we will construct maps of the flow filtration lines depending on the time of input of project wells and wells transferred from other objects. Figures 8a-e show the dynamics of the change in the oil flow filtration lines depending on the year of drilling and introduction of wells into commissioning. Fig. 8a shows the flow filtration lines of the active wells in the deposit, Fig. 8b – at the time of commissioning of the first 16 design wells (01.2017), Fig. 8c – 11 wells (01.2018), Fig. 8d – 4 wells (01.2019), Fig. 8e – 3 wells (01.2020), Fig. 8f – transfer of the first wells into injection.

In order to identify interference between the wells, we shall discuss the results of the three options, where we select 2 sections, as shown in Fig. 9a-b.

At the 1 site, we will select the area of wells Nos. 10,13,14,15,17,18,24,25,26. It should be noted that the wells are put into operation at different times: Nos. 24,25,26 – 02.2016, Nos.10,13,14,15,17,18 – 02.2017. The schedule of oil flow rates (Fig. 9a) shows that for the period of 02.2016 – 12.2020, the introduction of wells Nos.10,13,14,15,17,18 into operation influenced the increase in flow rates of wells No. 24,25,26. For example, the flow rate of oil in well No.24 increased by 0.29 t/day, well No.25 – by 0.32 t/day, well No.26 – by 0.27 tons per day, with an average increase of 21.2%.

In the future, with the fall in reservoir pressure, the oil flow rates of wells Nos. 10,13,14,15,17,18 decrease, but subsequently, after the transfer in August 2018 of well No.26 for injecting water, there is a noticeable increase. For example, in the well No. 13 oil production grew by 0.13 tons per day, in wells No.14 – at 0.48 tons per day in the well No. 15 – by 0.19 t /day, in well No. 17 – by 0.07 t / day and in well No. 18 – by 1.25 tons per day.

The arrangement of water injection also affected the flow rate of oil in well No. 25, the increase was 1.64 tons/day. Filtration lines of oil flow in wells Nos. 10, 13, 14, 15, 17, 18, 24, 25, 26 of this section are shown in Fig. 10a-d.

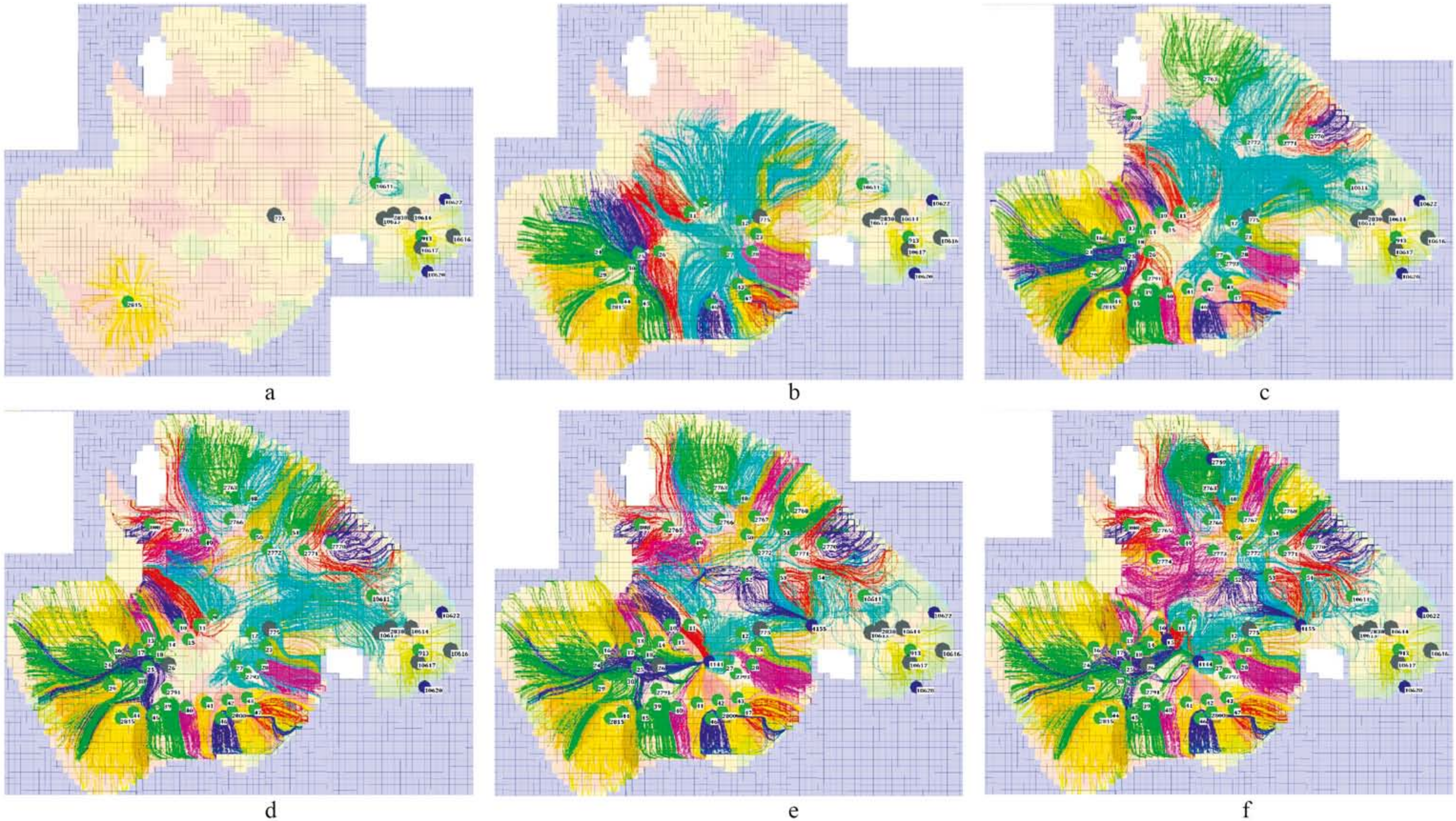

Fig. 8. Dynamics of the filtration lines of oil flow as on:
a) 01.2016, b) 01.2017, c) 01.2018, d) 01.2019, e) 01.2020, e) 01.2021

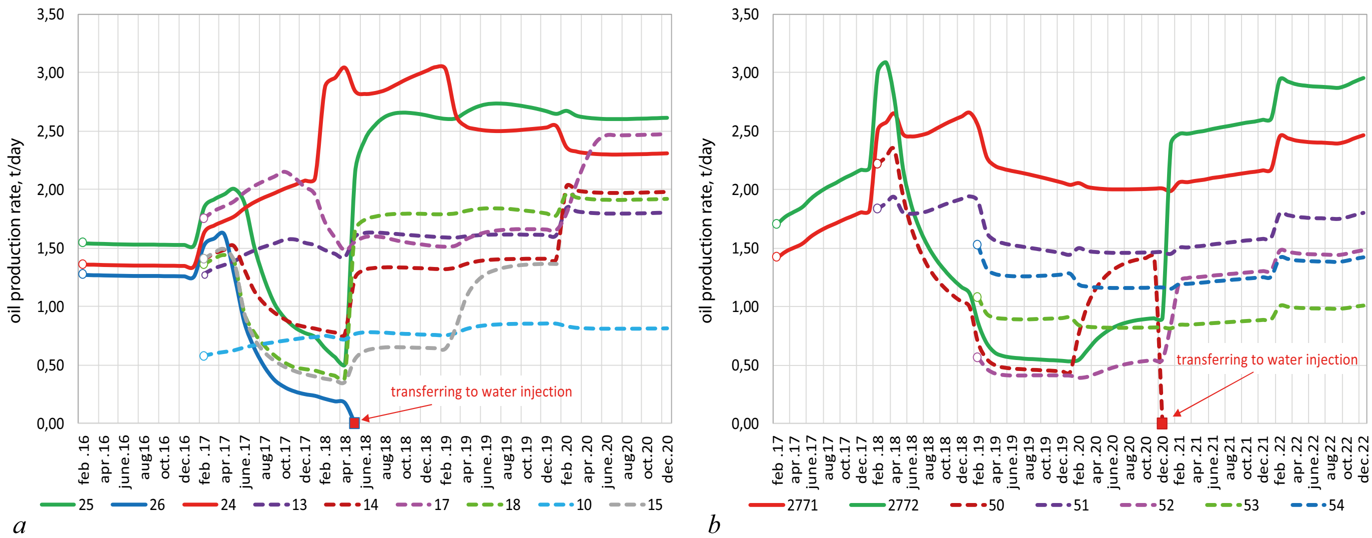

Fig. 9. Dynamics of oil production rates: a) for section 1 of 02.2016 – 12.2020, b) for section 2 of 02.2017 – 12.2022

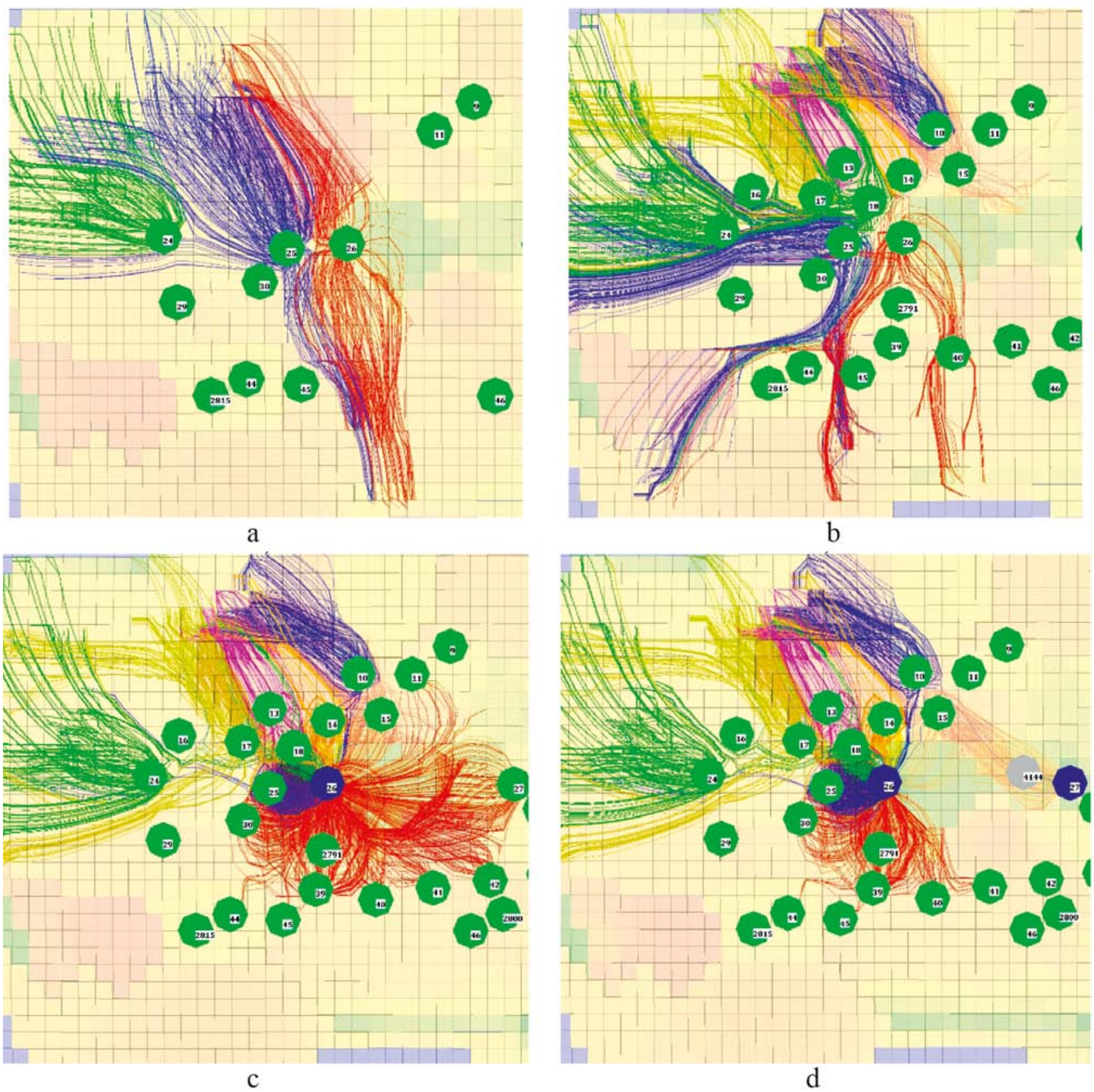

Fig. 10. Filtration lines of oil flow in 1 section as on: a) 01.2018, b) 01.2019, c) 01.2020, d) 01.2021

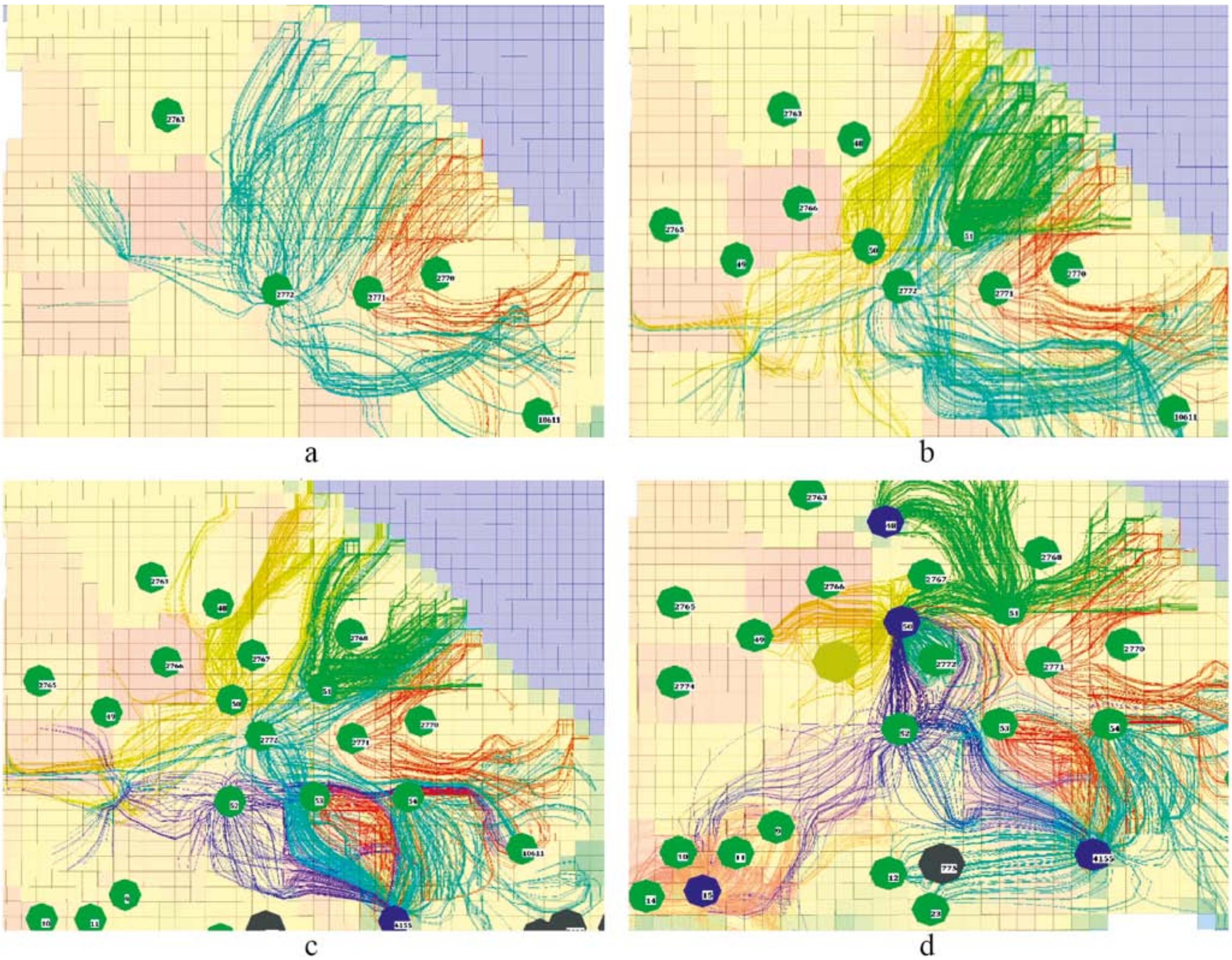

Fig. 11. Filtration lines of oil flow of oil in 2 sections as on: a) 01.2018, b) 01.2019, c) 01.2020, d) 01.2021

On the 2nd section we will select the area of wells Nos. 50,51,52,53,54,2771,2772 and it is worth noting that the wells are put into operation at different times: Nos. 2771,2772 – 02.2017 by transferring from other facilities, Nos. 50.51 – 02.2018, Nos. 52,53,54 – 02.2019. The dynamics of the oil flow rates of this group of wells for the period 02.2017 – 12.2022 is shown in Fig. 9b.

Fig. 9b shows that the introduction of wells Nos. 50,51 into operation significantly (spasmodically) affected the flow rates of wells Nos. 2771.2772. For example, in the well No. 2771 oil production increased by 0.68 tons/day, and in well No. 2772 – by 0.82 t/day, with an average increase of 37.2%.

In the future, with the fall in reservoir pressure, the oil production rate in wells Nos. 2771.2772 began to decrease sharply, by 0.64 t/day and 1.86 t/day, respectively.

In this regard, in February 2020 the well No. 48 and in December 2020 the well No. 50 are transferred into water injection. Wells No. 2772 and No. 52 reacted on the water injection, according to which the oil flow rate increased by 1.49 t/day and by 0.37 t / day, respectively. Fig. 9b also shows that in February 2022 in wells. Nos. 2771, 2772, 51, 52, 53, 54 there is a slight jump in oil flow rate, due to the breakthrough of injected water from wells Nos.15,4155. The filtration lines of the oil flow in the given section are shown in Fig. 11a-d.

Conclusions

1. The choice of the development system and the optimal well spacing are of great importance in the theory and practice of oilfield development. In this regard, a number of important issues remain relevant at all stages of the development of the national oil industry, and they are given constant attention (Abdulmazitov, 2004; Zakirov, 2002, Shchelkachev, 1984, Obobshchenie opyta razrabotki ..., 2005; Takhautdinov et al. 2009).

2. It is promising to establish deterministic permanent mathematical models of oil fields for optimizing the infill well pattern in order to increase oil recovery, with the help of which it is possible to identify poorly drained and stagnant zones of the reservoir, to establish their size and ways of involving them in active development.

3. Currently, in the context of a decline in oil prices, each development option can be characterized by three main indicators: the level of oil production, the economic

indicators of the hydrocarbon field development (net present value) and the oil recovery factor. These three indicators characterize the effectiveness of field development from different sides, often contradict each other, besides, the subsoil user and the government are sometimes interested in achieving the maximum values of various indicators.

In this regard, it is necessary to seek a reasonable compromise between these criteria of rationality, to find the best balance of interests between the subsoil user, the government and the requirements for protection of the subsoil and the environment.

4. The results of geological and hydrodynamic calculations to study the effectiveness of pilot works on the infill well spacing at the Sokolkinsky uplift of the Sokolkinsky field show that when justifying the design well spacing, it is necessary first of all to take into account factors that affect both current and forecast technological indicators:

- the number of simultaneously commissioned wells in the element;
- selection of the optimal development element (five-point, nine-point, etc.);
- arrangement of the reservoir pressure maintenance system (the ratio of production and injection wells);
- the time interval for the reservoir pressure maintenance system in the development element.

References

Abdulmazitov R.G. Povyshenie effektivnosti razrabotki zalezhei s trudnoizvlekaemymi zapasami: *dis. dokt. tekhn. nauk* [Increasing the development efficiency of deposits with hard-to-recover reserves: Dr. tech. sci. diss.]. Ufa. 2004. (In Russ.)

Dopolnenie k tekhnologicheskoi skheme razrabotki Sokolkinskogo neftyanogo mestorozhdeniya [Addition to the technological scheme for the development of the Sokolkinskoye oil field]. Institute «TatNIPIneft». Kuznetsova A.A., Salakhova S.N. Bugulma. 2015. 315 p. (In Russ.)

Obobshchenie opyta razrabotki melkikh mestorozhdenii (NGDU «Nurlatneft'» i «Yamashneft'») [Experience generalization of the development of small deposits (NGDU Nurlatneft and Yamashneft]. Institute «TatNIPIneft». Bakirov I.M. Bugulma. 2005. 1 book – 335 p., 2 book – 211 p. (In Russ.)

Pereschet zapasov nefti i TEO KIN Sokolkinskogo mestorozhdeniya (Prudkovskoe podnyatie). Tatarskoe geologorazvedochnoe upravlenie: Otchet [Recalculation of oil reserves and feasibility study of KIN of the Sokolkinsky field (Prudkovsky uplift). atar Geological Exploration Department: Report]. Akhmanova L.G. Kazan. 2009. 166 p. (In Russ.)

Shchelkachev V.N. On the confirmation of a simplified formula that estimates the effect of the well grid density on oil recovery. *Neftyanoe khozyaistvo = Oil industry*. 1984. No. 1. Pp. 26-30. (In Russ.)

Takhautdinov Sh.F., Slivchenko F.F., Khisamov R.S., Yusupov I.G., Zalyatov M.Sh. Dependence of oil recovery on the well grid density. *Neftyanoe khozyaistvo = Oil industry*. 2009. No. 3. Pp. 34-36. (In Russ.)

Zakirov S.N. Analiz problemy «Plotnost' setki skvazhin – nefteotdacha» [Analysis of the problem "Density of the well grid – oil recovery"]. Moscow: "Graal" Publ. 2002. 316 p. (In Russ.)

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